Efforts to Develop a Responsible Offshore Aquaculture Industry in the Gulf of Mexico:

A Compendium of Offshore Aquaculture Consortium Research

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Preface

"…to develop socially and environmentally acceptable offshore aquaculture models that are appropriate to all stakeholders in the Gulf of Mexico region." - OAC Goal from http://www.masgc.org/oac/

The contents of this book describe the collective journey of researchers involved with the Offshore Aquaculture Consortium (OAC) to determine the feasibility of offshore aquaculture in U.S. federal waters in the Gulf of Mexico. This initiative began in January 2000 and culminates with the production of this volume. Over its four-year life, the OAC received three awards from the NOAA National Sea Grant College Program's National Marine Aquaculture Initiative, totaling ~ U.S. $880,000. The initial OAC proposal was a collaborative effort between six Principal Investigators and was valued at less than U.S. $150,000. This initial proposal allowed a permitting review to conduct offshore aquaculture in the Gulf of Mexico and the purchase/deployment of an Ocean Spar Sea Station cage. A second grant was awarded to conduct further regulatory research related to marine aquaculture zoning solutions for offshore aquaculture. Finally, our third grant was awarded over a two-year period to conduct engineering, genetic, environmental, economic, fish health management, and outreach research. This final grant equaled the balance of our total research funds at ~ U.S. $650,000. This volume represents our final technical report to the NOAA National Sea Grant College Program and encompasses all research activities conducted by the OAC.

The challenge for the future will be to develop a sustainable—economic, social, and environmental—aquaculture industry that will be present for generations to come. As we progress and expand into this millenium, the global population must keep the principles of sustainability forefront in the development of aquaculture production systems. Throughout this book, I hope that we fully demonstrate to readers the breadth of research conducted by the OAC "to develop socially and environmentally acceptable offshore aquaculture models that are appropriate to all stakeholders in the Gulf of Mexico region."

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CHAPTER 1

STATUS OF UNITED STATES AQUACULTURE & WHY MOVE OFFSHORE

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ABSTRACT

Aquaculture arose in the United States during the mid-1800s, with most of the effort being placed on the production of fish and shellfish for stocking both inland and coastal waters. Commercial aquaculture production was insignificant until the 1960s when channel catfish farming led the way, followed by a host of other species. The first salmon cages were developed during the 1970s, and the net pen Atlantic salmon industry arose during the 1980s in Puget Sound, Washington and in some of the protected coastal waters of Maine. Other users existing in those waters prompted aquaculturists to look to the offshore environment as an alternative, and while that approach has significant merit, it has been slow to develop. The federal government is only now promolgating regulations for aquaculture in the Exclusive Economic Zone, so no permit system is available, which is a major limiting factor. There has been some activity in exposed waters in states that have regulations in place. A major constraint to open ocean aquaculture development is the cost associated with moving offshore. Facilities that can withstand the hostile ocean environment are much more expensive to construct, install, and maintain than those employed in protected coastal waters. Various cages have been designed for offshore use, but it is only within the past few years that the majority of the engineering problems have been resolved. Logistical problems become more and more significant as distance from shore increases. Travel time, the need for seaworthy vessels, and the fuel to run them all add to the expense. Finding a species that can be sold at a profit has been a major issue, particularly in the face of imported fish that are raised in ponds or protected coastal waters where regulations are often lax or lacking, labor is inexpensive, and overall production costs are much less than those required to rear the same species offshore. Finally, open ocean aquaculture has opponents who argue that such facilities will pollute the environment and may spread disease to wild populations, among other things. Despite the obstacles, interest in developing an offshore aquaculture industry in the United States remains strong and the government recognizes the inevitability of its development. There remains only the questions when and where the industry will develop, and with which species.

DEVELOPMENT OF UNITED STATES AQUACULTURE

Origins

Aquaculture was developed in the U.S. largely in response to the observation by Spencer F. Baird that the nation's fisheries were being overexploited (Stickney 1996). In 1871, Baird, a respected naturalist and then Secretary of the Smithsonian Institution, convinced Congress to establish the U.S. Fish and Fisheries Commission. Baird was named as the first Commissioner. One of his early actions was to seek out the few established fish culturists in the nation and employ them to produce fish for distribution into the freshwater and marine areas of the country. Those early fish culturists included such legendary figures as Seth Green, Livingston Stone, and Charles Atkins. All of them had been involved with salmonid culture (brook trout and Atlantic Salmon), but soon they, and others that followed, were spawning a wide variety of both marine and freshwater fishes. The activities of those early American fish culturists were augmented by crews that captured wild fish from areas where the fish were plentiful and distributed them into areas where populations of the same species had been greatly reduced, as well as, into areas outside the native range of the fishes. Distribution involved the use of railroad baggage cars modified to haul live aquatic animals.

Over several decades, billions of fish were captured or produced in hatcheries and stocked throughout the nation, and in some instances around the world. Nations that were supplied with U.S. fish often reciprocated, which is how brown trout and common carp became established in U.S. waters. Attempts were made to introduce Pacific salmon to the east coast and Atlantic salmon (along with American oysters, striped bass, American lobsters, and a variety of other species) to the west coast. Striped bass did become established in California, while rainbow trout (native to the region west of the Rocky Mountains) were established in nearly every state.

While the numbers of fishes and invertebrates hatched and distributed throughout the nation were almost inconceivable, successes in terms of increasing existing or establishing new populations were few. Most of the animals were released as larvae or fry since the technology required to feed the young stages of many species was not developed until many years after the program was initiated. Thus, it is a fair assumption that most of the animals that were stocked served as food for indigenous species or died to become animal detritus.

Be that as it may, many of the techniques that are still in use today can be traced back to the work of the pioneer fish culturists of the late 19th and early 20th centuries. Many of the methods required for spawning and hatching some of the species produced during the early years of the Fish and Fisheries Commission and its successor organization, the Bureau of Fisheries, were not written down and were thus lost. It has not been until the past few years that modern fish culturists have redeveloped the techniques required to spawn several species that the early culturists had pioneered.

Commercial Aquaculture

While a few of the early fish culturists produced modest quantities of fish commercially—sometimes while also producing fish on behalf of state or local government—it was not until the 1960s that private aquaculture of foodfish began rapid expansion to become the industry that exists today. Rainbow trout culture developed in the west, with the focal point becoming the Thousand Springs area on the Snake River in Idaho. That region produces the vast majority of the rainbow trout marketed today. The enormous quantities of high quality water of the proper temperature that flow from the north side of the canyon walls is diverted through raceways before entering the river. Modest production levels of rainbow trout can be found in many other states.

Channel catfish are the backbone of the freshwater cultured fish production industry in the U.S. Farmers in the south-central states first focused their attention on buffalo fish (*Ictiobus* spp.) as potential culture species. In the 1950s, Dr. Homer Swingle at Auburn University published a paper indicating that channel catfish could be reared to market size and that a profit could be made if farmers were able to obtain $1.20/kg at the pondbank (Swingle 1957, 1958).

The commercial culture of anadromous salmonids, in particular chinook, coho, and Atlantic salmon arose as a natural offshoot of the intensive hatchery programs developed by various states and the federal government, primarily in Washington, Oregon, Alaska, and Maine. Hunter and Farr (1970) described the first salmon net pen in Puget Sound, Washington (designed to hold adult fish) and Novotny (1975) described the process of producing salmon in net pens. Within several years the emphasis in the Puget Sound region shifted from native species to Atlantic salmon. While a modest Atlantic salmon culture industry has been developed on both the Atlantic and Pacific coasts, the vast majority of the salmon produced in the world come from Norway and Chile. Scotland and Canada are also significant producing nations. Permitting problems and objections to salmon culture in the U.S. have largely stifled further development of the industry.

Aquaculture in the U.S. was largely restricted to mollusks, and in particular, oysters until the latter two or three decades of the 20th century. Shellfish aquaculture then expanded into the production of mussels, clams, and abalone. Of much more interest and receiving the bulk of the attention by researchers looking for new shellfish species to rear, were shrimp—both marine and freshwater. Beginning with research in the 1970s, shrimp culture began to be developed, with commercialization being achieved and developing rapidly in the 1980s. Two approaches for rearing the larvae of marine shrimp were developed—one in the United States, the other in Asia—and both technologies were applied as the industry developed. Freshwater shrimp received a great deal of attention in the 1980s as well, but various problems led to the virtual demise of that industry, not only in North America but throughout the world where production is insignificant compared with the marine species.

Commercial production developed primarily in Latin America (in particular, Ecuador) and Asia (with Thailand and China being major producing nations). Texas leads the nation in U.S. commercial shrimp production today, and there are modest amounts produced in a few other states. The food shrimp industry in the U.S. is based exclusively on exotic species, so biosecurity has been a major issue and some have expressed concerns that escapees could reproduce and threaten the survival of native species, though no sign of that happening has been observed to date.

Marine fish culture is the most recent area under development. Commercial culture of red drum began in the 1980s, and was preceded by a few years by commercial hybrid striped bass culture. Both species were originally produced by government agencies, so the technology of spawning and rearing the early life history stages was in place prior to commercialization.

University and government researchers have been actively developing the procedures for culturing a number of other marine species. Included are red snapper, cobia, dolphin (mahi-mahi), Pacific threadfin, tuna, cod, ling cod, flounders, and halibut (Pacific and Atlantic). Some of those species enjoy at least a modest level of commercial production in the U.S. or elsewhere in the world.

U.S. AQUACULTURE PRODUCTION AND WHAT IS HOLDING IT BACK

According to the Food and Agriculture Organization (FAO) of the United Nations (http://www.fao.org), the United States is responsible for only about two percent of the world's aquaculture production, though the potential for increasing output from aquaculture is significant. Government statistics for 2001 (U.S. Department of Commerce 2003) show that the total amount of foodfish and shellfish produced was nearly 355,000 metric tons valued at over U.S.$786 million. Those figures exclude baitfish, algae, aquatic plants, alligators, eels, scallops and a few other miscellaneous items. A breakdown by species group of the animals that contribute to the totals mentioned is presented in Table 1.

Table 1. Estimated production (metric tons) and value (U.S. dollars) of major aquaculture food animal production in the U.S. in 2001 (U.S. Department of Commerce 2003).

Species or Species Group	Production	Value
Finfish		
Catfish	270,846	386,329
Salmon	20,769	72,019
Striped bass	4,946	28,520
Tilapia	7,983	30,000
Trout	25,813	64,482
Shellfish		
Clams	4,525	35,404
Crawfish	13,847	40,545
Mussels	303	1,169
Oysters	7,629	39,886
Shrimp	3,607	27,808

While aquacultural production has expanded rapidly in many nations, the United States, despite its enormous potential for producing aquacultured products, seems to lag further and further behind. That outcome is not because of lack of interest. There are certainly plenty of entrepreneurs and venture capitalists interested in becoming involved in U.S. aquaculture, the technology to produce a variety of species exists, and the U.S. market for aquacultured products continues to expand. However, further development of U.S. aquaculture has been limited by a number of factors. Among the most important are the legal and regulatory framework, the inability of domestic aquaculturists to compete with cheap imports in some instances, high overhead costs, and opposition.

Regulations

For inland aquaculture on private land, the regulatory environment is fairly benign in many states, though it can be quite imposing in others. Obtaining a permit to farm freshwater fish in a pond may be as simple as paying a license fee (though a much more arduous process is not uncommon). Developing an aquaculture facility in public waters tends to be much more difficult. In the marine environment the situation may involve working ones way through upwards of a dozen state and federal agencies during the permitting process. The court system has increasingly become involved in the process as opponents file lawsuits against aquaculture projects. For development of aquaculture in state waters and in the Exclusive Economic Zone (EEZ) of the United States—the topic that is the primary focus of this book—he permitting process is still under development in some coastal states and at the federal level.

While often not onerous to inland aquaculturists on private land, state regulations for those operating in public fresh, estuarine or coastal waters can be extremely rigorous. This has been particularly true in the case of salmon aquaculture, both in Maine and in the Pacific Northwest (commercial salmon farming is outlawed in Alaska except for not-for-profit ocean ranching operations in which some returning fish are utilized as broodstock while most are taken in the commercial fishery). Prior to establishing a facility, the applicant may be required to gather a significant amount of information to demonstrate that the proposed site is appropriate in that environmental degradation appears to be largely avoidable. Once a facility is established, frequent monitoring of water and sediment quality may be required, special and costly efforts may be mandated to ensure, to the extent possible, lack of escapement of the cultured species, and tagging of individual animals may be required so escapees can be identified. Other requirements regarding the genetics of the animals being reared and/or stocking of sterile or unisex fish have been proposed or implemented in some cases. The costs of meeting the regulatory requirements can be significant, though the intent of governments to maintain environmental quality and avoid negative impacts on native fauna by cultured animals is a goal that is understood and supported by society and, for the most part, those involved in the aquaculture enterprise. There is a point, however, where meeting the regulatory requirements can mean loss of any chance for profitability.

Most aquaculturists profess to be environmentalists in that they take their responsibilities for environmental stewardship very seriously. They also are dedicated to maintaining an excellent environment for their charges since degradation of the culture environment can only lead to problems for the species under culture. Maintaining a healthy culture environment usually translates into maintaining a good environment in the adjacent waters. That does not mean that aquaculturists are always being unfairly criticized. More on that subject is discussed below.

Imports

The United States channel catfish and Atlantic salmon culture industries, along with both the commercial and aquacultured shrimp industries, are suffering from the import of products that are being produced and sold at lower prices than must be obtained by the domestic producers if those producers are to stay in business. In the case of catfish, the primary competition is unrelated catfishes from Viet Nam. The U.S. farmed salmon industry is in competition primarily with Chile, though farmed salmon from Canada and elsewhere also enter the domestic market. Both captured and cultured shrimp from Asia and Latin America have caused many shrimp boat owners to tie up their boats during the 2003–2004 seasons as they cannot operate at a profit even with an abundant wild shrimp population. Similarly, cultured shrimp are more costly to rear in the U.S. than abroad so shrimp culturists are having difficulty breaking even, let alone making a profit in the face of inexpensive imports.

Aquaculturists have sought relief in various ways, including recommending tariffs on selected imported seafoods and searching for subsidies under the 2002 Farm Act legislation. In 2003, a tariff of up to 64% was placed on catfish called basa that are being imported from Viet Nam by the U.S. International Trade Commission. Basa compete directly with channel catfish though the two are members of different families. While the tariff led to a sharp decline in imports of basa, that did not lead to higher prices being paid to domestic catfish farmers. In fact, the average price of fresh channel catfish actually fell. Processors also claim that they are suffering from low prices. In the meantime, domestic catfish production continued to increase. The latest fear is that China, which as begun producing channel catfish, will begin flooding the U.S. market with fish in the future (http://www.seafoodbusiness.com).

Shrimp culturists and harvesters have also been seeking government intervention through the tariff process and for relief through subsidies through the U.S. Department of Agriculture Farm Bill.

Legislation was passed in 2004 to put import tariffs on shrimp exported by certain companies in some nations.

Support by culturists and wild harvesters for country of origin labeling legislation has also been strong. The assumption is that Americans will select the domestic product over imports even if the price of the former is higher. That theory remains to be tested in the marketplace.

Overhead

The cost of doing business can be significantly higher for U.S. aquaculturists compared with their counterparts in much of the rest of the world. Subsidies, tax breaks, low land and labor costs, disregard for environmental impacts, and in many cases, more suitable climates for aquaculture may all mitigate against the domestic producer. The cost of developing a culture system on private land one already owns is much less than that required for purchase and development of the same amount of land on the coast, yet costs in both cases can mean economic failure when the margin between cost of production and farm gate price is very low and can even be negative.

Opposition

Many chose to either disregard or elect to develop facilities in spite of the above-mentioned problems. However, those who proceed with plans to establish facilities in public waters cannot often ignore the opponents to aquaculture. Opposition takes multiple forms and is most aggressive and effective in coastal waters with regard to net pen and cage culture operations. The list of objections is long and includes:

- visual pollution;
- pollution of the water column with waste feed and feces;
- creation of anoxic zones due to deposition of waste feed and feces on bottom sediments;
- transmission of disease from cultured to wild fish;
- escapees interbreeding with native animals of the same species and reducing genetic diversity in the local population;
- use of antibiotics;
- noxious odors;
- excessive noise;
- interference with navigation;
- interference with fishing;
- use of exotic species; and,
- interactions with threatened or endangered species.

Broader issues include the use of fishmeal to feed fish and in the case of shoreside facilities, destruction of valuable wetlands such as mangrove swamps. The issues and what is being done and can be done to address them are considered in detail in a book edited by Stickney and McVey (2002).

NEW DIRECTIONS FOR COASTAL REGIONS

Appropriate space in coastal areas is limited in the United States, or in many cases where space is not an issue, competition with other users—many of whom are willing to pay much higher prices than can be afforded by the aquaculturist—makes establishment of fish farms impractical. The National Research Council of the National Academy of Sciences (NRC 1992) looked at the situation with respect to marine aquaculture in the U.S. over a decade ago and concluded that there were two options that represent the best possibilities for expansion of finfish aquaculture. The recommendations of the Council were to develop onshore recirculating water systems and establish offshore facilities. Since this book focuses on offshore aquaculture, that option is the one emphasized here, though there are a few words on recirculating systems at the end of this chapter. In addition, the discussion is directed toward finfish aquaculture in net pens and cages. Bottom culture of mollusks is somewhat less controversial in that it avoids many of the problems associated with aquaculture in the water column and does not require the use of prepared feeds.

Advantages of Moving Offshore

Offshore aquaculture facilities have a distinct advantage in having virtually unlimited space available for the activity. With proper attention to the density of fish per unit area (controlled by the number of cages or net pens allowed and control of total stocking density), impacts on water quality and the benthos can be avoided due to broad dispersal of waste products due to currents. Impacts on the culture species from pollution that might be present in protected bay and estuarine waters are obviated and, significantly, upland landowners do not object to offshore facilities if those facilities are located sufficiently offshore to be out of sight from land.

Fluctuations in water quality tend to be reduced in offshore areas. Daily and seasonal temperature fluctuations are somewhat dampened, dissolved oxygen tends to be more than adequate for good growth of the species under culture, pH is highly regulated by the oceanic buffer system, salinity remains highly stable, and nutrient levels are often quite low.

Offshore culturists may be able to take advantage of existing offshore structures as support facilities. The Gulf of Mexico, particularly the western Gulf, contains thousands of oil and gas platforms, many of which would be suitable as support facilities. While there remain issues associated with having ancillary personnel on active platforms and the conveyance of ownership of non-producing platforms to aquaculturists from the oil and gas companies, the potential for conversion of platforms from their original use to support aquaculture is attractive. Many platforms are sufficiently large to have living accommodations, helicopter landing pads, and plenty of room for feed storage. Platforms could also be used as hatcheries and early rearing facilities, thereby providing support for the entire life cycle of the species under culture.

Disadvantages of Moving Offshore

Being offshore in the EEZ also has some distinct drawbacks. A major one is logistics. People must be routinely present to inspect, clean, and repair net pens and cages, provide feed or fill feed bins if automatic feeding systems are employed, remove mortalities, stock and harvest fish, collect water quality and growth data, and perform various other duties associated with maintaining the facility. Having a suitable structure available such as an oil and gas platform or anchored barge large enough to house personnel will remove the need to service the facility from shore on a daily basis. In either case, working offshore is much more expensive than would be the case in bays and estuaries. Because of the exposure of offshore facilities to the elements, the cost of the cages or net pens is considerably higher than for similar culture chambers in the inshore environment.

Some of the early work with offshore containment structures showed that random wave motion wreaked havoc with shackles and other components. Storms accounted for more immediate failure and loss of fish and even the cages or net pens themselves. Advances in engineering technology have overcome some of the problems, and cages designed to be submerged at all times or at least during periods of storms have been developed and are currently in use in some places. Still, not all the engineering challenges have been overcome and work continues to be conducted in that arena. That work includes development of feeding systems for submerged cages.

Issues surrounding logistics were mentioned above with regard to the discussion on use of offshore platforms, but it is worth bringing the subject up again. If a facility is located in the EEZ, it could take up a considerable amount of time to travel by boat from shore to the cage or net pen system. Taking a helicopter would shorten the time considerably but would significantly elevate the cost involved. Having a support facility that would allow personnel to remain on station for extended periods (perhaps up to a month) would reduce transit costs, though premium wages would undoubtedly have to be paid.

Challenges to Overcome

Putting technological and sociological issues aside, the most immediate need is to get a permitting process in place that covers all state waters and the EEZ. Obviously, this will involve development of permitting policies by the individual coastal states and by the federal government, though there may also be straddling issues that need to be considered. It is easy to envision a request for permits of a site that is partially in two states, partially in one state and in federal waters, and even split among two states and federal waters.

Several states have developed a marine aquaculture permitting process, though the present processes may not always be applicable to offshore waters as the initial focus has been on aquaculture in intertidal and protected areas. Each states' permitting system should be re-evaluated with consideration given to whether it would be applicable to offshore areas within state waters.

With regard to the federal government, permitting has only been well developed for oil and gas drilling and for mining of the seafloor under a system overseen by the Minerals Management Service. When that process was developed, there was no interest in aquaculture in the EEZ, so no provision was made. Stickney (1997) reviewed the situation as it existed a few years ago and apparently continues to exist today.

Enormous economic benefit to the government has been obtained from leases of oil and gas blocks in the nation's state waters, and in particular, in the EEZ. Such will not be the case with respect to offshore aquaculture. Profit margins tend to be quite low to producers who have little or no control on the consumer prices paid for their products because the control lies at one or more other levels (among which are processors, wholesalers, and retailers) in the chain of custody. Imported competing seafood products that can be captured or raised at substantially reduced costs compared with those produced in the U.S. also mitigate against high profits for the industry overall, and in particular, for the nearly non-existent offshore industry. When the added costs involved in locating facilities offshore are taken into account, the bottom line is often not competitive with sources of the same product from other sectors of the industry.

One can argue that luxury products such as sushi-grade tuna could be the source of prodigious profits. Putting aside the technological development needs associated with producing such a product on a routine and sustainable basis, in all likelihood the process would unfold similar to that associated with predecessor species. That is, the first successful individuals or companies that produce a particular species or product may be able to demand very high prices. However, as others begin to compete, the price falls until—at least one would hope—everyone makes some profit, but no one receives a windfall any longer. Overproduction can, of course, lead to price collapse to the point that no one profits. As we are seeing with respect to channel catfish, shrimp, and salmon, foreign competition can also be a factor in driving down prices to domestic producers.

The regulators should recognize all of this as a signal for them to keep the costs of obtaining permits and leasing offshore sites to a minimum. States and the federal government are not likely to realize any more than the administrative costs associated with overseeing their programs. If high lease costs are imposed, those interested in the offshore aquaculture industry will either not proceed to the development phase, of if they do, could in many cases be forced into bankruptcy. Until those interested in the offshore industry have a clear set of running rules and associated costs, many will be reticent about proceeding with development even under research permits (which apparently can be obtained at present).

Closed Systems

The NRC report (NRC 1992) indicated, as previously mentioned, that more consideration should be given to recirculating water systems on land, as well as, to development of offshore systems. While recirculating system technology has developed to the point where such systems are highly dependable and can produce aquatic animals quite effectively, they have largely been economic failures in cases where the entire life cycle of a species, or even rearing from juvenile to market size are undertaken. Exceptions occur with respect to unique situations such as when water of the proper temperature is available at virtually no cost and a considerable amount of water exchange (partial recirculation) is employed. Another exception has been associated with at least some tropical fish producers. Polyculture systems that incorporate high cost plants or other valuable specialty items have also sometimes been economic successes.

Since fish stocked in offshore facilities must be large enough to remain contained within the mesh of the cages or net pens, it will be necessary to either purchase fingerlings or grow them at a second facility. That facility could be established on an offshore platform or floating facility (an anchored barge for example) or on land. (An offshore facility could also be operated as an open system.) Logistics and costs associated with an on land recirculating facility might make that the most attractive option. Such a facility (whether at sea or on land) could maintain broodstock, provide spawning and hatching facilities, and house larvae, fry, and early juveniles until they are large enough for stocking offshore. When employed in that fashion, recirculating systems can be economical and may be necessary in order to ensure a continuous supply of animals to stock out in the offshore location.

CONCLUSIONS

Open ocean aquaculture facilities offer another choice that may be available to the aquaculturist, but while there are some significant benefits associated with employing that option, there are also negatives that must be given due consideration. A few successes and many failures associated with past attempts at moving aquaculture offshore have been seen and it is clear that the risks are high. As research produces new technology and expands the number of species that are suitable for offshore culture, and as the permitting situation becomes resolved, the risks and other negative aspects of establishing aquaculture facilities in the open ocean may be reduced considerably. In the meantime, risk-takers will continue to push the proverbial envelope and can be given credit for having the intestinal fortitude to stand up to the challenges. While many may fail, adaptive learning obtained from their experiences will help others to succeed. Marine aquaculture has entered a new phase—one that holds a great deal of promise and may provide one mechanism whereby the United States can expand production and begin to meet domestic demands.

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CHAPTER 2

THE GULF OF MEXICO OFFSHORE AQUACULTURE CONSORTIUM[1]

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ABSTRACT

Marine aquaculture may be classified into four categories according to the degree of protection afforded to the operation by the site characteristics: land-based operations; coastal, protected aquaculture; coastal, exposed aquaculture; and, offshore aquaculture. Offshore operations have all the logistical challenges of both remote coastal and exposed aquaculture but at an escalated scale. In 1999, the Gulf of Mexico Offshore Aquaculture Consortium (OAC) was formed to create a collaborative, Gulf-wide university-based interdisciplinary research program to address social, environmental and technological issues that have plagued offshore aquaculture endeavors in the Gulf of Mexico, OAC research and development efforts were focused on legal/regulatory review, engineering and logistics mitigation, marketing, genetic forensic analysis, environmental impact monitoring, economic feasibility, disease assessment, and education/outreach.

DEFINITIONS OF MARINE AQUACULTURE

Marine aquaculture may be classified into four categories according to the degree of protection afforded to the operation by the site characteristics and resultant advantages/disadvantages (Table 1). Land-based operations pump the water to tanks, on-shore, thereby being protected from storm surges and adverse weather conditions. These operations require large capital investments in infrastructure and are restricted by coastal development to the extent that future land-based operations may be focused only on hatchery and processing facilities to complement open ocean grow-out. Similarly, coastal aquaculture sites are located in protected, remote bays or fjords, away from populated areas and presumably anthropogenic sources of pollution associated with coastal communities.

In coastal aquaculture, farm workers either make day trips to the near shore sites or may rotate in shifts, upwards of a week, living on-site for the duration if the site is a considerable distance from the homeport. Farm workers have their quarters in a cabin either floating on the water near the cages or on-shore in line-of-sight of the cage flotilla. This close proximity to the cages and fish stock provides security against losses to vandalism, theft, predators, or adverse weather. Most logistical issues have been overcome with

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Table 1. Comparison of marine aquaculture strategies as categorized by degree of exposure of the operation to natural oceanographic and storm events.

Location	Advantages	Disadvantages
Land-based Facility	- Control water quality - Isolation of operation from populated areas not required - Complete protection from storm surges	- Limited space - Expensive capital investment
Coastal Environments (protected bays and fjords)	- Less capital investment - Protected from much of the natural elements - Surveillance possible with minimal investment	- Possible self-pollution - Limited space for expansion - Isolation more desirable to be free of anthropogenic coastal pollution - User conflicts exist close to shore
Exposed Sites	- Utilizing environment previously unexploited - Consistent and high quantity water supply - Visual protection still possible from near by land	- Exposed to destructive natural elements - Limited space near shore - User conflicts exists close to shore - Increased infrastructure necessary with increased exposure - Rely more on automation
Offshore Sites	- Decreasing user conflicts with increasing distance from shore - Very consistent water supply - Large potential for industry expansion	- Truly exposed with no protection from either side - Increased capital costs associated with increased technology and mechanization - Large investments required to ensure economic feasibility - Complete isolation from shore bases with no land in sight

barges designed to hold large quantities of feed, regular site visits to change crew and replenish fuel and food, and constant communication maintained through VHF/UHF radios or cellular telephone. Site protection to the cages allows farm operators to perform necessary tasks, such as multiple daily feeding, net changing, size grading, and stock sampling. Although automation is becoming more of the norm owing to the large scale of some of these operations and operator desire to minimize fish stress through minimal direct handling, site protection allows for minimal dependence on automation.

A simple move of the farm to the open ocean environment increases the logistical demands of the operation. For exposed locations land is still not far away but the degree of exposure—from at least three directions—increases the risk of storm damage to the cage infrastructure and complicates routine farming operations. Rudi et al. (1996) consider the regularity of farm chores and the effect of operating in more exposed locations. The aquaculturist must now rely more heavily on mechanization to allow feeding at set times during the day. Routine operations, taken for granted in protected sites, now become a substantial chore. Exposed sites, not far from a land base, still enjoy the luxury of visual observation of the cages and stock, and quick response time to emergency situations that are not present in the offshore environment.

Offshore aquaculture operations have all the logistical challenges of both remote coastal and exposed aquaculture but at an escalated scale. In such instances, the degree of exposure, from all directions, is substantial, with the farm being truly exposed to any and all natural elements and out of sight from shore bases. Operators will require large infrastructure to produce fish at the quantity necessary for economic feasibility. In addition, excellent husbandry practices are required to ensure a stress free, healthy stock that is growing in a uniform fashion. Routine operations such as net changing may be impermissible in this exposed offshore environment or certainly require appropriate selection of fair weather days and prioritization of farm chores. Due to the extreme remote conditions, offshore aquaculture will require innovative technologies to allow numerous chores that otherwise require much human intervention in existing farm operations.

Lack of, or decreased, human presence will require a substantial change in the mindset of both owners and managers, trusting more in technology to communicate with the farm site particularly during storm events. Indeed, as Muir (2000) points out "…a major challenge for future systems may be to overcome the psychological dependence on human-based management, allowing greater reliance to be placed on automatic monitoring, control and management systems." Such monitoring and control systems will be essential for functions requiring daily attention—appropriate levels of feeding at set times regardless of weather; monitoring ambient parameters such as oxygen, temperature, and current speeds; determination of fish stress that might alter feed quantities and time, and potential monitoring of depth in the water column to avoid energetic surface conditions; and, security sensors to inform of breaches due to structural damage, predators and poaching. Finally, owing to the distance and unpredictability of weather conditions, dependable forms of long-distance communication in the potential absence of cellular phone coverage and carefully planned emergency response need to be developed.

OPEN OCEAN AQUACULTURE AND THE UNITED STATES

The United States is presently confronted with an ever-increasing seafood trade deficit that is estimated to be approaching U.S. $9 billion annually. Some research investment has been made to offset this trade imbalance through domestic aquaculture production following creation of a Department of Commerce Aquaculture Policy signed August 10, 1999 "…to create sustainable economic opportunities in aquaculture in a manner that is environmentally sound and consistent with applicable laws and policy."

Specific DOC objectives, by 2025, are to:

- Increase the value of domestic aquaculture production from the present U.S. $900 million annually to U.S. $5 billion, which will help offset the U.S. $6 billion annual U.S. trade deficit in seafood.

- Increase the number of subsequent jobs in aquaculture from the present estimate of 180,000 to 600,000.

- Develop aquaculture technologies and methods both to improve production and safeguard the environment, emphasizing where possible, those technologies that employ pollution prevention rather than pollution control techniques.

- Develop a Code of Conduct for responsible aquaculture by the year 2025 and have 100 percent compliance with the Code in federal waters.

- Double the value of non-food products and services produced by aquaculture in order to increase industry diversification.

- Enhance depleted wild fish stocks through aquaculture, thereby increasing the value of both commercial and recreational landings and improving the health of our aquatic resources.

- Increase exports of U.S. aquaculture goods and services from the present value of U.S. $500 million annually to U.S. $2.5 billion.

Recognizing a presently overburdened coast with numerous user conflicts and substantial anthropogenic sources of pollution, this investment has been directed towards developing aquaculture technologies for the open ocean, including areas out of the sight of land within the U.S. Exclusive Economic Zone.

The pace of open ocean aquaculture development globally has been slow owing to the lack of suitable technology that allows efficient farm operations in high-energy exposed environments. Technology advancements have been more forthcoming over the past decade with industry expansion from coastal operations pushing the development of exposed sites. The impetus for moving further offshore has come from numerous sources:

- Environmental degradation issues associated with overstocking near shore sites that have low rates of flushing and subsequent lower carrying capacity than more exposed sites.

- Numerous user conflicts for coastal regions with traditional fisheries, coastal developers, recreational users, and environmental advocacy organizations that limit further industry expansion near shore.

- Lower health management risks associated with well flushed open ocean environments having more stable water columns than near shore sites thereby decreasing stress to the stock.

- Realization of the vast opportunities present in the underutilized open ocean environment including the possibilities for economies of scale not previously attained near shore.

Development of exposed aquaculture sites around the globe has been further expedited by nations not having intricate coastlines that otherwise allows protected aquaculture development. Such countries include those in much of the Mediterranean, Ireland, Faeroe Islands, Japan, and Australia. Each of these countries is aware of their present, and/or future, dependence on foreign seafood supplies and potential for domestic seafood production through aquaculture. A desire to develop domestic aquaculture production in the open ocean has been the result. In many of these cases, developing exposed sites does not simply represent an evolution of near shore aquaculture operations and technology. To the contrary, many regions presently operating in exposed sites did so without first occupying protected coastal sites. Some individuals would consider the omission of protected sites a disadvantage. Others have grasped the opportunity for technological innovation that might otherwise have been constrained by technologies developed for near shore aquaculture.

Major research and development projects have been funded in several regions of the U.S. with funding allocated following the DOC Aquaculture Policy—including New Hampshire (Chambers et al. 2003), Puerto Rico (O'Hanlon et al. 2003), the Gulf of Mexico (focus of this book), and Hawaii (Ostrowski and Helsley 2003). Progress of these projects range, owing in large part to the very different environmental and oceanographic conditions experienced and degree of involvement from private investment driving the research agenda (i.e., Hawaii and Puerto Rico both presently have private investors, although commercial scale operations are relatively small; the Gulf of Mexico regional project has ceased to exist owing to fiscal constraints; and, New Hampshire remains in the middle of these two extreme situations).

Open ocean aquaculture operating in high energy exposed environments is expected to have numerous advantages over comparable operations in protected near shore sites. Direct comparison of near shore and offshore water bodies illustrate stark differences that will greatly benefit aquaculture operations and warrant costs associated with developing technologies for open ocean sites. Gowen and Edwards (1990) make comparisons related to biological and physical interactions in near shore and offshore environments. In broad terms, offshore water: 1) is in constant motion with presence of a residual flow regardless of tide or wind; 2) has decreased stratification owing to more frequent turbulent mixing and less likely to experience oxygen depletion at depth; 3) is less influenced by freshwater inflow, maintaining salinity regardless of season; 4) is less susceptible to summer heating and winter cooling that can be problematic in coastal waters; 5) has increased vertical mixing coupled with greater horizontal dispersion of farm wastes both resulting in decreased environmental loading; and, 6) has greater assimilative capacity of nutrients owing to increased water movement and decreased recycling compared to tidally driven near shore locations.

Anticipated broad advantages of open ocean aquaculture include increased production on a site area basis in better flushing water (Sveälv 1988), increased stocking density per cage volume with decreased stress (Gace 2003), decreased fish health issues in more suitable water conditions (e.g., Vågsholm and Djupvik 1998, 1999), minimal mortality also related to decreased fish stress, decreased environmental impacts with increased dilution of wastes over a larger spatial area (Gowen and Edwards 1990), increased economy of scale related to both larger site capacity and increased stocking density, and reduced user conflicts for necessary space (or volume) in vast expanses of ocean. Many of these advantages are as yet based upon expectation, but gradually becoming accepted with increasing scientific investigation and commercial experience in the open ocean environment.

As can be expected, new operating considerations exist for aquaculture establishments in the open ocean. Most importantly are: 1) increased logistic complexity resultant from operating in frequently hostile locations; 2) increased capital outlay to attain the desired economy of scale to meet the fiscal demands of operating further from a shore base; 3) more complex engineering considerations including enhanced mooring and cage designs to withstand the environmental loads; 4) increased dependency on technology for automation that may sometimes fail in the most foul weather; and, 5) the need to design entire farm operations from a holistic systems approach and not follow the traditional piecemeal strategy frequently adopted for near shore operations.

THE GULF OF MEXICO AND OFFSHORE AQUACULTURE

The Gulf of Mexico is the seventh largest marine area in the world and may be considered a very productive eutrophic sea; once described as the 'fertile fisheries crescent' (Gunter 1963). This productivity could potentially increase the assimilative capacity of the water, thereby reducing the environmental impacts associated with aquaculture effluents from offshore farms.

Selection of candidate aquaculture species is not trivial (Webber and Riordan 1976). Numerous species indigenous to the Gulf of Mexico have been identified as candidate species for aquaculture with excellent grow-out and market potential characteristics, including red drum (*Sciaenops ocellatus*), red snapper (*Lutjanus campechanus*), cobia (*Rachycentron canadum*), and greater amberjack (*Seriola dumerili*). Numerous criteria are used to select candidate species for aquaculture including the growth rate to a market size. A growth performance index (Φ'; Longhurst and Pauly 1987), using L_∞ and K values from wild stock literature for each of these species in the northern Gulf of Mexico, provide favorable growth attributes for economically feasible grow-out (Table 2). With the subtropical growing conditions, fingerlings for all of these species are anticipated to reach a consumer-driven market size within a 1–2 year grow-out cycle, increasing the economic feasibility of open ocean aquaculture ventures in the Gulf of Mexico.

Acquiring a site having water depth in excess of 25 m to avoid hurricane damage would be desirable and may require locating as far as 40 km from land. Further, some areas of the Gulf of Mexico are prone to experience seasonal hypoxia associated with runoff from the Mississippi River (Rabalais et al. 1994, 1996) and thermally stratified water during late summer that will not experience a turnover in the absence of tropical fronts. Although this hypoxic layer is generally restricted to the lower one-third of the water column, large cages or submerged operations may be impacted. An additional layer commonly experienced in Gulf of Mexico waters is the nepheloid layer developed from resuspension of fine sea-floor sediment generated from bottom turbulence (Shideler 1981). Little is known of this layer's impact on fish health or its seasonal extent in much of the Gulf of Mexico.

Complete hurricane avoidance is unlikely in the northern Gulf of Mexico. However, it may be possible to decrease hurricane impacts to aquaculture ventures by sinking cages to avoid such storms. With this strategy comes the risk of exposing the fish stock to sediment resuspension that may subsequently irritate the gills, create secondary bacterial infections, and result in mass mortality (Sherk et al. 1974; Brown 1993) and subsequent economic loss to the operation.

Finally, much of the Gulf of Mexico has long supported both commercial and recreational fishing. User conflicts must be carefully considered and dealt with to ensure success of a future open ocean aquaculture industry. All of these issues limit appropriate sites for open ocean aquaculture in the Gulf of Mexico to some degree.

There have been previous offshore aquaculture attempts in the Gulf of Mexico (reviewed in Kaiser 2003). However, although

Table 2. Growth performance index (Φ')[a] calculated from cited L∞ (cm) and K values for potential aquaculture species indigenous to the northern Gulf of Mexico. Values shown in parentheses are standard errors.

Species	Sex	L∞ (cm)	K	Φ'	Source
Rachycentron canadum	male	117.07 (2.808)	0.432 (0.046)	3.77	Franks et al. (1999)[b]
	female	155.50 (3.514)	0.272 (0.017)	3.82	
Lutjanus campechanus	combined	95.0 (1.35)	0.175 (0.005)	3.20	Nelson and Manooch (1982)[c]
Sciaenops ocellatus	combined	91.8 (2.1)	0.422 (0.023)	3.55	Doerzbacher et al. (1988)[d]
Seriola dumerili	combined	127.2 (N.P)[e]	0.227 (N.P)	3.57	Manooch and Potts (1997)[f]

[a]Φ' = log10K + 2log10L∞ (Longhurst and Pauly 1987)

[b]Cobia were caught from northeastern Gulf of Mexico within the recreational hook-and-line fishery and aged with sagittal otoliths (male $N = 170$; female $N = 395$).

[c]Red snapper were caught in the commercial hook-and-line fishery off Louisiana and aged with scales ($N = 403$).

[d]Tagged red drum returns from recreational and commercial fishery off Texas and growth determined from tag and release measures ($N = 2010$).

[e]N.P. = not provided

[f]Greater amberjack captured from headboats operating in the Gulf of Mexico from Naples, Florida, to Port Aransas, Texas and aged with sagittal otoliths ($N = 340$).

proving invaluable from lessons learned, none of these have produced large quantities of fish for market or resulted in a commercial offshore aquaculture sector in the Gulf of Mexico.

THE GULF OF MEXICO OFFSHORE AQUACULTURE CONSORTIUM

In 1999, the Gulf of Mexico Offshore Aquaculture Consortium (OAC) was formed to create a collaborative, Gulf-wide, university-based interdisciplinary research program to address social, environmental and technological issues that have plagued offshore aquaculture endeavors in the Gulf of Mexico. By developing university/industry partnerships and seeking broad public/commercial input, the Consortium's goal was to develop socially and environmentally acceptable offshore aquaculture models that are appropriate to all stakeholders in the Gulf of Mexico region.

In most aquaculture development projects throughout the world, it has been fairly easy to accomplish the mere task of raising fish to a marketable size. However, in almost all cases, environmental and management decisions have been based upon primary scientific data collected from other regions of the world or models in an attempt to describe and predict impacts. The OAC intended to not only develop an economically feasible open ocean aquaculture sector, but also to defend the sustainability of the industry based on primary scientific data, collected throughout its development and subsequent commercialization, from the Gulf of Mexico. Primary data collection and industry development was planned using a proactive approach from the outset, learning from mistakes made by previous aquaculture development elsewhere, and in consultation with all Gulf of Mexico stakeholders, regardless of their perspective.

The OAC was officially created during its first workshop, hosted by the Texas Sea Grant College Program during February 2000. This workshop was designed to effectively bring together scientists, economists, engineers, legal experts, state and federal agency representatives, and industry leaders who had the interest and expertise to develop offshore aquaculture in the Gulf of Mexico. All aspects associated with the OAC research project and the protocols developed were discussed in an open forum. In addition, teams of participants were identified that possessed the capabilities to submit collaborative proposals for funding in subsequent years.

The ultimate goal of the workshop was to develop one or more groups of industry/academic/agency partnerships interested in developing demonstration projects in the Gulf of Mexico. In addition to forming partnerships, the meeting provided a forum for discussion of various engineering approaches to offshore aquaculture, site evaluation, species selection, social and economic implications, and related topics.

Following the success of the first OAC workshop, researchers chose a site having 26 m of water approximately 40 km off the coast of Mississippi in federal waters (Fig. 1; 29°58.649′N, 88°36.297′W). This distance separates OAC research from other U.S. open ocean aquaculture initiatives by extending aquaculture operations outside the sight of land to federal waters in the EEZ. The research operation was adjacent to a ChevronTexaco manned gas production platform, which minimized user conflicts with fishing and shipping activities while providing continuous surveillance of the cage to monitor for vandalism and storm damage.

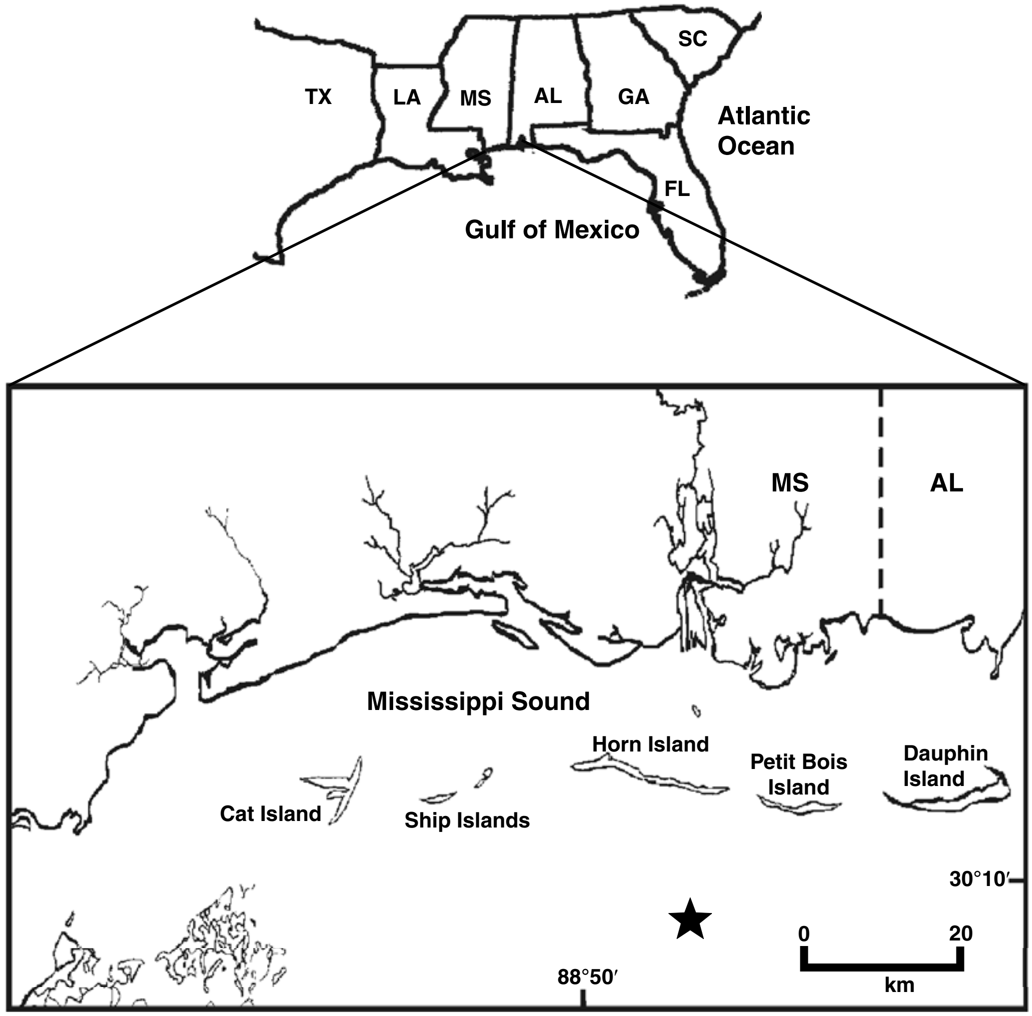
CONCLUSIONS

OAC research and development efforts were focused on legal/regulatory review, engineering and logistics mitigation, marketing, genetic forensic analysis, environmental impact monitoring and modeling, economic feasibility, disease assessment, and education/outreach. The remainder of this book consists of individual chapters that focus upon these broad research and development issues addressed by OAC researchers.

Following legal permitting review, the OAC acquired necessary permits to establish and operate an offshore aquaculture site in U.S. federal waters approximately 40 km off the Mississippi coast. The OAC offshore aquaculture cage was deployed without fish to observe the cage/mooring system and develop logistic mitigation procedures prior to transporting fingerlings to the site. An environmental impact model was developed to predict potential impacts from commercial-scale offshore aquaculture operations in the Gulf of Mexico. Economic modeling research was conducted for the Gulf of Mexico candidate species—red drum, red snapper and cobia—and anticipated grow-out costs and potential returns analyzed to determine commercial-scale economic feasibility.

Genetics researchers developed a genetic library (based on microsatellites and mitochondrial DNA) to identify aquaculture products from wild conspecifics. A Health Management Plan was considered for offshore aquaculture in the Gulf of Mexico based upon the regional oceanographic and biological characteristics and accepted cage culture health management practices adopted throughout the world. Finally, education/outreach was of utmost importance for proper

Fig. 1. OAC offshore aquaculture experimental site (★) located in 26 m of water approximately 40 km off the coast of Mississippi, in federal waters (29°58.649′N, 88°36.297′W), near a ChevronTexaco gas platform.



and effective OAC research dissemination. An aquarium exhibit was developed to help the general public visualize and understand commercial offshore aquaculture operations and outline specific research efforts of the OAC. Additionally, the OAC hosted a second two-day regional workshop to allow further discussion of research and development efforts in the Gulf of Mexico and resulted in a focused research and development strategy for offshore aquaculture based on consensus from the workshop attendees (Bridger 2002). Finally, the OAC maintained a web site to effectively disseminate research results and logistics procedures for a developing industry.

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CHAPTER 3

LAW & OFFSHORE AQUACULTURE: A TRUE HURDLE OR A SPEED BUMP?[1]

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ABSTRACT

The legal and regulatory environment surrounding offshore aquaculture is cited consistently as one of the major hurdles to its development in the United States. Despite the adoption of the National Aquaculture Act in 1980, the lack of a sound legal and regulatory structure is still cited as the culprit for lack of a U.S. industry. In reality, the present regulatory regime is inadequate because it is based upon laws that were adopted to address issues or industries other than aquaculture. Because aquaculture facilities affect traditionally governed areas such as water supply, the use of navigable waters, food production, and environmental protection, multiple federal and state agencies have jurisdiction over the industry. While these agencies have excelled at regulating and permitting land-based aquaculture regimes with refined and stream-lined licensing procedures and regulations, the offshore aquaculture regulatory structure looks significantly different with no single lead agency and differences in regulations between states and regions. Many claim that these issues must be resolved before a sustainable industry can emerge. Law and policy research conducted in tandem with the environmental and technological research of the Gulf of Mexico Offshore Aquaculture Consortium revealed some specific legal mechanisms that need to be addressed but highlighted the reality that offshore aquaculture can develop within the present structure. This chapter describes some of these immediate legal hurdles but concludes that political and scientific issues serve as much greater hurdles than the legal and regulatory regime.

INTRODUCTION

The legal and regulatory environment related to offshore aquaculture is cited consistently as one of the major hurdles to its development in the United States. In 1978, the United States National Research Council (NRC) found that the procedures required to obtain permits and licenses for offshore aquaculture "have been a severe deterrent" to the development of the industry explaining that "constraints on orderly development . . . tend to be political and administrative, rather than scientific and technological. Advances are needed in all areas, but for overall progress, the essential requirements are policy decisions and administrative actions."[2,3] The U.S. Congress responded in part in 1980 with the

[1] Portions of this chapter have been reprinted from: Fletcher, K.M. and E. Neyrey. 2003. Marine Aquaculture Zoning: A Sustainable Approach in the Growth of Offshore Aquaculture. Pages 15–22 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, United States. ISBN: 1-888807-13-X/MASGP-03-008. with permission from The World Aquaculture Society.

[2] National Research Council, Aquaculture in the U.S.: Constraints and Opportunities. Washington, DC: National Academy Press (1978).

[3] Additionally, the National Oceanic and Atmospheric Administration's 1977 Aquaculture Plan called for government promotion of the aquaculture industry as a key component of the United States' aquaculture future. NOAA Aquaculture Plan, Washington, DC: U.S. Gov Printing Office (1977).

passage of the National Aquaculture Act noting the "diffused legal jurisdiction" and "lack of supportive Government policies." Even with these criticisms of the lack of a legal and regulatory structure, the codified national policy in the National Aquaculture Act was to "encourage the development of aquaculture in the United States"[4] without specific direction toward creating such a structure.

Twenty-five years after the adoption of the National Aquaculture Act, shortcomings in the law is still cited as the culprit for lack of a U.S. industry. While the existence (or nonexistence) of a law is not the only (and, arguably not the primary) reason for the lack of an industry, the present regulatory regime is inadequate because it is based upon laws that were adopted to address issues or industries other than aquaculture.[5] In general, aquaculture facilities affect traditionally governed areas such as water supply, the use of navigable waters, food production, and environmental protection. As a result, multiple federal and state agencies have jurisdiction over the industry and while these agencies have excelled at regulating and permitting land-based aquaculture regimes with refined and stream-lined licensing procedures and regulations, an offshore aquaculture regulatory structure would look significantly different with no single agency consistently taking the lead and differences in application of regulations between regions.

Findings about these legal and regulatory hurdles are not new. There have been numerous calls for improvements during the last two decades.[6] Individuals interested in developing sustainable offshore aquaculture face challenges in the form of a fragmented and often inconsistent permitting process among the federal, state, and local agencies and questions regarding leasing, siting, and property rights. Many claim that these issues must be resolved before a sustainable industry can emerge. Interestingly, law and policy research that was conducted in tandem with the environmental and technological research of the Gulf of Mexico Offshore Aquaculture Consortium revealed some specific legal mechanisms that need to be addressed but highlighted the reality that offshore aquaculture can develop within the present structure. This chapter describes some of these immediate legal hurdles but concludes that political and scientific issues serve as much greater hurdles than the legal and regulatory regime.

The chapter begins with a background of present aquaculture laws and regulations in the United States within the context of other marine aquaculture nations. A complete list of the laws, permits, and agencies and their contacts related to offshore aquaculture siting in U.S. federal waters and the five Gulf of Mexico states waters is presented in Appendix A of this book. Next, impediments to the development of an offshore industry in the Gulf of Mexico, focusing on the maze of legal and regulatory provisions, the leasing provisions (and lack thereof), and the traditional

[4] 16 U.S.C. § 2801(7) (2004).

[5] This is not necessarily unique to the U.S. For example, Canadian aquaculturists are presently operating with policies and regulations that were, for the most part, designed for the capture fishery. Communications Directorate, Department of Fisheries and Oceans. Federal Aquaculture Development Strategy, p. 12 (1995).

[6] The National Aquaculture Act of 1980 and 1985, proposed to promote aquaculture and direct government to untangle the present legal and regulatory regimes. 16 U.S.C. 2801 *et seq.* See, "Marine Aquaculture Opportunities for Growth," Committee on Assessment of Technology and Opportunities for Marine Aquaculture in the United States, National Academy Press, Washington, DC (1992). Also see, Anne Hayden, "Current and Potential Regulation of Open Ocean Aquaculture," Open Ocean Aquaculture 1997 Charting the Future of Ocean Farming, Conference Proceedings, p.57–63.

users of marine areas under the public trust doctrine are examined. Lastly, the chapter concludes with a perspective on the legal and regulatory hurdles in the context of an underdeveloped industry that faces political and environmental challenges in its future.

AQUACULTURE LAW IN THE UNITED STATES

The U.S. government began to promote aquaculture to develop certain sport fishing in the late nineteenth century, and the government did not regularly support marine aquaculture research until the late 1960s and early 1970s.[7] The 1980 National Aquaculture Act (NAA) established a national policy of encouraging development of aquaculture in the United States.[8] The NAA called for the creation of a National Aquaculture Development Plan to identify species with significant commercial potential and include research and development, technical assistance, and training programs as necessary.[9] The NAA also established an interagency Coordinating Group to increase the effectiveness and productivity of federal aquaculture programs and to assess the industry and report to Congress[10] and a National Aquaculture Information Center. Congress called for a review of regulatory constraints that may have a negative impact on the industry[11] and the NAA was reauthorized in 1985 with the passage of the National Aquaculture Improvement Act[12] and again in 2002 with the Farm Security and Rural Investment Act of 2002.[13]

While the National Aquaculture Act directed the development of a number of planning and policy tools and revealed the growing demand for aquatic food products, the Act itself does not provide a legal framework for aquaculture development.[14] The Department of Agriculture, named lead aquaculture agency in the NAA, has not pursued any lead regulatory or permitting authorities in the offshore aquaculture industry. The main role of the Department of Agriculture has been as a source of research and planning funds and organization. However, even though permitting and/or regulatory requirements have not grown out of the NAA, other agencies and their regulatory programs do create a maze of legal requirements for the aquaculture industry.

Both the United States Corps of Engineers (Corps) and United States Coast Guard (USCG) have a role in the placement/siting of an aquaculture facility in federal waters. Under Section 10 of the Rivers and Harbors Act of 1899, as extended by the Outer Continental Shelf Lands Act (OCSLA), the

[7] "Marine Aquaculture Opportunities for Growth," Committee on Assessment of Technology and Opportunities for Marine Aquaculture in the United States, National Academy Press, Washington, DC (1992) p. 65. In 1870, the U.S. Congress spent its first federal funds ($100.00) for fish research investigations at Woods Hole, MA, *Id* p.15.

[8] 16 U.S.C. § 2801 (c) (2003) "Congress declares that aquaculture has the potential for augmenting existing commercial and recreational fisheries and for producing other renewable resources, thereby assisting the United States in meeting its future food needs and contributing to the solution of world resource problems. It is therefore, in the national interest and it is the national policy, to encourage the development of aquaculture in the United States."

[9] 16 U.S.C. § 2803 (2003).

[10] 16 U.S.C. § 2805 (2003).

[11] 16 U.S.C. § 2804 (c)(1)(B) The National Aquaculture Information Center is within the U.S. Department of Agriculture and acts as a repository for aquaculture research.

[12] The reauthorization saw the addition of two major amendments: (1) USDA was assigned lead agency for aquaculture and (2) two new studies on exotic species introductions and captured fisheries potential impacts on commercial fisheries, "Marine Aquaculture Opportunities for Growth," Committee on Assessment of Technology and Opportunities for Marine Aquaculture in the United States, National Academy Press, Washington, DC (1992) p. 68.

[13] 7 U.S.C. § 7139 (2002).

[14] 16 U.S.C. § 2801 *et seq*. (2003).

Corps requires a permit for the creation of "any obstruction to navigation" in federal waters.[15] This authority is aimed at preserving and protecting unhindered navigational access to the waters of the United States. The OCSLA grants the Corps the authority within the exclusive economic zone (EEZ) to regulate "installations and other devices permanently or temporarily attached to the seabed, which may be erected thereon for the purpose of exploring for, developing or producing resources from [the outer continental shelf]."[16]

A Section 10 permit may be granted or a nationwide or general permit may be applicable. If the latter applies, the Corps will issue a letter of permission in lieu of a permit.[17] Permits will be reviewed for cumulative impacts upon the water quality; effects of the facility or structure on recreation, fish and other wildlife; pollution problems; economic factors; safety; aesthetics; protection of navigational integrity; and, accurate charting of any structures.[18] In addition, the USCG has regulations governing the proper lighting and signals required for structures in United States waters to ensure safe passage of vessels. Aquaculture facilities will need proper structure markings as specified by the USCG.[19] Typically, the USCG marking requirements will be included in the Section 10 permit as a condition.[20]

[15] 33 U.S.C. § 403 (2003), see 33 C.F.R. 322.1-.5, for Corps regulations governing "Permits for structures or work in or affecting navigable waters of the United States."

[16] 43 U.S.C. § 1333(a), (e) (2003).

[17] 33. C.F.R. 322.1.

[18] 33 C.F.R. 325.3(c)(1).

[19] See 43 U.S.C. 1333(e), 14 U.S.C. 81–87, 33 C.F.R. 64–67.

[20] Fletcher and Weston, The Legal & Regulatory Environment: Offshore Aquaculture Permitting Process in the Gulf of Mexico, Report published by Mississippi-Alabama Sea Grant Legal Program, available at http://www.olemiss.edu/orgs/SGLC/Offshore%20Aquaculture.pdf (last visited 9/2/04).

The National Marine Fisheries Service (NMFS) and the relevant Regional Fisheries Management Council examine an aquaculture facility's impacts on fisheries resources. NMFS is directed by the Magnuson-Stevens Fishery Conservation and Management Act to regulate and manage commercial fishing operations, including aquaculture, within the EEZ.[21] For the OAC's research project and offshore cage, NMFS provided a Letter of Acknowledgement.[22]

For commercial aquaculture ventures, however, the lack of consistent federal policy has been highlighted by recent activity. At the beginning of the project, it was assumed that NMFS would have to grant an "exempted fishing permit" (EFP) in order to allow an aquaculture facility to hold juvenile fish in federal waters[23] and that the Gulf of Mexico Fisheries Management Council (Council)[24] would have a consulting role, especially regarding potential conflicts between the tra-

[21] 50 C.F.R. 229.2. In a February 7, 1993 memorandum to James W. Brennan, then NOAA's Acting General Counsel, from Jay S. Johnson, Deputy General Counsel, and Margaret F. Hayes, Assistant General Counsel for Fisheries, it was stated that, "Aquaculture facilities are subject to the Magnuson Fishery Conservation and Management Act because they engage in the "harvest" of fish from the EEZ. Barges and other vessels used to support such facilities are "fishing vessels" within the meaning of the Magnuson Act. U.S. vessels that support such facilities and that measure five net tons or larger must obtain Coast Guard documentation, including a "fishery endorsement." U.S. vessels are subject to additional regulations at the discretion of a Regional Fishery Management Council, subject to the approval of the Secretary of Commerce.

[22] Fletcher and Weston, supra note 20.

[23] 50 C.F.R. 600.745. An "exempted fishing permit" is needed to harvest a federally regulated species in federal waters. Without an EFP an aquaculturist may violate regulations by possessing fish that are less than minimum size, out of season, beyond regulated fish trip limits, or fish that are altogether banned from possession in federal waters.

[24] See generally, 16 U.S.C. 1801 *et seq*; later amended and renamed the Magnuson—Stevens Fisheries Conservation and Management Act, See, 16 U.S.C. 1852(a)(1)(E), for creation of Fisheries Councils, See 50 C.F.R. 601 and 605, for the regulations governing Fisheries Councils.

ditional users of commercial fish resources in the Gulf of Mexico and aquaculture planning and siting. In fact, in preparation for new sites, the Council developed a Mariculture Policy, which is designed to "encourage environmentally responsible mariculture."[25]

However, when the NMFS was faced with a request for an exempted fishing permit, the agency responded that taking fish from an aquaculture cage was considered "harvesting" under the Magnuson-Stevens Act and would be regulated by the size and catch restrictions determined by the agency for all federally managed species. This instance highlights the inadequacy of both the Magnuson-Stevens Act and the National Aquaculture Act to address the distinctions between commercial fishing and aquaculture. If the NMFS continues to use this interpretation of harvesting under the Magnuson-Stevens Act, then the Act will need to be amended to allow for commercial facilities.

Beyond the fishing permit requirements, potential environmental concerns related to aquaculture facilities in offshore waters are addressed by the U.S. Environmental Protection Agency (EPA). The Clean Water Act specifically directs the EPA to require point source pollution discharges from aquaculture facilities.[26] These facilities will be permitted under the National Pollution Discharge Elimination System (NPDES).[27] On June 30, 2004, EPA finalized a new rule establishing regulations for concentrated aquatic animal production (CAAP), or farm raised fish facilities, in response to a legal settlement with the Natural Resources Defense Council (NRDC) and others which required EPA to set regulations for 19 industrial categories.

The regulation applies to approximately 245 facilities that generate wastewater from their operations and discharge that wastewater directly into U.S. waters. The rule was adopted to reduce discharges of conventional pollutants (such as total suspended solids), as well as non-conventional pollutants (such as nutrients). To a lesser extent, the rule is to reduce drugs that are used to manage diseased fish, chemicals used to clean net pens, and toxic pollutants (metals and PCBs).[28]

Other natural resources and natural resource production that may be affected by aquaculture are under the authority of the United States Fish and Wildlife Services (USFWS) and Minerals Management Service (MMS). The Fish and Wildlife Coordination Act[29], Endangered Species Act[30] and the Marine Mammals Protection Act[31] require that the USFWS review and comment on any federal permit application for any activities that impact aquatic plants and animals, specifically endangered species or marine mammals. Furthermore, aquaculture sites proposed near oil and gas leases on the outer continental shelf will need to consult with MMS,

[25] Gulf of Mexico Fisheries Management Council, Mariculture Policy, on file with author.

[26] 33 U.S.C. § 1328 (2003).

[27] 33 U.S.C. § 1342, NPDES statutory provisions and 40 C.F.R. §122.24, NPDES regulations. (2003).

[28] The final rule applies to direct discharges of wastewater from existing and new facilities that produce at least 100,000 pounds of fish a year and discharge at least 30 days a year and facilities that produce at least 100,000 pounds of fish a year in net pens or submerged cages. When the rule is fully implemented, discharges of total suspended solids will be reduced by more than 500,000 pounds a year and biochemical oxygen demand and nutrients will be reduced by about 300,000 pounds per year. This affects newly permitted facilities, and existing facilities upon renewal of their (CAAP) permits. Issuance of this rule completes all regulations addressed under the settlement agreement. Information about this program and the final regulation is available at: http://www.epa.gov/guide/aquaculture (last visited 9/3/04).

[29] 16 U.S.C. § 661 *et seq*. (2003).

[30] 16 U.S.C. § 1531 *et seq*. (2003).

[31] 16 U.S.C. § 1361 *et seq*. (2003).

because the Outer Continental Shelf Lands Act grants jurisdiction over these leases.[32] Any facility that connects to an oil and gas rig or depends on the transfer of ownership of a rig structure will need permission from MMS.

Along with the questionable application of the Magnuson-Stevens Act to aquaculture facilities and the implementation of the new EPA effluent rule, several other legal components are missing from the present system. Most noticeable is the lack of a federally designated agency responsible for coordinated leasing or siting of offshore aquaculture facilities. Furthermore, there is no mechanism to ensure that efforts to regulate the industry are approached in an efficient and streamlined manner. Overlapping and unclear jurisdictional lines between agencies lead to repetitive requirements and unnecessary paperwork.

STATE LAWS ADDRESSING OFFSHORE AQUACULTURE

For the most part, waters in the Gulf of Mexico are so shallow that many cage facilities will need to be located in federal waters (three miles offshore of the shorelines of Alabama, Mississippi and Louisiana and nine miles offshore of Texas and Florida). Thus, state laws and policies applicable to offshore aquaculture in the Gulf of Mexico pertain to the potential effects of aquaculture facilities on the coastal area of the neighbor state and laws that states have put in place regarding landings, access through state waters, and water quality protections.

One of the most powerful tools provided to states to protect their coastal waters from activities in adjacent federal waters can be found in the consistency provisions of the federal Coastal Zone Management Act (CZMA).[33] The CZMA states in part, "Each Federal agency activity within or outside the coastal zone that affects any land or water use or natural resource of the coastal zone shall be carried out in a manner which is consistent to the maximum extent practicable with the enforceable policies of approved State management programs." While the types of activities that fall under the CZMA consistency provision have been subject to dispute and litigation, in the case of aquaculture leasing and permitting, states may claim that a federally permitted aquaculture facility is not consistent with the coastal program of that state. In short, states will play an important role in the development of offshore aquaculture and ensuring that their coastal environmental concerns are addressed.

The states also have some permitting, licensing and registration requirements that could affect activities in federal waters that require passage through state waters. All of the Gulf of Mexico states have their own particular sets of laws and regulations designed to manage and conserve fishing resources, targeting transportation, gear types, and tagging and container regulations. For example, Alabama requires that boats transporting fish/equipment through Alabama state waters, in order to conduct activities within federal waters, acquire an Alabama state permit. Similarly, Mississippi law requires vessels

[32] 43 U.S.C. § 1331–1356 (2003).

[33] 16 U.S.C. § 1456(c) (2003). "[The CZMA] has as its main purpose the encouragement and assistance of States in preparing and implementing management programs to preserve, protect, develop and whenever possible restore the resources of the coastal zone of the United States . . . *There is no attempt to diminish state authority through federal preemption*. The intent of this legislation is to enhance state authority by encouraging and assisting the States to assume planning and regulatory powers over their coastal zones." *Granite Rock Co. v. California Coastal Comm'n*, 107 S.Ct. at 1431, quoting S. Rep. No. 753, 92d Cong. 2d Sess. at 20 (1972).

used to "transport fish in the waters of the State of Mississippi for commercial purposes shall, before beginning operations, obtain an annual license from the commission and pay a license fee."[34] As highlighted above these laws could impact aquaculture activities in federal waters by requiring facility operators to meet certain state requirements, however these state requirements are not likely to completely prohibit the development of offshore aquaculture ventures. If federal aquaculture legislation is passed, many of these issues may be solved due to the preemption of state law by federal legislation.[35] Aquaculture requirements contained in federal law may either directly and expressly preempt the state laws mentioned above or an implied preemption may be found.[36]

IMPEDIMENTS TO DEVELOPING AN OFFSHORE AQUACULTURE INDUSTRY IN THE GULF OF MEXICO

The Public Trust Doctrine & Aquaculture

The Public Trust Doctrine (PTD) provides that the state holds submerged and submersible lands in trust for public use in navigation, fishing, and commerce and recreation. As one commenter explains, "the doctrine's operation exacerbates a growing clash in liberal ideology within natural resources law—between the need for individual autonomy and security, traditionally tied up in private property rights, and the demands of longer-term collectivist goals expressed in environmental protection and resources conservation laws."[37]

It is this need for autonomy and security over a particular area of surface water, water column, and, in some cases, submerged lands, by the offshore aquaculture industry that is challenged by the traditional uses allowed under the PTD. The PTD has not completely halted the use of zoning in marine areas, both coastal and offshore, but certainly does present additional hurdles for new activities or new industries that cannot claim the same traditional uses. For example, areas in federal waters have been designated for offshore oil and gas exploration through a lease system that grants rights to the minerals below the surface. The owners and operators of the platforms have the limited right to exclude others from the area for the purpose of protecting the platform and associated property or for other safety concerns. Oil and gas companies have made few efforts to enforce these safety zones around the platforms, allowing local fishers to "hook up" to the platform in order to fish its rich artificial reef below. Other areas are off-limits to traditional uses for military purposes or environmental protection with varying levels of enforcement and restrictions on uses.

Depending on the type of cage and fish and depth of water, the siting of offshore aquaculture pens potentially requires a greater level of protection for the property and fish from traditional users as it is significantly easier to access a submerged or partially submerged cage than an elevated platform and significantly more difficult to protect without a human presence.

Leasing

Once public trust issues are addressed, a sustainable industry in the Gulf of Mexico

[34] MS RS § 49-15-80 (2003). *Also see*, La R.S. 56:307 (2003) (requires state license for transportation of fish in state waters).

[35] Supremacy Clause, U.S. Const. art. VI, cl. 2. Federal activities, such as implementing regulations, federal common law, treaties and executive agreements, all possess the same status as legislation for purposes of preemption.

[36] 435 U.S. 151, 157–158 (1978) Ray v. *Atlantic Richfield Co* (an instructive case on federal preemption of state regulation dealing with marine affairs.)

[37] Richard J. Lazarus, *Changing Perceptions of Property and Sovereignty in Natural Resources: Questioning the Public Trust Doctrine*, 71 Iowa L. Rev. 631, 692 (1986).

(and in federal waters in other regions) will require a mechanism to ensure the availability of a secure property right to the water column and associated bottom area within and upon which the aquaculture cage/net pen will reside. Any significant investment of capital will require such a property right. The federal government manages both federal waters and water bottoms as natural resources owned by the government in trust for the public. The leasing of these resources would give the aquaculturists the needed property rights and security, while the resources would remain in the ownership of the federal government.

A lease is an agreement under which the owner (here, the U.S. government) gives up use of certain property for valuable consideration and for a definite term; at the end of the term, the owner has the absolute right to retake, control and use the property.[38] Leasing is key to the industry because ownership of property gives the owner a number of rights and responsibilities, often analogized to a bundle of sticks. When leasing land the owner grants the lessee some of these rights and responsibilities, or gives the lessee a few of his sticks, according to the terms of the lease.

Leasing state and federal lands and water bottoms for private uses is not uncommon.[39] For example, "the U.S. Department of the Interior leases federal land for logging, grazing, and mining; states lease shellfish beds for oyster culture and harvest; piers, docks, and marinas extending into public waters may be built by riparian landowners."[40] However, leasing of activities offshore in the EEZ has thus far been reserved for oil and gas activity. The Minerals Management Service, acting on behalf of the Department of the Interior, grants oil and gas leases in the EEZ through a competitive bidding process.[41]

Leasing of state coastal water bottoms for aquaculture ventures is a practice employed by all the Gulf of Mexico states; all five states have general leasing authority granted to either the state lands office or natural resource department.[42] This authority gives one agency or state office the ability to lease state lands and submerged water bottoms to private persons or entities. Generally, the states' (water bottom) leases grant the lessees the exclusive right to conduct a specified activity on the water bottom, however, activities in the associated water column are not always under the exclusive control of the aquaculture lessee. Florida and Mississippi law do provide for aquaculture leases to grant control over the water column "to the extent required by such activities."[43]

Furthermore, some of the Gulf of Mexico states have made a connection between obtaining a water bottom lease and specific aquaculture requirements. In Mississippi, obtaining a lease will require application for an aquaculture lease, which is tailored to

[38] Black's Law Dictionary 889 (6th ed. 1990).

[39] See, Mayer, Carl J., and George A. Riley, *Public Domain, Private Dominion A History of Public Mineral Policy in America*, 1985, p. 33, for discussion of an early Supreme Court decision upholding leasing of federal lands. "The decision in *United States v. Gratiot* was a victory for the government; it firmly established the power of Congress to retain and manage public property. If Benton [representing the Gratiots] had succeeded, the legal history of the public domain would have been drastically altered. Benton's interpretation of the Constitution would strip Congress of the power to create national parks, lease rights to grazing land, and sell timber in national forests. In rejecting this position, the Court recognized Congress's broad latitude in managing federal lands."

[40] Rubino, Michael and Charles A. Wilson, I*ssues in Aquaculture Regulation*, p. 15.

[41] See 43 U.S.C. § 1331–1356 (2003).

[42] See Alabama - Code of AL § 9-17-62, Mississippi - Miss. Code Ann. § 29-1-107, Louisiana - La. R.S. § 30:172, Florida - Fla. Stat. 18 § 253 *et seq.* and Texas - TX Natural Resources Code § 51 *et seq.*

[43] Fla. Stat. 18 § 253.68, Rule 5 (D)(3).

review of the scope and type of aquaculture venture.[44] Also, in Florida a lease for aquaculture purposes is connected to the lessee obtaining an aquaculture certificate.[45] Florida aquaculture certification provides the state with a mechanism to ensure best management practices for aquaculture are being met.[46]

Looking outside of the Gulf of Mexico, Hawaii has made history in recent years by granting an aquaculture lease for offshore cages. The Hawaii Department of Land and Natural Resources agreed to lease a 28-acre patch of ocean for the commercial production of fish in sea cages.[47] The 15-year lease between the state and Kailua-based Cates International Inc. allows for up to four cages, to be anchored, 40 feet below the water surface, to the ocean floor two miles off ‘Ewa Beach for the production of moi, a valuable local species.[48] While the lease has not been finalized at present, Cates is expected to lease the ocean floor substrate, a column of water above it, and corresponding surface area, with a ten-year option to extend the lease. Rent will likely be based on a percentage of gross revenues to be determined by state officials and appraisal.[49]

The movement toward offshore aquaculture must establish a leasing mechanism that addresses questions of agency jurisdiction, property rights, enforcement and environmental concerns. Designation of an agency that has authority to grant offshore leases specifically for aquaculture enterprises will increase the transparency of the process. Clearly, a structure designed for aquaculture will facilitate problem-solving that does not occur when aquaculture is governed by a system designed for another activity. A single leasing agency will also provide more consistent public interest reviews to analyze the interference with access by riparian owners, navigation, fishing or other uses of the area, the ability of the lease site and surrounding area to absorb environmental changes or damages, the use of municipality, state or federally owned beaches, parks or docking facilities, and to determine size limits for leases based on type and scope of the facility.

A comprehensive leasing statute at the federal level can provide the aquaculture industry and lenders with the property rights certainty needed for capital investment. The right of exclusive use of the water column and water bottom within the leased area and the assurance of a sufficient term length, combined with the zoning designations, can provide the stability that proponents of the aquaculture industry are seeking.

CHALLENGES FOR DEVELOPING U.S. OFFSHORE AQUACULTURE

Bills introduced in recent years have noted that even though the National Aquaculture Act has been reauthorized through 2007, the U.S. has still “not adequately address[ed] emerging national issues such as offshore aquaculture development, water quality concerns, invasive species impacts, and a coordinated siting, permitting, and licensing process.”[50] These bills call for the following:

1. ensuring the sustainable development of production where aquaculture is econom-

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[44] *Id.*

[45] Fla. Stat. 35 § 597.004.

[46] Fla. Stat. 35 § 597.004(2).

[47] Joint News Release from The Department of Land and Natural Resources and the Department of Agriculture, State of Hawaii, NR01-06, March 9, 2001, *State Authorizes First Ocean Leasing Agreement*.

[48] *Id.*

[49] *Id.*

ically viable, environmentally feasible, and culturally acceptable;

2. analyzing the supply and demand for domestic and exported aquacultural products to enable the United States to compete in the global marketplace;

3. increasing the availability of new technical and scientific information that supports aquacultural development;

4. with regard to marine aquaculture, providing encouragement and identification of marine zones favorable to aquaculture that take into consideration desired environmental conditions and potential use conflicts; and,

5. establishing a goal of a 5-fold increase in United States aquacultural production by 2025.[51]

The question remains whether a change to the Magnuson-Stevens Act to clarify the permitting of aquaculture facilities as distinct from commercial fishing operations and the implementation of the EPA rule regarding discharges from such facilities will magically pave the way for the development of an offshore aquaculture industry in the U.S. As difficult as implementing new discharge rules and amending the nation's fisheries statute might seem, the development of offshore aquaculture in this country faces other greater hurdles. Even with a unified governmental approach, the development of an industry is challenging at best; without a unified approach, the questions of economic and environmental feasibility might represent those greater hurdles.

CONCLUSION

Questions abound: will non-native species be used and how is "non-native species" defined in the context of an ecosystem such as the Gulf of Mexico? If a species is shown to be viable, is the technology available to construct a cage that can withstand offshore environmental pressures? Once we have the cage prepared, how will we avoid widespread disease within the farm and escapees from the farm that might affect wild stocks? Will the markets bear the influx of domestic aquaculture species? Lastly, will the offshore aquaculture industry be able to climb the political mountain as a new industry in public waters that see heavy traffic already?

These questions are not presented as insurmountable; rather, they are offered as food for thought. When determining if the offshore aquaculture industry should develop in the U.S. and creating a strategy for it, the legal and regulatory hurdles should be kept in their proper perspectives. For better or worse, law often responds to industry needs (as will likely occur with the interpretation of aquaculture as commercial harvesting under the Magnuson-Stevens Act) as the industry develops. The first inland aquaculture farmers in the U.S. did not have the clear, streamlined permitting process guided by one lead agency when the industry began; it developed over time and laws were tweaked during its development. Also during that time, the industry, like many around the country, addressed the political, economic, environmental, and technological needs in tandem.

[50] See S. Res. 160, 108th Cong., 1st Sess. (June 5, 2003) ("To express the sense of the Senate that the Federal Government should actively pursue a unified approach to strengthen and promote the national policy on aquaculture."). And, see H. Res. 301, 108th Cong., 1st Sess. (June 26, 2003) ("Expressing the sense of the House of Representatives that the Federal Government should actively pursue a unified approach to strengthen and promote the national policy on aquaculture").

[51] *Id.* at S. Res. 160, 108th Cong., 1st Sess. (June 5, 2003).

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CHAPTER 4

ENGINEERING REQUIREMENTS & LOGISTIC ALLEVIATION FOR OFFSHORE AQUACULTURE[1]

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ABSTRACT

Offshore aquaculture—operating out of the sight of land—will have the logistic requirements associated with near shore operations, plus a new set of issues associated with the higher energy of the site and increased distance from shore. The Gulf of Mexico Offshore Aquaculture Consortium has been confronted by these challenges and has developed a suite of components to manage offshore aquaculture systems. This manuscript will present a system design—integrating all developed components—that meets the logistic requirements of offshore aquaculture. Emergency preparedness in the event of an approaching tropical front will be discussed that helps ensure the survival of farm capital and fish stock while maintaining system integrity and worker safety. Distance communication and monitoring of the farm is explored for situations having decreased human presence and during severe storm events. We also include a discussion of potential site configurations and production planning that can be realized by using the logistic alleviation methods described. Finally, a list of future engineering and logistics needs are provided.

INTRODUCTION

The Offshore Aquaculture Consortium (OAC) chose a site having a depth of 26 m approximately 40 km off the coast of Mississippi in federal waters (29° 58.649′N, 88° 36.297′W). This specific location was not chosen for its convenience to Offshore Aquaculture Consortium (OAC) researchers or its suitability for grow-out of any candidate species in the Gulf of Mexico. Given the shear size of the Gulf of Mexico and heavy marine traffic deploying a cage near an existing structure offshore would decrease the likelihood of vessel-cage collisions and subsequent damage. To this end, the research operation was sited adjacent to a ChevronTexaco manned gas production platform, which minimized user conflicts with fishing and shipping activities while providing continuous surveillance of the cage to monitor for vandalism and storm damage.

[1]Portions of this chapter have been reprinted from: Goudey, C.A., T. Boaz and C.J. Bridger. 2003. The design, installation, and performance of a single-point mooring for an offshore cage. Pages 191–195 in C.J. Bridger and B.A. Costa-Pierce, editors. Open Ocean Aquaculture: From Research to Commercial Reality. The World Aquaculture Society, Baton Rouge, LA. ISBN: 1-888807-13-X/MASGC-03-008 with permission from the World Aquaculture Society and Bridger, C.J., C.A. Goudey, D. Good and G.T. White. 2002. Development of a lift-boat suitable for offshore aquaculture logistics. Pages 121-125 in Oceans 2002 MTS/IEEE. October 2002, Biloxi, MS and Goudey, C.A. and C.J. Bridger. 2002. Evolution and performance of a single-point mooring for an offshore aquaculture cage. Pages 126-130 in Oceans 2002 MTS/IEEE. October 2002, Biloxi, MS with permission from the Marine Technology Society.

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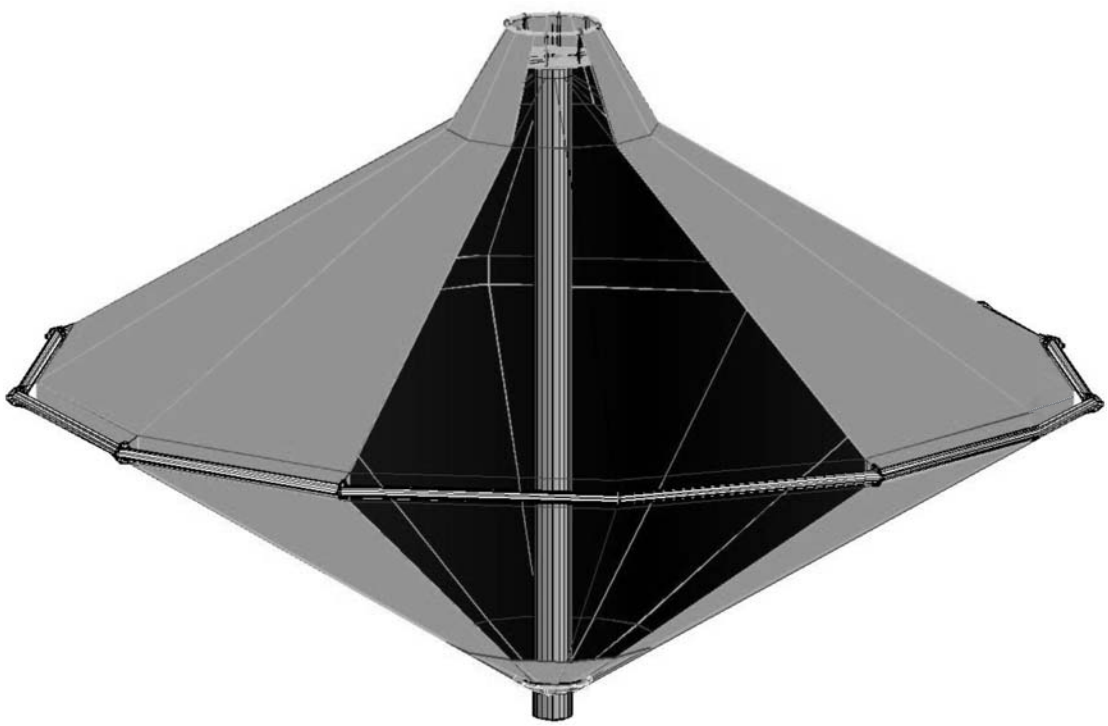
According to Loverich and Gace (1998), coastal aquaculture cages may be classified as gravity or Class 1 cages. This cage configuration often experiences deformation and loss of internal cage volume associated with water movements due to wind, wave and current action. Up to 80% of the expected growing volume, used to base stocking density calculations, may be lost in currents of 1 m/s (Aarsnes et al. 1990). Gravity cages also have all their buoyancy located at the water surface resulting in significant wave-induced motions and internal forces. To endure the high-energy environment found in the Gulf of Mexico and to allow cage sinking to decrease hurricane damage while maintaining possession of the fish stock, a more rigid cage structure is called for. For this reason, an Ocean Spar Sea Station was chosen for the OAC research site (Fig. 1; Loverich and Gace 1998).

To maintain constant volume and shape, the net remains taut between a central spar buoy and a mid-spar rim. The rim is octagonal; composed of eight flanged sections of steel pipe that are individually sealed to provide positive buoyancy. The central spar buoy has a lower variable buoyancy chamber that allows the Sea Station to be submerged to approximately 25 m (82 feet) in a 15-min period. Submergence may be desirable to avoid extreme storm events, dodge harmful algal blooms, or to allow operation in areas that are sensitive to visual aesthetics.

Submergence is accomplished by ballasting the spar buoy with water that enters from the bottom when air is released through a valve located at the top of the spar buoy. Raising the system simply requires displacing the ballast water in the spar buoy with air

Fig. 1. Schematic of the Ocean Spar Sea Station cage.



introduced from a SCUBA tank. The experimental size cage used by the OAC provides a nominal growing volume of 600 m^3. Sea Station volumes up to 35,000 m^3 have been designed (Loverich and Goudey 1996) although the largest used commercially to date provides a 3,000 m^3 internal volume.

The challenges presented to OAC researchers, due mostly to its chosen site, include the severity of the offshore environment particularly in the Gulf of Mexico. These conditions challenge both work safety and structural integrity. The distance from shore limits workdays and increases operating costs requiring innovative mechanization. Separately, individual components have been developed to mitigate these challenges including an Aquaculture Support Vessel (Bridger et al. 2002), single-point mooring (Goudey and Bridger 2002), and Robofeeder (Goudey et al. 2002). Each component was developed to fit within a coherent system design envisioned for effective and safe farm management within the Gulf of Mexico and other potential regions requiring development of distant aquaculture sites.

SYSTEM COMPONENTS

Developing an offshore aquaculture sector, in the absence of near shore operations, allowed innovation that might otherwise have been stifled by attempts to adapt existing operations to more exposed high-energy locations. Offshore aquaculture will require innovative technologies to support offshore operations, maintain cages on station even during extreme storm conditions, allow appropriate levels of feeding, provide long-distance communication often in the absence of cellular phone coverage, and carefully planned levels of response to emergency situations.

Aquaculture Support Vessel

Due to the increased capital investment and operating costs associated with offshore aquaculture, economies of scale will be essential. This will, in turn, demand increased feed inputs to large stocks of fish during grow-out. Daily transport of feed, and other supplies, might prove uneconomical due to transport costs. In addition, daily visits could introduce unacceptable risk due to the unpredictability of offshore sea-state conditions.

A more reasonable approach to manage offshore aquaculture operations involves establishment of a permanent support structure near the cages that can handle these feed requirements and other daily operational logistics. Indeed, previous visions of offshore aquaculture in the Gulf of Mexico placed operations adjacent to existing (and future) oil and gas platforms that would serve as support structures to satisfy logistic needs (e.g., Chambers 1998; Kaiser 2003; Stickney 1999; Waldemar Nelson Inc. 1997). However, though an oil and gas approach may seem intuitive, this strategy is burdened with numerous constraints, including the operation of both sectors simultaneously; requirement to establish an Abandonment Bond to address the removal of a decommissioned platform (estimated at U.S. $2 to $5 million); and, inappropriate platform design and location for aquaculture operations (Table 1). Although the OAC cage is sited near a ChevronTexaco gas structure, the benefits of proximity have been achieved without the liabilities of conflicting use of an active oil and gas platform or those associated with using an obsolete structure. However, this relationship does not provide any of the benefits of a dedicated nearby platform for feed storage or crew housing that a carefully designed facility would offer.

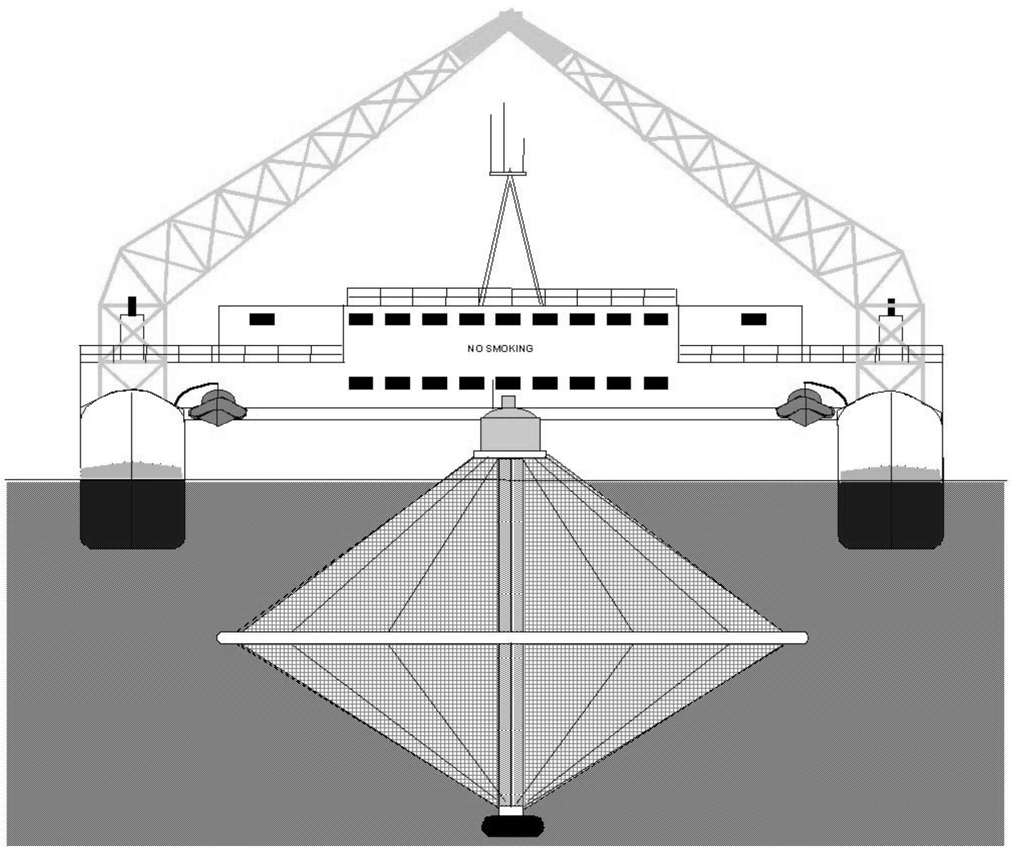
Table 1. Comparison of scenarios for integration of oil and gas (O&G) platforms in the development of offshore aquaculture in the Gulf of Mexico.

Offshore Aquaculture Operations Strategy	Advantages	Disadvantages
O&G Invest into and Integrate Offshore Aquaculture Within Operations	– Increase economic potential of O&G structure	– Leasing modifications required – Present platform design will not allow mooring offshore cages to the structure and not designed for safe aquaculture operations – Future platform design criteria modified for safe operations – Potentially interfere with O&G operations
Offshore Aquaculture Investors Lease Abandoned O&G Structures	– Offset costs associated with structure removal – O&G industry are not direct investors to offshore aquaculture	– Present platform design will not allow mooring offshore cages to the structure and not designed for safe aquaculture operations – O&G industry will still have liability issues: 1) Maintenance of aids to navigation 2) Structural integrity of the structure for its life 3) Injuries or property damage associated with the structure – O&G original operator may be responsible for removal if new operator neglects removal
Near O&G Platform but as a Separate Operation	– No transfer of ownership required – Passive protection to the cage facility – Visual surveillance offered to vandalism and storm damage	– No benefits of platform to the aquaculture operator as a 'shore-base' – Potentially interfere with O&G operations – O&G operator potentially liable for aquaculture mortality near its structure
Lift-boat within Marine Aquaculture Zone	– Eliminates all O&G concerns to aquaculture – Specifically designed for aquaculture operations – Avoids storm impact	– Increased user conflicts if competing for new space with traditional use

An alternative approach involves the design and deployment of a purpose-built Aquaculture Support Vessel (ASV) to meet the requirements of offshore aquaculture. An ASV could be economically competitive with approaches that use existing oil and gas structures owing to the required abandonment bond. The operational requirements of such an ASV would include:

- cage fleet communications and control;
- mooring system installation and removal;
- cage installation, towing, maintenance, and repair;
- fish stocking, sorting, harvesting, and transport;
- feed hopper re-supply;
- fish health monitoring and treatment laboratory;
- environmental monitoring laboratory;
- diver and ROV support;

Fig. 2. Conceptual design of a catamaran designed specifically to service offshore aquaculture cages (Goudey 2001).



- a helicopter-pad;
- sufficient living space for workers;
- maintenance and office space; and,
- a crane capable of lowering and raising a farm workboat and feed.

The ASV may also be designed with a central feed system onboard to feed cages in its vicinity.

Loverich and Forster (2000) briefly mentioned a purpose built catamaran to service offshore aquaculture cages in exposed sites to meet these ASV criteria (Fig. 2). However, the exploitation of proven approaches to operating in the Gulf of Mexico must also be considered. Therefore, the OAC, in conjunction with Good Streak Marine (Slidell, LA), initiated the design process for a lift-boat technology to service offshore aquaculture cages in the Gulf of Mexico (Fig. 3) and serve as the focal point for a permitted offshore aquaculture site.

Within the present design, the lift-boat has a total usable deck space of 500 m^2 and four hydraulic legs appropriate for water 26 m deep. These legs can be lengthened according to site specifics and appropriate levels of available financing. The regular operational

Fig. 3. A typical lift-boat used in the Gulf of Mexico oil and gas industry to service the needs of the industry and lay pipelines.

mode would see the lift-boat jacked-up, perhaps to 7-m above the water surface, to provide a stable working platform. In severe or hurricane conditions, workers would sink the fish cages prior to either raising the lift-boat legs and moving to shore or keeping the lift-boat in its operational mode and being evacuated by a helicopter. The lift-boat may also be designed with a central feed system onboard to feed cages in its vicinity (Figs. 4a and b).

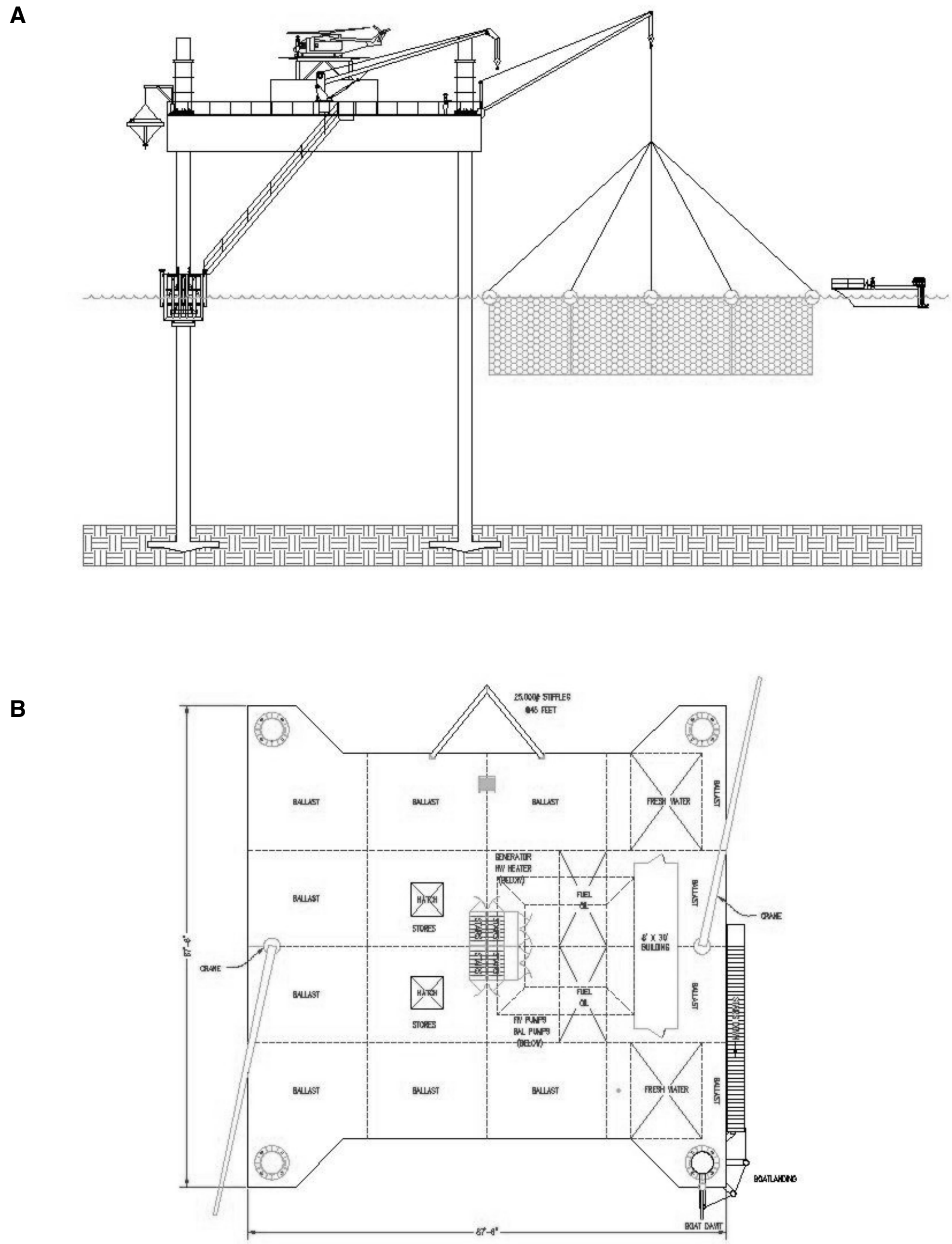
Lift-boats are designed to take on ballast water during positioning to increase the weight within the structure and set the legs into the bottom. Once elevated, the ballast water is removed and the setting into the sediment provides the necessary stability during high winds and poor sea-state conditions. These same ballast chambers may be used to provide a live-haul capability for fish stocking and harvesting.

A preliminary economic analysis has revealed that a lift-boat ASV, supporting twelve 3,000-m^3 offshore aquaculture cages, could be economically feasible (Posadas and Bridger, this volume). Additional economic returns could be realized by using the lift-boat to service multiple cage clusters within the operating range of the vessel's home base. In such cases, the lift-boat would serve as the base for farm workers managing numerous cage clusters. Effectively, this strategy would decrease the distance to aquaculture sites further offshore and allow more efficient use of good weather windows frequently experienced during the hostile winter season with high seas more typical due to frontal movements.

Single-Point Mooring

Single-point moorings are the favored method for anchoring most floating marine systems such as oceanographic buoys and marine vessels. Use of a multi-anchor grid

Fig. 4. A conceptual design of the lift-boat ASV in its operational mode elevated up to 7 m above the water surface (A). Aerial view of the lift-boat ASV (B).



arrangement commonly in sheltered water aquaculture is a by-product of regulatory siting constraints that are not necessary in open water. Baldwin et al. (2000) concluded that deployment of grid mooring systems for open ocean sites should be avoided if possible to decrease installation complexity and costs. Fredriksson et al. (2000) investigated the potential for using a single-point mooring for open ocean aquaculture applications. However, in this case a multi-anchor grid system was chosen owing to the risks involved with a single taut line holding their experimental systems and the need for unqualified engineering success during the early stages of a research program.

Goudey et al. (2001) first described benefits associated with using a single-point mooring, as we have developed, including:

- Decreased complexity associated with requiring precise adjustment of multiple anchors in typical grid mooring systems.

- Predictable location of loads that allow appropriate engineering of the mooring to ensure survivability during expected storm events.

- Decreased costs associated with a single mooring line compared to multiple lines.

- Decreased maintenance requirements with a single mooring line.

- Improved accessibility to the cage or cage array regardless of weather direction.

- Allowance for advanced production planning and cage arrangements for stocks that require high oxygen levels and faster water flow compared to other cage stocks.

- Decreased environmental impacts compared to a cage system fixed spatially within a multi-anchor system. The SPM allows the cage system to wander within a watch circle of a diameter dependent on the length of mooring line.

- Minimize the bottom area required for the mooring system thereby decreasing the costs associated with leasing of necessary space especially in instances having deep water and therefore requiring expansive bottom area for multi-anchor mooring systems.

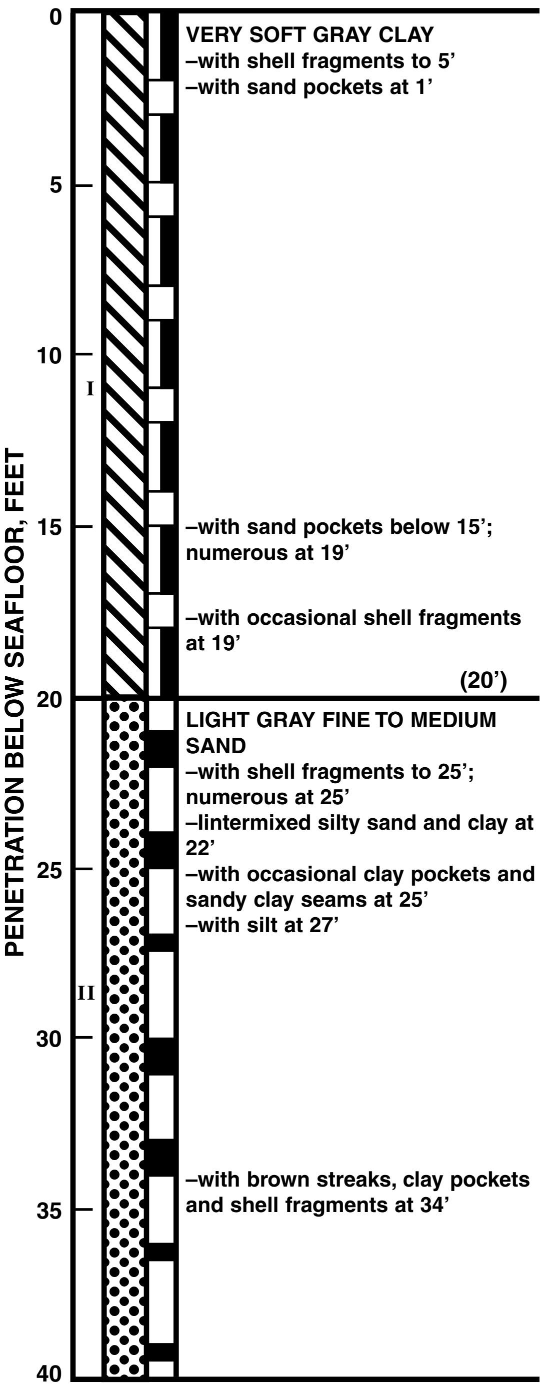
- Minimize the potential impacts on and entanglement with marine mammals in the vicinity of open ocean aquaculture sites by having fewer lines present in the water column associated with the farm mooring system.

Design Criteria

For many of the reasons provided above we decided to deploy the OAC cage on an SPM. However, fiscal constraints presented the most compelling reason for this choice. The greatly reduced complexity associated with the SPM substantially reduced the costs associated with the offshore mooring system. Furthermore, anticipated costs for cage-mooring installation would be far less compared to deploying a multi-anchor array followed by cage installation within such an array.

Based on empirical test data, the resistance characteristics of the OAC 600 m^3 cage are known (Loverich and Gace 1998). A worst-case storm current condition for the site was estimated to be 1.03 m/s (2 knots). The cage resistance in that current was determined to be 9,091 kg. Two anchor types were determined to be appropriate for the site—a helical anchor or a deadweight anchor (Taylor 1991).

Fig. 5. Soil profile of the offshore aquaculture site illustrating the depth of unconsolidated sediment.



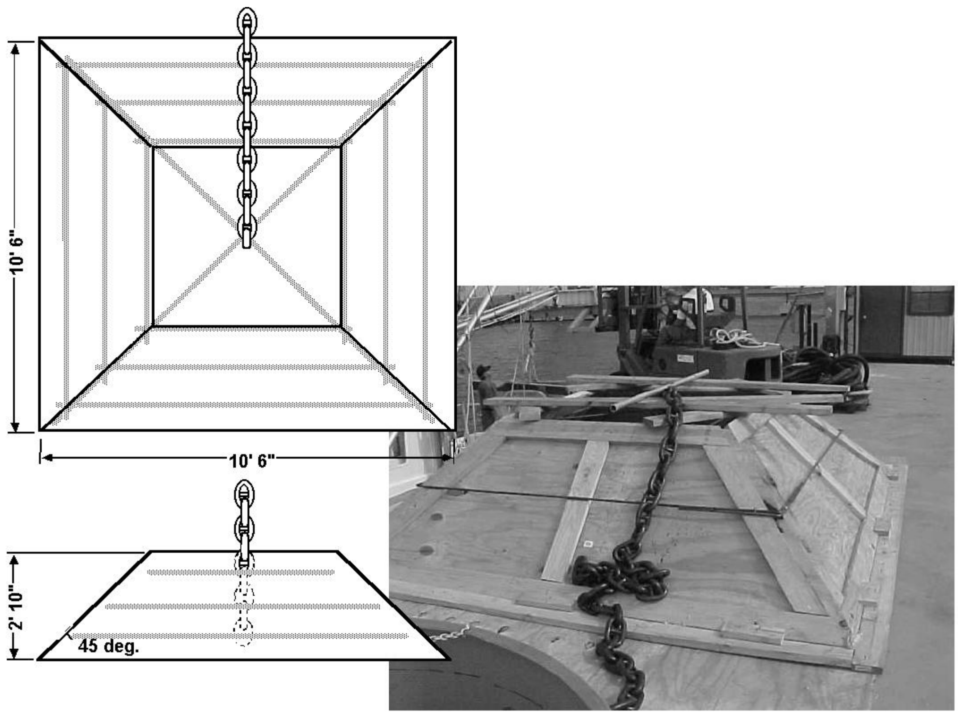
Because of the depth of unconsolidated mud at the site (Fig. 5), a single, vertical helix anchor would present insufficient shaft strength for omni-directional holding. A cluster of three anchors angled in at 45° in a 120° rosette would provide sufficient holding strength to maintain the cage. However, the installation costs of such an anchor array would not be competitive with the dead weight option. Likewise, helical anchor deployment in 25 m water depth and extremely low visibility following seabed disturbance was not considered appropriate compared with dropping a dead weight mooring block from the vessel to the seabed.

General design rules for deadweight anchors on mud bottoms (Taylor 1991) suggested a 22,727 kg block would be required. However, the installation barge to be used had a maximum lifting capacity of 11,364 kg. Therefore, with this as a weight limitation, an anchor geometry was developed that would offer some embedment capability should the deadweight resistance to movement be exceeded. A 175 cu. ft. block was designed in the form of a 10.5’ x 10.5’ x 2.8’ truncated pyramid (Fig. 6). This design would be resistant to tipping and its upper corners are resistant to line tangling. Also, the form for casting this anchor could be built from four pieces of 4’ x 8’ plywood.

Cage-SPM Deployment

Although deploying any cage and mooring is site and environment specific, siting a cage and mooring in a distant offshore location poses new challenges to overcome. Perhaps the most efficient mode of deploying the cage and mooring 40 km from shore would have involved carrying the assembled rim, central spar buoy, ballast weight and single-point mooring components to the site on a barge. This strategy would have decreased the

Fig. 6. The OAC SPM 12,273 kg deadweight mooring block.



necessary travel time associated with towing system components, similar to other project deployment strategies (Baldwin et al. 2000). Further, the OAC research team expected use of a lift-boat, with sufficient working deck space, would have created the safest and optimal deployment conditions by jacking the lift-boat out of the water and creating a stable work platform, offshore. However, just days prior to the scheduled cage deployment, the northern Gulf of Mexico experienced approximately 2.5 m waves which delayed access to a lift-boat, creating the necessity to explore alternative methods for cage and mooring deployment. At this time, The University of Southern Mississippi research vessel IX 508 was chosen for towing the cage and mooring block to the site and subsequent system deployment following careful consideration and discussion.

The cage rim sections were assembled at the NOAA National Marine Fisheries Service dock in Pascagoula, MS. This dock provided sufficient workspace to assemble the 15 m octagonal rim and stage the various cage and mooring components, near the water, for efficient transfer to the water surface.

On October 28, 2000, a crane was contracted to lift the 12,275 kg (27,000 lbs) mooring block in position, approximately 3 m below the surface and well clear of the IX 508's propellers and rudders, and supported by its A-frame. The mooring block was suspended by the lower mooring chain, which had been embedded into the concrete during casting and welded to its rebar armature.

The central spar buoy was hoisted to the water surface and allowed to float in a horizontal position for towing. The assembled octagonal rim was hoisted to the water surface and positioned around the central spar buoy to ease towing and cage assembly. Finally, the ballast weight, harvest ring, work platform and netting were placed on the IX 508, prior to departing Pascagoula.

To ensure site arrival at sunrise, towing began at approximately 1800 hrs. At a maximum towing speed of 1.54 m/s (3 knots), the IX 508 arrived on station at approximately 0400 hrs, at which time the vessel remained in the vicinity of the ChevronTexaco gas platform until sunrise.

Mooring deployment commenced at sunrise, October 29, 2000. The octagonal rim and central spar buoy components were released from the IX 508 prior to lowering the mooring block to the sea floor to increase safety and maneuverability of the vessel. The mooring block and single-point mooring chain were slowly lowered to the desired location, followed by divers descending to inspect the block on the seafloor and release the lowering IX 508 rope. The octagonal rim and central spar buoy were then retrieved and connected to the single-point mooring line.

The central spar buoy had to be in a vertical position to create the taut netting, double-cone configuration of the Ocean Spar Sea Station. The ballast weight, a circular concrete block weighing approximately 3,181 kg with a toggle through its middle to attach it to the bottom of the spar buoy, was lowered to the water surface, attached to the bottom of the spar buoy, and further lowered until the spar buoy was vertical and divers could release the crane cable. Once in a vertical position, the harvest ring was lowered over the spar buoy. The netting was attached to this harvest ring, which could later facilitate fish harvesting by raising it up the central spar buoy and effectively decreasing the internal cage volume. The netting was further lowered over the spar buoy and attached to the top of the spar buoy, followed by the work platform, positioned on the top of the spar buoy.

The spar buoy was then floated to the central portion of the octagonal rim. The netting was stretched to each flanged region of the octagonal rim and shackled to the inside corner of the rim section. This completed formation of the upper-cone section of the cage and created a very taut net. The lower portion of the net was attached to the harvest ring and tightened as much as possible. The cage and netting were secured for the night and the vessel departed the site.

The following morning the deployment team returned to the aquaculture site in a smaller research vessel (RV Tom McIlwain) and completed cage assembly. The net was further tightened over the central spar buoy and the netting, mooring shackles and connections were inspected. This entire deployment (cage and mooring) required a total of 2-days.

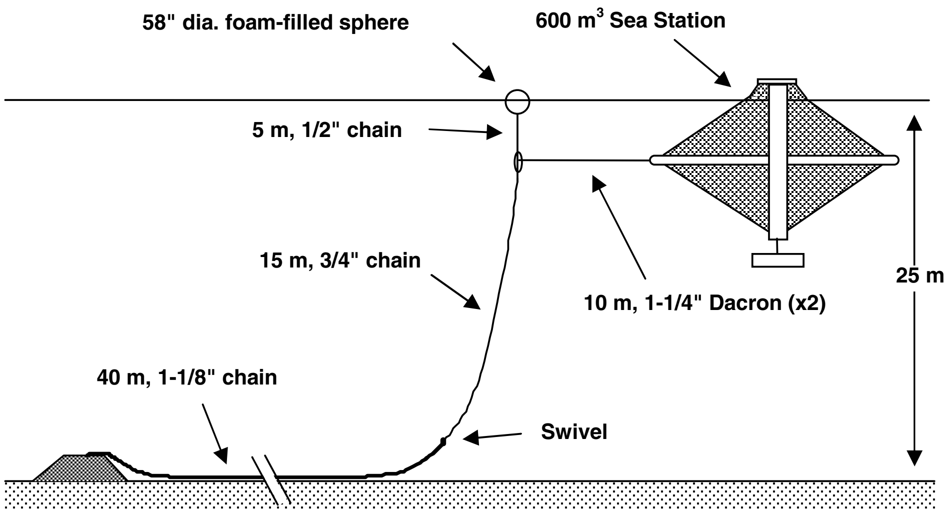
<u>SPM Tension Member Evolution</u>

- Initial SPM Deployment

Our mooring system design goal was for all tension member components to have a five to one safety factor over the design cage resistance of 9,091 kg (i.e., 45,455 kg tensile strength). We also sought proven technology and low lifetime costs. Shock load damping was provided by the use of chain as a tension member. The only exception to the tensile strength requirement was the suspended portion of the chain, which was proof tested at a 9,091 kg safe working load and a 36,360 kg tensile strength.

Following SPM deployment, the cage was connected to the SPM using bridles running

Fig. 7. The original SPM highlighting the deadweight, tension member, and horizontal synthetic bridles.



horizontally from the submerged cage rim and intersecting the SPM chain in a pear link connection 3 m below the 1.5 m diameter spherical mooring buoy. The overall length of chain and bridles provided a "watch circle" radius of approximately 70-m (Fig. 7). The costs of this SPM, installed, were determined to be equal to or less than a single anchor element of a multi-anchor array (Table 2).

The original SPM was regularly inspected and it had endured several northerly fronts, considered typical for the Gulf of Mexico during winter (Fig. 8). However, just 50 days after deployment (on December 18, 2000), the cage broke free of the SPM and was adrift in the northern Gulf of Mexico for a period of 40 days prior to its recovery and being safely towed to shore for inspection and to await redeployment. Inspection of the intact SPM and the recovered cage determined that the failure was due to the bridle shackles connected to the mooring pear link that has not been welded. Impacts between the shackles dislodged the shackle pin keeper and allowed the pin to drop out. We later concluded that the heave motion of the surface float was transmitted to the submerged attachment intersection, where the two shackles resisted heave due to the horizontal drag of the synthetic bridles. Based on this experience, a specially designed rigging plate was incorporated into the SPM system, replacing the pear link, which will properly capture the tension members leading from the anchor, float, and cage, and preventing impacts among them.

- Three-point Mooring System

Initial redeployment utilized a three-point mooring system incorporating the original SPM deadweight and tension member and adding two new anchor legs consisting of 454-kg Danforth-type anchors and chain/tennex tension members (Fig. 9).

This system proved very problematic in the environmental conditions experienced at the site, with the Danforth-type anchors frequently dragging in the soft seabed and mooring lines subsequently tangling in the cage. Prior to removal, the new three-point mooring system caused the formation of several large

Table 2. SPM costs.

Item	Description	Cost
Mooring block	Form	$341.71
	Rebar	$43.05
	Concrete 6 yd	$300.00
Bottom chain	135’ - 1 1/8”	$1,087.50
Chain connector	1 1/8”	$145.00
Jaw-jaw swivel	1 1/8”	$135.00
Middle chain	50’ - 3/4”	$510.00
Buoy chain	15’ - 1/2”	$52.50
Conn. Hardware	Asst.	$308.41
Foam-filled buoy	58” dia.	$1,350.00
Bridles	35’ - 1 1/4” x 2	$445.80
Total		$4,718.97

holes in the cage netting, from chafing with the additional tension members and one of the new floats actually finding its way into the netting of the cage.

- “Redundant”-SPM

In addition to the connection plate, the final SPM design includes a redundant bridle system that will serve to retain the cage should the primary bridles detach under excess storm stress, wave-induced chafe, or damage from vessel impact or vandalism. Both sets of bridles are connected to the mooring line by a specifically designed rigging plate to allow independent connection of shackles not previously allowed using an open pear link. The redundant bridles are longer than the primary bridles and are connected to a second rigging plate approximately 1.5 m below the primary

Fig. 8. Typical northerly front wave heights experienced during winter in the northern Gulf of Mexico (http://www.ndbc.noaa.gov/station_page.phtml?$station=42007).

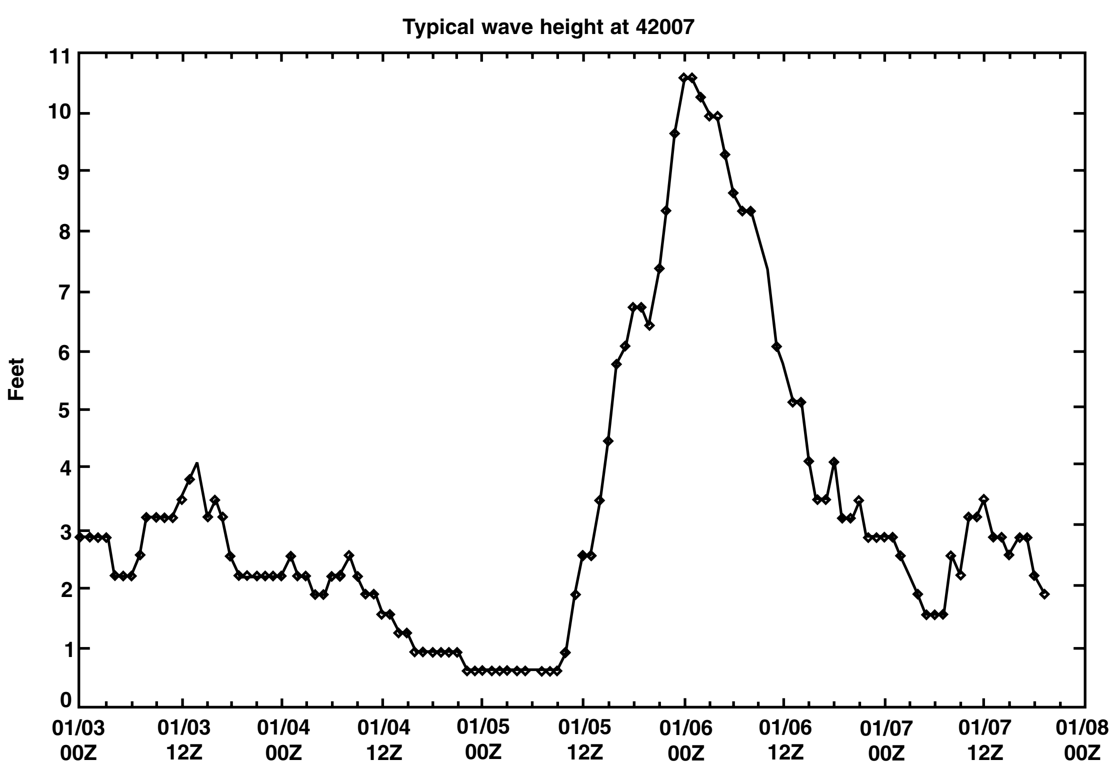


Fig. 9. Three-point mooring system utilizing the original SPM deadweight and tension member and incorporating two additional mooring legs with Danforth-type anchors and chain/tennex tension members.

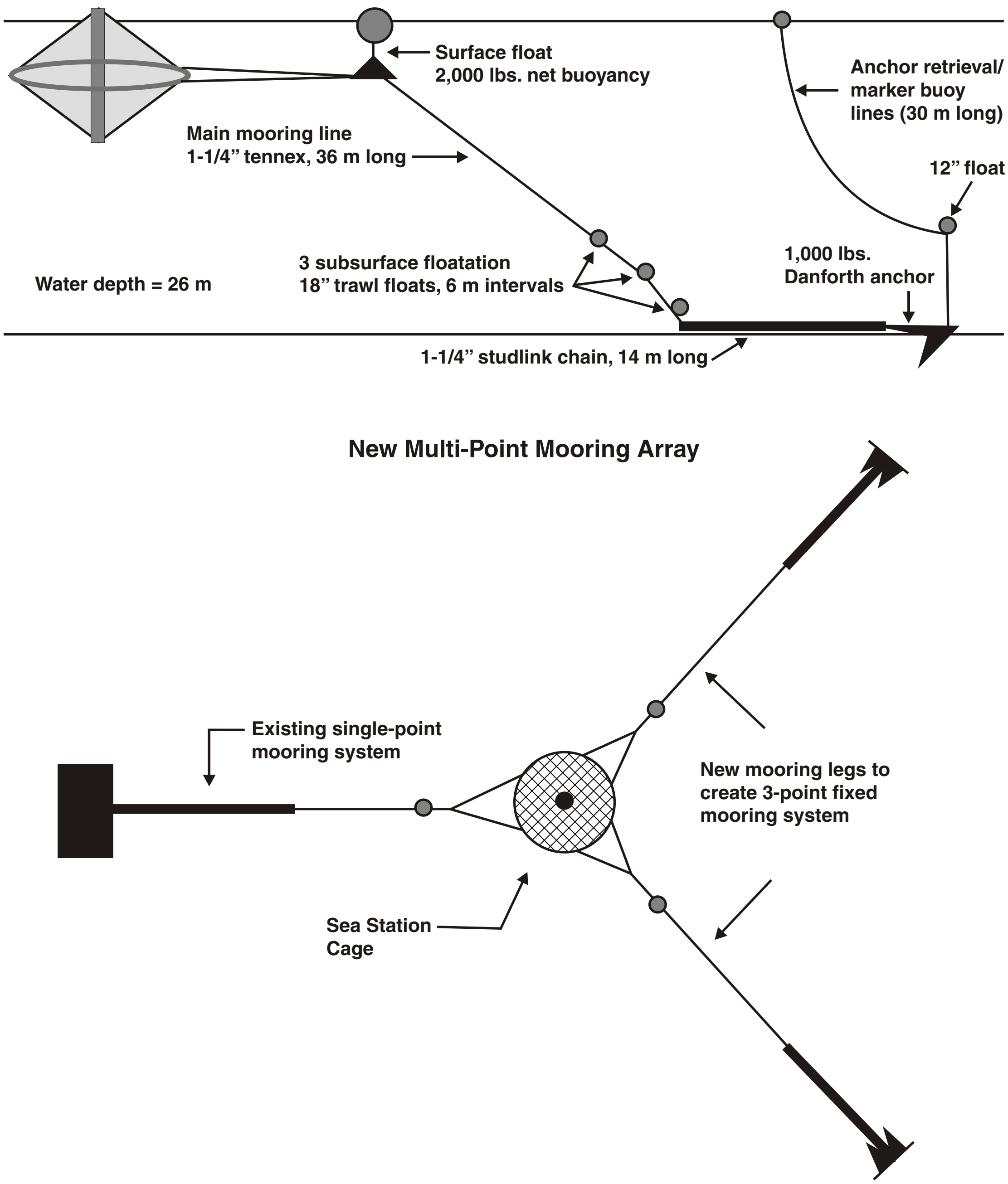
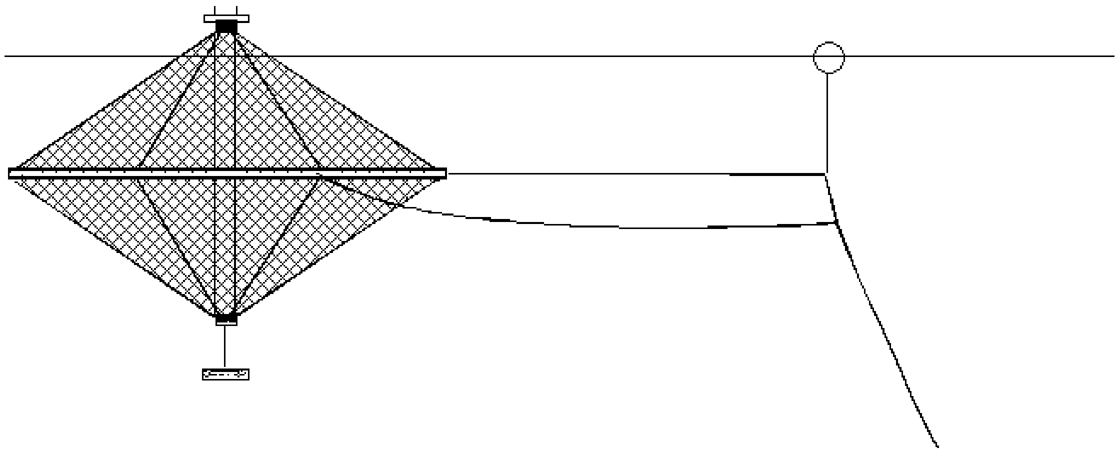


Fig. 10. Illustration of the OAC SPM showing the position of the shorter primary bridles 1.5-m above the longer redundant set of bridles and their respective connection points on the cage rim.

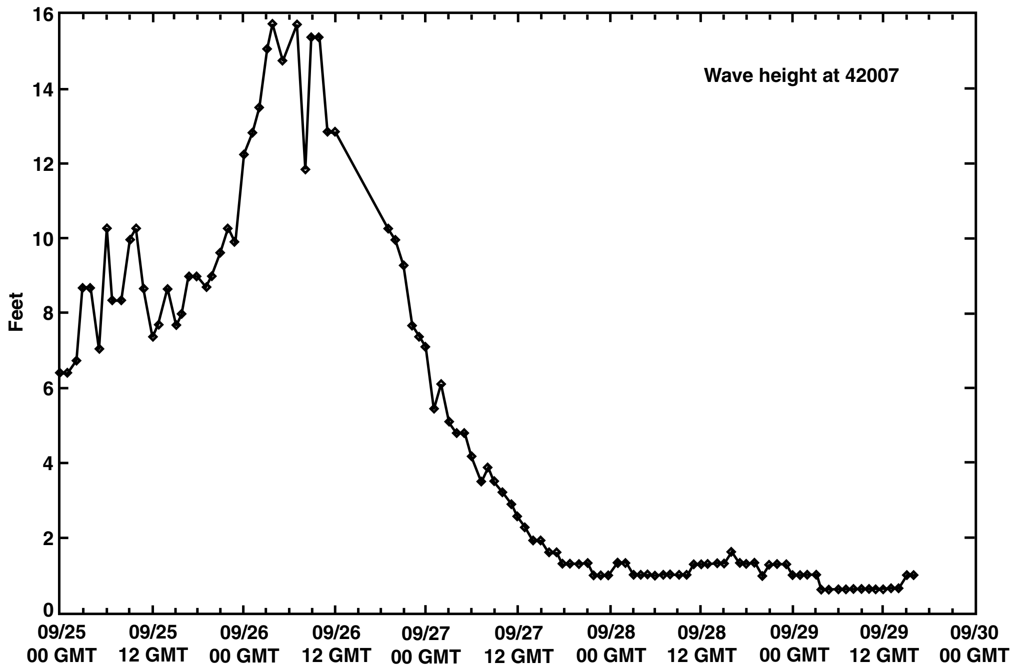


one (Fig. 10). Additional improvements over the original SPM include use of a rope tension member between the primary rigging plate and surface buoy to dampen the heave motion and bridles that have only one connection point to the rigging point and split to the cage approximately 2 m from the rigging plate.

This "redundant-SPM" system is considered a significant improvement to the first SPM system and as worked without problems in the Gulf of Mexico through the 2003 hurricane season, including two tropical storms and two hurricanes. The system provided trouble free performance prior to cage removal during the summer of 2003. Sea Station cages can be maintained at the water surface for day-to-day operations and submerging only in the event of extreme storm conditions, such as strong northeasterly gales or tropical frontal systems. Submergence could occur directly by the fish farmer by de-ballasting the spar buoy as discussed earlier. Alternatively, the cage-mooring complex can be adjusted to a specific bouyancy that will allow the cage to submerge due to anchor line tension from high currents associated with storm events. Once the storm-induced current subsides, the cage would passively return to the surface. This latter approach was used operationally by the OAC and the system behaved predictably during passage of both hurricanes.

While the cage-SPM complex was deployed trouble free in the Gulf of Mexico, numerous questions regarding the detailed behavior of the cage-SPM during extreme hurricane conditions remain. To better understand the system, numerical modeling was conducted. In cooperation with engineers from the University of New Hampshire, a model was developed to predict the cage motion response (heave, surge, and pitch) and tension at various points along the mooring line under incrementally large hurricane forces (Fredriksson et al. 2004). The numerical model uses the Finite Element Analysis approach most recently described by Tsukrov et al. (2003). In past simulations, the results of the model have compared well with both physical model tests and field measurements for a variety of conditions (see for example DeCew 2002; Fredriksson et al. 2003a;

Fig. 11. Hurricane Isidore wave height data (http://www.ndbc.noaa.gov/station_page.phtml?$ station=42007).



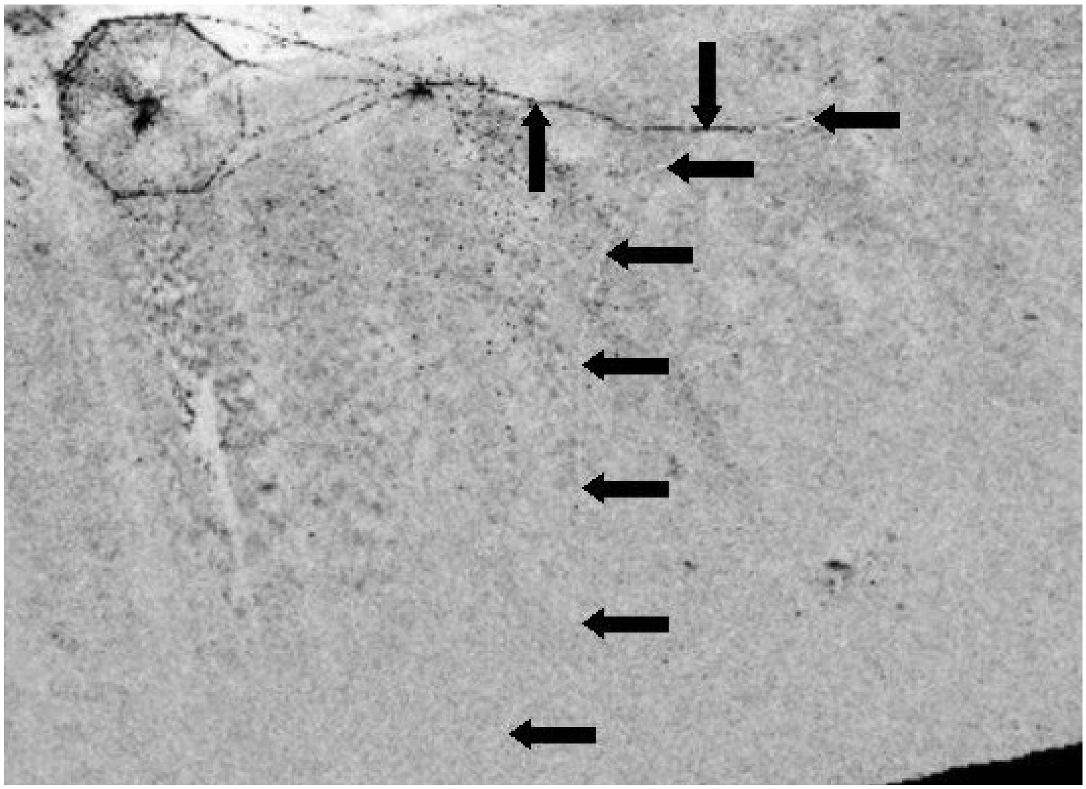
Fredriksson et al. 2003b; Fredriksson et al. 2003c). No field data on cage motion or mooring tension is available for comparison with the numerical results.

One of the largest storms that occurred during the deployment period was Hurricane Isidore (September 26, 2002; Fig. 11). Maximum wave data obtained from the National Data Buoy Center moored instrumentation platform (#42007) located near the site were used as input to the numerical model. Ocean currents also dominate the tension and motion response of the cage and mooring system. Since current measurements were not made directly at the site, simulations were performed using a range of values consisting of 0, 0.25, 0.50, 0.75, 1.00 and 2.00 m/s (constant with depth). The ocean current value was applied in the model superimposed with waves. A complete description of these model results can be found in the final modeling report (Fredriksson et al. 2004). We will present a brief overview of model findings here for discussion purposes.

The mean vertical position of the cage during these six hurricane situations was predicted. These values were computed from the initial floating position of the cage. In general, it was observed that the cage vertical position in the water column decreased slightly with the current. The simulation performed without current (load case #1) indicated that average vertical position was unchanged. While at a current velocity of 2 m/s (load case #6), the value was –2.51 m.

Qualitatively, this trend is in keeping with the design goals of the SPM. However, a side scan sonar survey conducted after the hurricane indicated that the ballast weight, sus-

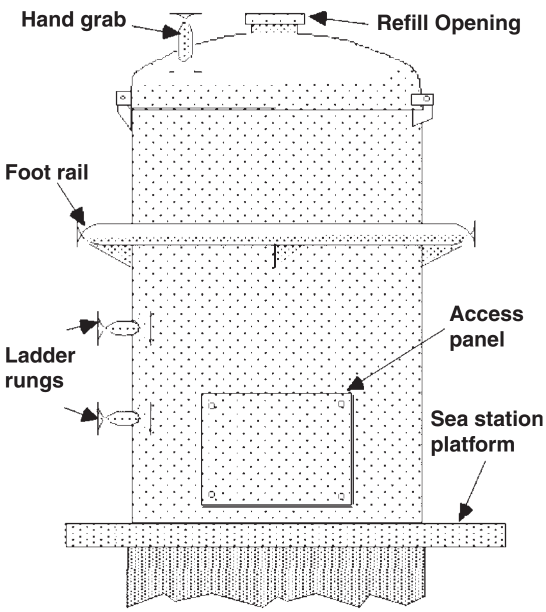
Fig. 12. Side scan sonar image of the cage and SPM arrangement illustrating the pattern of distribution of the SPM chain along the seabed.



pended beneath the cage, touched the bottom during the hurricane passage and created divots in the sediment. Additional drag experienced by the system could be responsible for this discrepancy by changing the dynamic response of the system causing it to sink further than what the model predicted (this situation was further corroborated by the fact that the cage was barely floating following the hurricane). Additional simulations were therefore performed (using the same load cases) but with the cage properties set at values so the system was only slightly buoyant. Results now indicated that indeed the ballast weight would touch the sediment during a current velocity of 2 m/s (load case #6) with the maximum vertical position of the cage being –11.84 m.

Model results also indicated that the SPM provided more tension to the secondary set of bridles than previously anticipated. The simulations also show the entire cage mooring line becoming taut and completely off bottom. However, we know that much of the larger bottom chain remained buried in the fine mud sediment. The consequence of having this chain resisted by the mud was not included in the modeling effort. Diving inspection prior to and after hurricane occurrence indicated that the mooring line might never have been pulled from the sediment but rather the cage pivoted from the point of exit from the mud and not from the mooring deadweight. This situation can be seen in the side scan sonar image provided in Fig. 12.

Fig. 13. Schematic of the automated, mechanized on-board Robofeeder system deployed by the OAC within the Gulf of Mexico.



Robofeeder

Feeding fish in any aquaculture venture is arguably the most important task to ensure profitability. Offshore aquaculture ventures are unlike near shore operations located within the confines of protected bays and fjords where inclement sea states are episodic. Relying on daily site visits for feeding would certainly ensure the fish stock are not fed on a continuous basis, and jeopardize farm worker safety in unfavorable conditions. Offshore aquaculture must therefore rely on mechanization and automation for many of its day-to-day operations to be feasible. Feeding is one such task and without cost-effective, reliable unmanned feeding systems, offshore aquaculture is commercially impractical.

Feeding fish in a Sea Station cage using a surface spreader is particularly challenging given the shape of the cage, the resultant small surface area, and the presence of a central spar buoy obstructing even spread. This situation is exacerbated when the cage is moored below the water surface. Near shore sites using Sea Station cages (Hawaii and Puerto Rico) have opted to make daily visits to the site and deliver feed from the boat via a feed hose that extends inside each cage. This approach is not feasible at locations further from the homeport because day trips are unreliable. Two approaches are being developed within regional U.S. open ocean aquaculture programs for specific use with the Sea Station—the feed buoy at the University of New Hampshire (Rice et al. 2003) and Robofeeder developed at MIT and deployed in the Gulf of Mexico (Goudey et al. 2002). Both systems were built as experimental prototypes to reveal their potential for commercialization.

The Robofeeder is an on-cage pellet storage and dispensing system with a 225 kg capacity. Having a multi-day feed storage capacity only requires periodic site visits to replenish feed thereby removing the necessity for daily visits in the relatively hostile environment experienced in the Gulf of Mexico. Employing electronic control and pneumatic actuation, the system relies on gravity dispensing of feed. The on-board timer system will allow dispensing of controlled amounts of pellet feed up to 24 feeding times per day. Other than the routine re-supply of pellets, Robofeeder is relatively trouble free since its one battery and one air tank are expected to last at least three months.

The OAC Robofeeder was installed in December 2001. The silo is designed to specifically fit on top of the Sea Station work platform (Fig. 13). Feed is dispensed via a pneumatic-controlled gate-valve that opens to a 2” Y-fitting. All electronic components are contained in a submersible housing. The initial configuration had a 2" diameter hose connected directly to the Y-fitting and exiting the spar through 2" holes cut below the structural bar of the spar but above the upper bulkhead weld. However, this arrangement resulted in some feed settling in a slight bend in the hose and eventual clogging. Feed settling was remedied by reducing to 1½" PVC pipe that exited straight through the holes from the Y-fitting and then connected to the 2" hose. From this fitting, sinking pellets fall through tubes into the cage volume.

Throughout development, some lessons regarding feed type and size were also learned. Initial thoughts were to move fingerlings offshore at a very small size, 8–10 g in weight. However, to do so would require the ability to feed a crumble feed which has proven difficult given the high humidity in the Gulf of Mexico and use of the 2" hose that easily clogged with damp crumble feed. With a feed size limitation, fingerlings must now be moved offshore at a larger size, 40–80 g, which can be fed 1/8" feed pellet. Initially, we used a slow sinking pellet to increase the residence time of the feed in the cage thereby minimizing the amount of potentially wasted feed. However, slow sinking feed absorbs water while in the 2" hose and again resulted in clogging. A faster sinking pellet was eventually used to ensure feed is dispensed to the fish in the cage. Observations have determined that even this faster sinking feed has sufficient residence time to allow efficient feeding without expensive wastage. If neutral or floating pellets are used in future operations, then the dispensing tubes would be provided with a flow of seawater to propel the pellets into the cage.

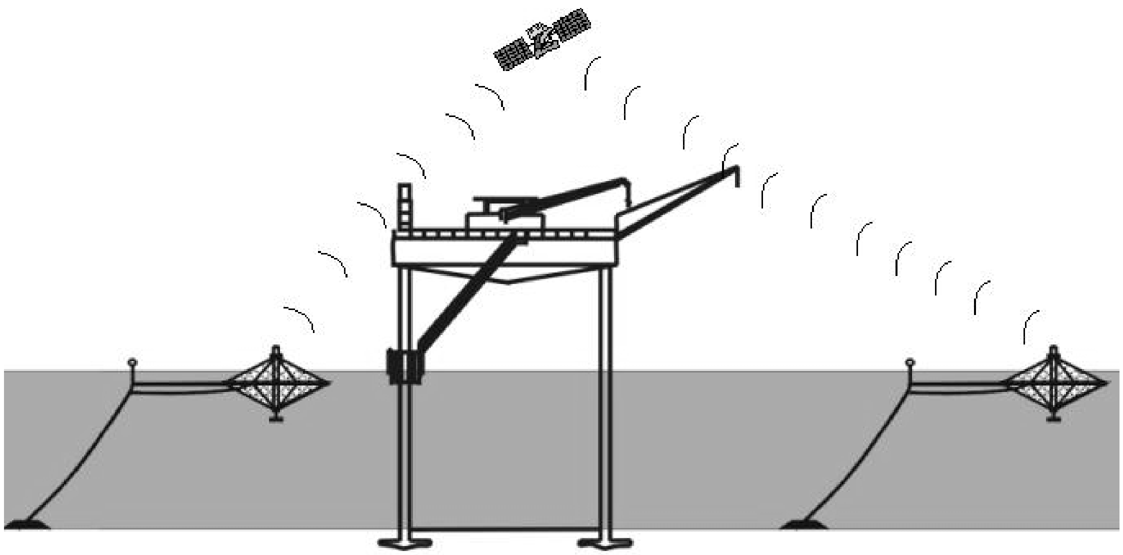
The Robofeeder can be modified to operate in a submerged mode, which may be purposely chosen for operations or periodically occur during times of tropical frontal movement (i.e., hurricanes). Modifications for submerged feeding will include pressure compensation of the feed hopper at depth. Techniques for the re-supply of a submerged pressurized hopper have also been developed but we have not needed to implement them.

INTEGRATION OF SYSTEM COMPONENTS

There is no doubt that risks increase with distance from shore and greater exposure of an aquaculture site to natural elements. Economic, environmental, and management risks might best be avoided through a systems approach that integrates the numerous individual components of farm infrastructure and management into a holistic design. It is precisely this approach that has been adopted by the OAC for developing an offshore aquaculture system by evaluating farm components—cages, moorings, nets, feeders, service and logistics support, applicable regulations, economic inputs, and market outputs—and considering the interactions of these components to create the system. All of the system components described have been designed while maintaining a vision for an operating offshore farm and how best to service cages offshore in a safe and efficient manner.

Normal operation would have cages positioned at the surface and necessary farm chores completed while sea state conditions allow (Fig. 14). An essential chore will be to maintain adequate feed levels within the Robofeeder hoppers sufficient to cover extended periods of inclement weather. Operators would be urged to feed fish using Robofeeder at all times and not by other means during favorable conditions. This method will ensure that fresh food is always

Fig. 14. Normal operational configuration of the ASV, cage/SPM, feeder, and mooring monitor.



placed within Robofeeder and fed to the fish during poor conditions thereby not providing rancid feed that may have been held over a long duration in the hopper.

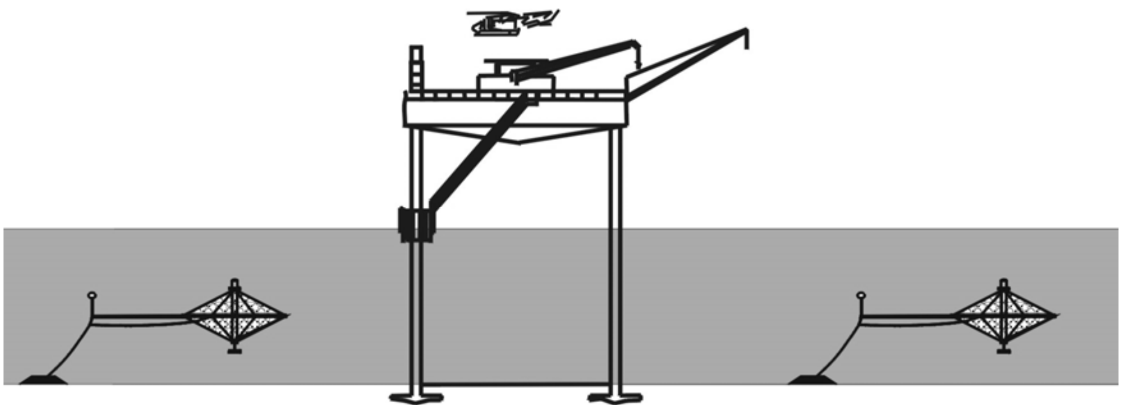
The lift-boat would serve as the central point of operations for the farm, which might service cages both within its immediate vicinity and some distance from the lift-boat. Feed would be stored in air-conditioned sections of the hull. Cages near the structure might have feed replenished directly through a hose running between the lift-boat and Robofeeder during very calm conditions. Alternately, feed pellets could be transferred to farm workboats that ferry feed to each Robofeeder as necessary.

In severe or hurricane conditions, workers would sink the fish cages prior to either raising the lift-boat legs and moving to shore or preferably keeping the lift-boat in its operational mode and being evacuated by a helicopter (Fig. 15). The single-point moorings will be independent of the lift-boat (as illustrated in the Figure) and ballasted with water to facilitate sinking.

Of course cages submerged in this fashion will also require active de-ballasting to again bring them to the surface. The OAC has overcome this issue by designing its single-point mooring to have excess reserve buoyancy in its surface float that does not immediately sink with the ballasted cage. Instead the ballasted cage remains just below the water surface, avoiding the building waves. As storm conditions increase and wind driven currents rise, the surface float will be pulled underwater by the added tension in the mooring line. Its depth will therefore be dependent on the storm intensity.

As the storm passes or subsides the cage reappears at the surface in the same position as prior to the storm event. This configuration allows immediate communication and monitoring of the cage systems once the storm passes rather than relying upon return to the

Fig. 15. Submerged position of the cages and evacuation of the farm operators during severe storm events.



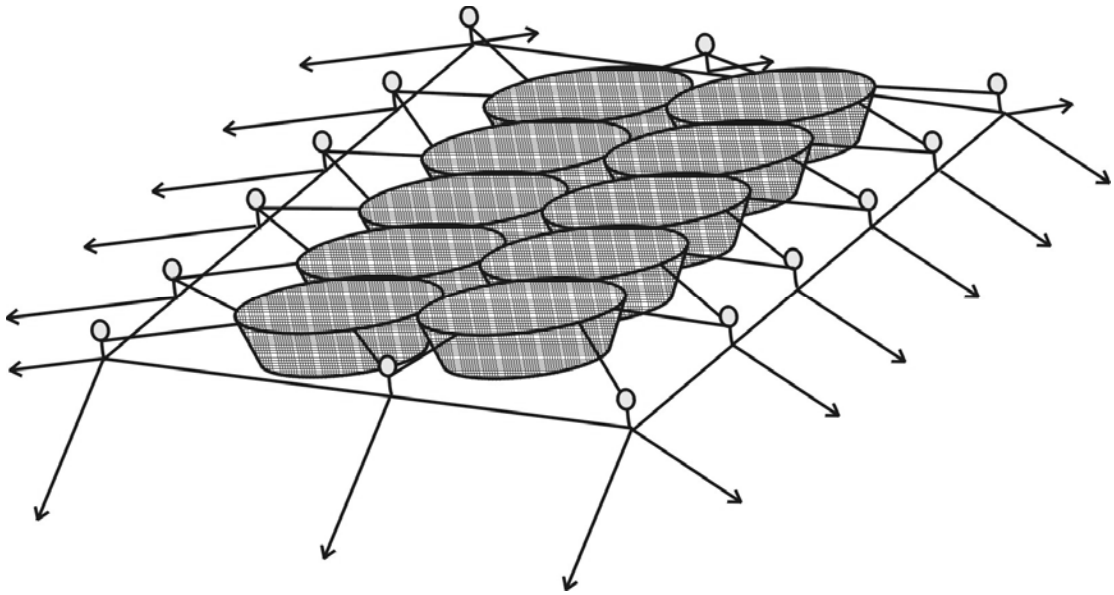
site, which might be a few days following the storm for conditions to be safe again.

Lack of, or decreased, human presence, particularly for cages some distance from the lift-boat or following severe storm events, will require a substantial change in the mindset of both owners and managers of offshore aquaculture ventures. These individuals will need to rely more on technology to communicate with the farm site particularly during storm events. Indeed, as Muir (2000) points out "a major challenge for future systems may be to overcome the psychological dependence on human-based management, allowing greater reliance to be placed on automatic monitoring, control and management systems."

To this end, the OAC partnered with Brightwaters Instrument Corporation to initiate the development of a remote monitoring and communication system for offshore cages (Fig. 14). The basis for this system is a GPS/ARGOS mooring monitor that checks the cage position at a user-defined time interval and compares determined positions with a defined 'watch circle' of where the cage should be located (e.g., the cage position could be checked every 30 minutes). An alarm will be activated, emailing those involved of present cage positions should the determined and defined positions not correspond based on three successive position fixes. The instrument also possesses a depth sensor that will notify the operators when a cage is sinking, potentially due to structural failure or excess biofouling. An additional data port is available on this unit to monitor feed levels within the hopper and provide an alarm should levels extend below a predetermined level needed to meet daily feeding requirements.

The mooring monitor is invaluable during hurricane conditions. A cage would be expected to submerge during hurricanes if deployed on a single-point mooring in the configuration described above. During hurricane passage the lift-boat would likely be evacuated for worker safety. While submerged, no communication with the cage would be possible through satellite systems. However, once the cage resurfaced, an email message would be expected as the mooring monitor again locates its position and communicates with the satellite. Feeding would continue to the fish following hurricane passage with food main-

Fig. 16. Nested cage arrangement creating an array of cages typically used throughout the world for finfish aquaculture.



tained in the hopper and which would be replenished a few days later when sea conditions again allow.

SITE CONFIGURATION & PRODUCTION PLANNING

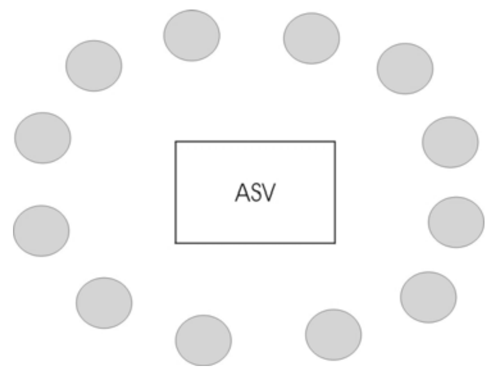
Near shore aquaculture operations have established site configurations and production planning protocols that are reasonably consistent throughout the world. Aquaculture cages are typically moored together in a large group or array of cages within a submerged multiple anchor grid system (Fig. 16). Numerous individual arrays generally comprise an aquaculture site. The majority of species grown in cages require a minimum of two years of grow-out to attain a suitable market size. Single year class management systems are frequently applied to ensure that odd and even year class fingerlings are not retained on a single site to minimize the impact from potential fish health issues to the entire stock. A further complication for near shore operations is the need to allow a site to fallow for a minimum period of time (generally one year) to mitigate negative environmental and fish health impacts to the production process and local ecosystem (McGhie et al. 2000). Combined, species requiring multiple years of grow-out, single year class management systems, and fallowing requires a single corporation to apply for grow-out sites in groups of three (i.e., to ensure access to a fingerling site, a harvest site, and a fallow site) to ensure continuous production and harvesting schedules can be met.

Offshore aquaculture in the Gulf of Mexico could differ considerably from this near shore model. The majority of species considered will only require a single year to attain a suitable market size, because the water temperature will facilitate better growth rates for a larger portion of the year and the market size for many candidate species can be attained within a one year grow-out cycle. The offshore environment will also provide considerably greater assimilative capacity owing to greater volumes of water flowing through the site thereby potentially removing the need for site fallowing to minimize environmental impacts. However, site fallowing might be required from a fish health management perspective (Blaylock and Whelan, this volume). Likewise, some indication for the benefits of short-term site fallowing in the open ocean has been observed in Hawaii (Bybee and Bailey-Brock 2003). Finally, Bay Management Areas are becoming increasingly popular to mitigate fish health concerns and must also be addressed when siting and setting production volumes for offshore aquaculture. All of these considerations, coupled with integration of farm technologies as discussed, provide numerous potential permutations for commercial-scale production planning.

Economic modeling has demonstrated that a single ASV servicing 12 aquaculture cages is feasible for all three candidate species—red drum, red snapper and cobia – having a stocking density of 30 kg/m^3 (Posadas and Bridger, this volume). A likely site configuration for this base investment would use the ASV as the site focal point and surrounded by the 12 offshore cages for efficient farm management (Fig. 17).

However, traditional economic realities in global aquaculture industries require that a larger volume of water be used and serviced by a single ASV structure. Any offshore aquaculture venture adopting the proposed system design will therefore likely require deployment of many more offshore cages to benefit from economies of scale. We have designed the ASV with this point in mind and to have the ability to service many more offshore cages. Deploying more than 12 cages poses the challenge to effectively arrange these cages while allowing efficient farm management. One obvious extension on the basic configuration would be to site all cages in a circular fashion within the immediate vicinity of the ASV. This approach, however, could potentially exert additional pressure on the local assimilative capacity of the offshore environment. Therefore, a more suitable configuration might have the cages spatially separated to into numerous, multiple cage sites, all being serviced by one ASV.

Fig. 17. Schematic illustrating a hypothetical arrangement to operate 12 offshore cages with one ASV as the site focal point.

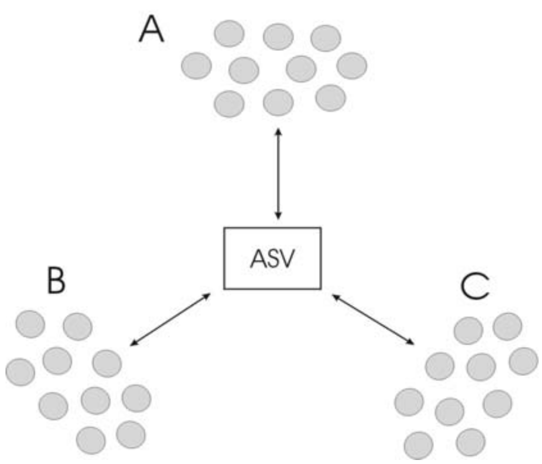


Applying the rules associated with site fallowing and potential Bay Management Areas might require the offshore aquaculturist to also apply for sites in groups of three. However, in the case of offshore aquaculture in tropical and sub-tropical regions requiring a single year to reach market size, two sites could conceivably be used for each grow-out season while leaving the third site to fallow in a standard crop rotation format (Fig. 18). A reasonable configuration for this approach would have the ASV positioned equidistant from each site and serving as the focal point within an equilateral triangle arrangement of the sites.

Fig. 18. Production planning scenario requiring each offshore aquaculture enterprise to acquire sites in groups of three to allow a schedule that uses two sites for each grow-out cycle and one year for a site to fallow following two years of use. The production schedule table further illustrates this plan of use and fallowing.

Production Schedule

Year	Site A	Site B	Site C
2000	X	X	--
2001	X	--	X
2002	--	X	X
2003	X	X	--
2004	X	--	X
2005	--	X	X



The general assumption here is that all offshore cages are moored using a single-point mooring system. Each SPM will either retain a single offshore cage, two cages attached in tandem, or possibly numerous cages held in a line. Use of the SPM will also decrease the total required space for offshore sites by allowing cages attached to different SPMs to swing over adjacent mooring anchors. This is possible because the local oceanographic conditions will interact with all moored cages in comparable fashion, thereby removing the probability that adjacent cages will interact with one another and cause unnecessary damage.

LOGISTICS ALLEVIATION

Throughout its research operations in the Gulf of Mexico, OAC researchers encountered numerous situations that demanded critical thinking and innovation to mitigate challenges before situations developed into catastrophic events. Below we describe some of the solutions that have been developed to meet the requirements for operating in the Gulf of Mexico offshore environment.

Net Maintenance and Cleaning

Spectra knotless netting, comprised of Dyneema fiber, is the netting of choice for Ocean Spar cages. This supplier has noted reduced drag, biofouling resistance, and reduction of overall cage weight by 0.3 times when compared with equal strength nylon netting (Loverich 1999). Knotless netting has become more prevalent in the cage culture industry because of several key attributes: a) up to 50% reduction in weight due to reduced material in the absence of knots, b) ease of handling as a direct consequence of having less weight, c) less material (decreased costs), d) smoother surface (less abrasion to contained fish), and e) higher breaking strength (Christensen 2000). However, knotless nets tend to be more difficult to repair, having the requirement to place new twine in the netting prior to mending the net (referred to as double salvage) to prevent further or recurring damage. Weighing these attributes makes the use of knotless netting more useful with gravity class cages given the higher likelihood for fish abrasion when the net is bagging in high currents. To the contrary, anchor-tensioned or (semi) rigid cage systems prevent such bagging of the net and therefore reduce some of the justification for knotless netting.

Fouling of the net mesh is undesirable in cage aquaculture. During peak settlement, fouling organisms may rapidly clog net meshes and subsequently limit the flow of high quality oxygenated water. Net cleaning may be required as often as every 5–8 days for each cage during peak summer fouling (Hodson and Burke 1994) and can require up to 20–38% of the total aquaculture labor requirements (Huguenin and Ansuini 1978). Aarsnes et al. (1990) demonstrated that the water flow to interior cages in an array might be 10–20% of that outside the cages due to increased structural complexity and extensive biofouling. Stresses on cultured animals will increase, growth decrease, and removal of metabolites will be limited to the point that biofouling may be detrimental to fish health (Brown 1993). In addition, fouling organisms may contain fish pathogens (Kent 1992) that, coupled with increased stress due to poor water quality, could result in disease outbreaks. Increased biofouling could also lead to structural failures and sinking of aquaculture cages (Huguenin 1997), leading to fish escape and subsequent adverse environmental, economic, and social implications.

Coastal aquaculture 'gravity' cages, having a surface collar structure to hang an appropriate netting and using weight to maintain the overall cage structure, can easily have a fouled net replaced with a clean net to minimize the impact of biofouling. However, cages used in the offshore environment do not rely on gravity in this hostile environment but rather are commonly internally tensioned and independent of gravity or mooring lines to maintain its volume and shape. Self-tensioning cages rely on heavy hardware, such as large shackles and other components, throughout the system that will not be taken apart until the net is replaced only at the end of a grow-out cycle. Maintaining the same net in the offshore environment for upwards of a year at a time requires innovative methods to clean the net *in situ* thereby providing the most optimal growing environment for the fish.

Changing a fouled net is not an option for the tensioned Sea Station cage. Alternatively, the net may be treated with an antifoulant to mitigate fouling impacts. Fortunately, the Sea Station rigid design is also conducive to mechanized cleaning *in situ*. Cleaning nets while they are maintained in the ocean may be accomplished using specifically designed underwater pressure washers, such as the Ideama pressure washer (http://www.quadra-services.com/net_home.html) with its rotating disc that allows safe and efficient use by farm workers from a workboat or along the cage walkway, or scuba divers in the water. *In situ* net cleaning of 'gravity' cages has proven difficult owing to the non-rigid nature of the netting (Hodson et al. 1997). Even with taut netting, failure to entirely remove fouling debris could result in farm wastes accumulating inside the cage, resulting in decreased oxygen concentrations and increased stress to the fish stock.

Net cleaning during offshore aquaculture research in the Gulf of Mexico became a routine and efficient farm task. The pressure washer engine/pump unit is mounted in the bow of the maintenance vessel while a diver orients the washer head on the net surface. The boat tender starts the pump allowing the diver to move slowly over the net surface and clean the netting in an effortless motion. We have found net cleaning to be most optimal when stretched over a 2-day period. The first day concentrating on the upper surface of the offshore cage from the outside while the lower surface is cleaned on the second day from the inside of the cage. This approach allows resultant debris from the upper surface to settle overnight and subsequent removal of that which settles through the cage volume to be effectively removed on the second day. The lower surface is cleaned from the inside to optimize our diving effort by using gravity on the washer head and to also push the lower fouling through the netting to the outside and not back within the cage volume. In total, one diver can accomplish net cleaning using this approach, over the 2-day period, and requiring just 4 dive tanks and 2 tanks of gas within the pressure washer. We further found that the diver should always wear a hood to minimize risks associated with fauna removal from the netting, particularly amphipods, that are sent in a plume around the diver and attach themselves to any nearby surface, or body part including entry into the ears.

Even with the efficiency experienced in the Gulf of Mexico, only one offshore cage was maintained and working a commercial scale farm would likely become unmanageable in very short order. *In situ* net cleaning will also likely be prohibited in locations having fish health issues to minimize unnecessary spread of pathogens throughout the grow-out region. Fish in any cage design will be exposed to fine particulate matter during *in situ* cleaning that may irritate fish gills and disperse potential pathogens (Hodson et al. 1997). Researchers have also reported that some fouling organisms will re-colonize quicker from remnant rhizoids and reproductive cells following *in situ* cleaning (Nickels et al. 1981), this is especially the case with macroalgal remnants surviving in the netting crevices (Hodson et al. 1997). Finally, *in situ* net cleaning will require acceptable sea state conditions for the safe deployment of scuba divers to perform this task thereby removing some of the advantages compared to net changing in exposed sites.

Innovative methods to develop unmanned *in situ* net cleaning devices, comparable to automatic swimming pool vacuums, represents an area of research showing much technological promise for open ocean applications. Such technologies could continuously or intermittently move around the net of an aquaculture cage, either from the inside or outside, to remove biofoulants and prevent substantial buildup prior to affecting the growing volume within the cage. Taut netting designs (including use of a rigid mesh on gravity cages) would be most suited for unmanned net cleaners. Fortunately, the Sea Station cage design has spoke lines that could serve as tracks for automatic net cleaners and could become part of the farm system to continuously clean the net surface of biofoulants, although such technology has yet to be developed

Net Deployment

Offshore aquaculture sites have no protection from the natural elements and may experience relatively poor sea-state conditions on a consistent basis. These conditions may be amplified when large work vessels are positioned alongside offshore cages causing reflection of local waves, in a pattern comparable to an oceanographic seiche. Worker safety might be compromised in these conditions, especially when a crane is required during the operation. This situation was evident while installing the net to the OAC Sea Station cage. Further, increased water motion resulted in the net being twisted while lowering it over the spar buoy. In this case, the net had to be removed from the water and re-bundled for another attempt. OAC researchers subsequently developed a method of installing a net to the offshore Sea Station cage from the bottom-up, as opposed to the standard top-down deployment method, using a smaller boat, no crane, and scuba divers to negotiate the net and mitigate unwanted water motion situations. A bottom-up strategy takes advantage of the more favorable work conditions at depth and neutral buoyancy of the spectra net.

Critical to this deployment method is properly bundling the net to secure all loose ends and to ensure twisting does not occur once the net is placed in the strong offshore currents. The net is placed in the water oriented such that the top of the net leads to the ballast weight. One rope is tied to the ballast weight, passed through the middle of the net, and tied to the boat to ensure divers can maintain control of the net in the strong current. A second rope is also tied to the boat, passed through a shackle on the ballast weight, and tied on the other end around the net. The latter rope is used to pull the neutrally buoyant net to the ballast weight while divers guide the descent. Once to the ballast weight, the ropes are untied and divers place the net over the ballast weight. Two new ropes were lowered down the length of the spar and tied around the netting. As the divers moved the net up the spar, two other workers standing on the spar kept these ropes taut thereby maintaining position of the net as it moved up the spar while relieving divers of this duty in the water.

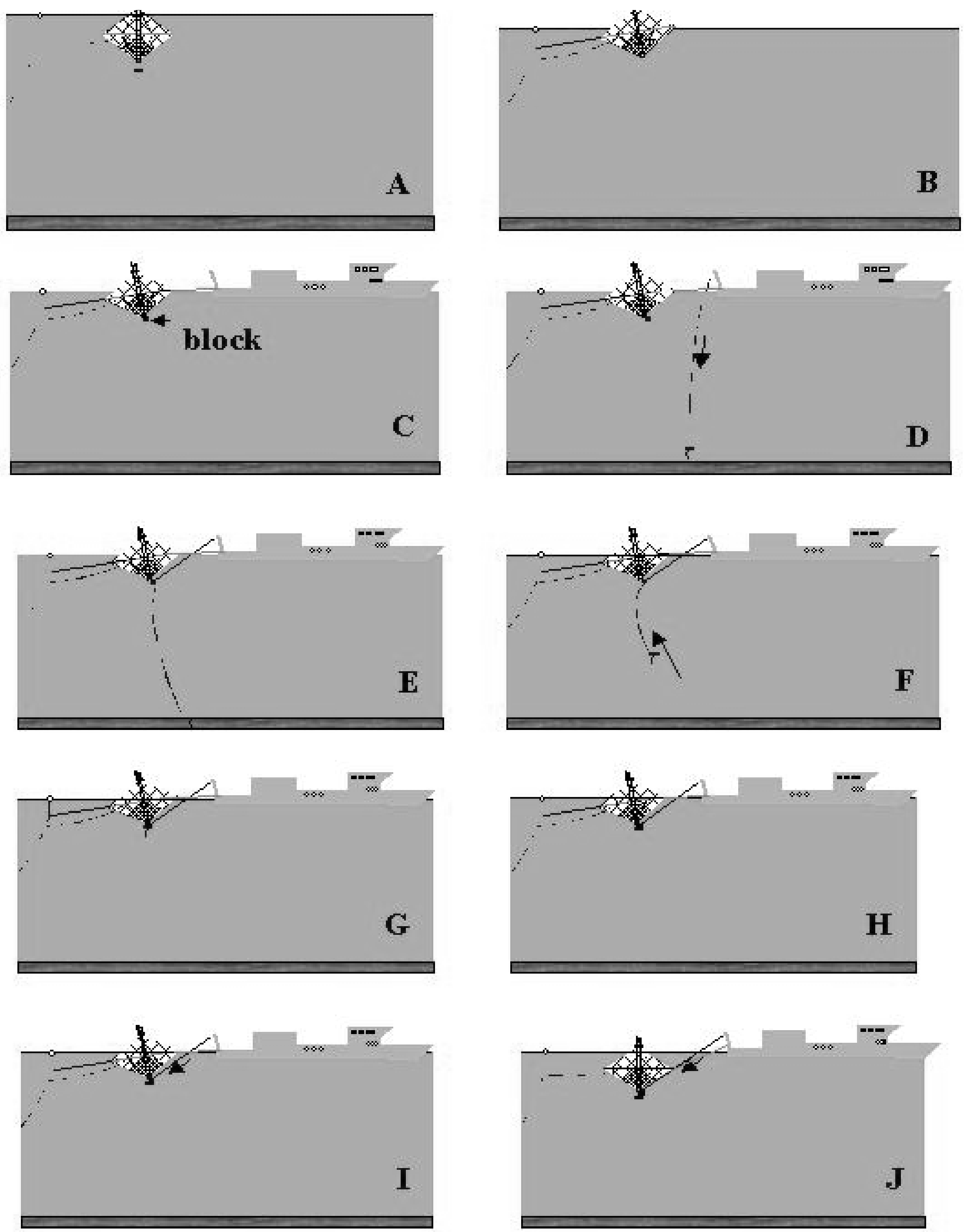
Eventually, the net is moved up to the water surface and shackled to the top of the spar. The net is attached initially to the up-current side of the cage to take advantage of the strong current as the net becomes more taut and eventually the entire net is secured to the rim with all 16 shackles. Securing the harvest ring to the bottom of the spar creating the desired taut netting completes the deployment.

Changing the Ballast Weight

The ballast weight is a circular concrete block weighing approximately 3,181 kg for the OAC 600 m^3 cage and having a toggle through its middle to attach it to the bottom of the spar buoy. In its proper position, the ballast weight provides necessary weight to maintain the cage upright and at the proper position in the water column in spite of high seas and wind (Fig. 19a). Initial deployment of the ballast weight is performed while uprighting the spar and therefore not having any netting to impede the attachment procedure. However, periodically a farm operator might have the need to exchange an existing ballast weight or deploy a new ballast weight should the existing one fall off during extreme storm conditions. This would have to be completed without disrupting the fish or other operations of the farm and without requiring the complete breakdown of the cage. The OAC was faced with a situation whereby the ballast weight fell off the spar during tropical frontal movement requiring quick response to the replace the ballast weight to prevent further damage to the very vulnerable cage.

Upon arrival to the site, the cage was noticeably listing to one side on the single-point mooring system due to the absence of the ballast weight (Fig. 19b). The OAC was forced to develop an innovative approach to replace the ballast weight while retaining simplicity and keeping diver safety in mind even in relatively high seas. The University of Southern Mississippi research vessel IX 508 was tied to the cage rim and divers attached a block to the spar edge closest to the vessel (Fig. 19c). Next the new ballast weight was lowered to the seabed using the vessel winch and U-frame (Fig. 19d) and divers re-entered the water to move the lowering rope to the block and secure it (Fig. 19e).

Fig. 19a–j. Sequence of events required to deploy a new ballast weight on an already deployed and operating Sea Station cage.



Once the lowering rope was secured within the block, the vessel slowly lifted the new ballast weight using its winch (Fig. 19f) until the ballast weight was eventually close to the bottom of the spar (Fig. 19g). In this position, divers could easily maneuver the ballast weight line in position at the bottom of the spar and insert the shackle pin for attachment (Fig. 19h). Following attachment, the vessel slowly let the lowering rope back out until the cage begins to take the weight (Fig. 19i) and eventually stabilizes in the water column (Fig. 19j). Divers enter the water for the final time to release the vessel rope and retrieve the block from the bottom of the spar. Upon completion, the cage is back to its proper position in the water column and properly upright (Fig. 19a).

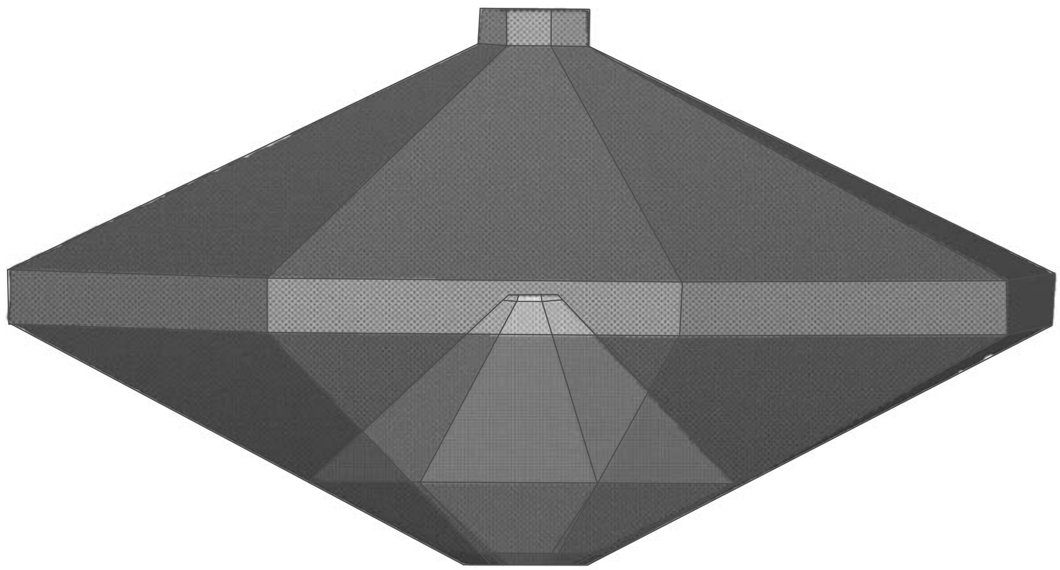
Transport of Fingerlings Offshore

Three general methods to transport large numbers of fingerlings to distant offshore aquaculture sites are possible: a) hauling fingerlings in live-haul trucks from the nursery, transferring these fish to barge tanks thereby keeping the fingerlings safely on deck during the offshore transport, and a final transfer to the awaiting cage; b) craning fingerling tanks from a flatbed truck to a barge deck can eliminate one handling step while maintaining safe transport offshore; and, c) towing fingerlings in a cage to the offshore aquaculture site eliminates the need to transfer fingerlings to the cage offshore. (The economics for each of these methods are compared within Posadas and Bridger, this volume.) Throughout its existence the OAC only moved a number of cobia fingerlings offshore (provided by Dr. Joan Holt, University of Texas). In this specific case, OAC researchers decided to move these fingerlings to the offshore cage using the first option presented.

Cobia fingerlings were being maintained within tanks at the Gulf Coast Research Lab (GCRL). These fingerlings were compromised by the presence of *Amyloodinium* spp., which is a prevalent dinoflagellate species common in warm saltwater environments and all along the Gulf of Mexico coast (also see Blaylock and Whelan, this volume). This parasite attaches to the gills and skin and causes severe pathology at the point of attachment leading to hemorrhaging, inflammation, and extensive epithelial hyperplasia (Southgate 1993) eventually compromising the overall health of affected fish. Copper sulphate has been shown to destroy dinospores found in the holding water and actively searching for new fish hosts. Throughout their time spent at the GCRL, cobia fingerlings were treated with a copper sulphate solution to reduce the potential impact of *Amyloodinium* spp. on those fingerlings. These fish were heavily infected regardless, causing the gills to be much less efficient than would be anticipated for a normal healthy individual. The infection had its greatest impact during passage of Hurricane Isidore, which caused a power failure at the GCRL and resultant deteriorating water quality within the cobia holding tanks. The cobia stock prior to this event suffered zero mortalities but this record rapidly changed following the power outage with consistently high mortality recorded on a daily basis. A decision was then made by OAC researchers that since the compromised cobia fingerlings were dying within their holding tanks, we would transport the remaining fingerlings to the offshore aquaculture cage to provide insight related to long-distance transport logistics issues.

Fingerlings were initially stocked within transport tanks on trailers to move the cobia from their holding tanks to live-haul tanks secured on the deck of the transport vessel.

Fig. 20. Shape and location of the nursery net placed within the larger grow-out cage.



Both tanks were aerated during the entire transport to the offshore cage site. Once reaching the site, the vessel was secured to the cage in preparation to transport the fingerlings to the nursery net. The nursery net was placed within the cage prior to moving fingerlings to ensure it could be installed and not waste precious time doing so with fish held in tanks on the deck of the vessel. The nursery net had a volume of 43.7 m^3 (equivalent to 46.3 m^3–2.57 m^3 of space occupied by the central spar) and was constructed of 2.5 cm (1") stretch mesh. The nursery net was designed such that each bottom portion would rest on the cage netting along its bottom so that the fingerlings were maintained as deep in the water column as possible and away from the energetic surface waves (Fig. 20).

The initial thought was to transfer the cobia fingerlings to the nursery net through a hose connected to each live-haul tank. This proved difficult when transporting cobia fingerlings to the cage. Cobia are extremely strong swimmers and consistently resisted the downstream water flow into the hose once the baffle was opened to release the water, with the fingerlings. Once in the hose, the fingerlings further resisted transport to the nursery net by swimming against the water current and back up the hose to the tanks. The fingerlings were eventually removed from the tank and hose and manually transferred to the nursery net in dive bags. This experience illustrated the need for several adaptations necessary for transporting this species offshore including: a) a metal screen grate was constructed that fit snugly within the tank to decrease the space available to the fingerlings prior to opening the baffle to facilitate transport; and, b) a pump to actively move the fingerlings to the nursery net would have better facilitated transport. We do not anticipate that these same observations would have been experienced during transport of less active candidate species, such as red snapper and red drum.

Realizing that the OAC operated at a scale much smaller than commercial ventures, each general option was extrapolated to transport commercial fingerling numbers for economic analyses. These results are discussed in Posadas and Bridger (this volume) with other economic modeling activities.

FUTURE RESEARCH NEEDS

While we have made great strides towards the eventual reality of establishing an offshore aquaculture industry in the U.S. EEZ, there is much engineering and logistics research necessary prior to fully commercial operations. Specific research and development issues requiring attention include:

1. Although regional projects in the U.S. have opted to deploy the Ocean Spar Sea Station cage, more engineering would also be welcome to design and test additional cage configurations. Additional modeling efforts, however, would be more beneficial if focused on a holistic system that integrates cages/moorings and feed systems to ensure these components are appropriately designed to minimize interactions between them.

2. Coupled with holistic system design is the choice of containment material for offshore cages. Our Ocean Spar Sea Station was deployed with knotless spectra netting. The knotless design proved problematic to mend in the open ocean environment (requiring double salvaging the net to maintain the new netting) and could have been replaced with knotted netting to alleviate these issues. Further, use of rigid mesh material, such as AquaMesh (welded, galvanized, vinyl coated steel mesh; http://www.riverdale. com), would likely result in decreased maintenance issues compared with spectra netting.

3. During the design process, other considerations might be accounted for such as the species to be raised (pelagic species, groundfish species, or flatfish) and the ability to service the farm site efficiently and safely.

4. Development of suitable ROV technologies and practices that decrease the present reliance of offshore aquaculture operations on scuba diving would be welcome. In some sense our heavy usage of diving in the more energetic offshore environment (compared to near shore aquaculture practices) represents a backward step in aquaculture progress.

5. Dependable feeding technology is critical for success. Adapting commercially available feed systems to survive in exposed conditions is necessary prior to establishing commercial offshore sites. In the absence of completing this task, moving aquaculture to the offshore environment is not warranted at this time. Alternatively, new innovative feeding approaches deserve additional attention.

6. Some consideration should be given to designing a feed system that also has the ability to rapidly provide medications to compromised fish. An optimal solution might be having a separate, unused feed bin that is only used when necessary. This removes the need to empty the main feed bin, with the possibility of feed wastage, prior to providing medications.

7. While the OAC has studied fish health management (Blaylock and Whelan, this volume) additional consideration is

required during the system and site planning stages. An assumption that opportunistic concerns might never arise is naïve, particularly in tropical environments where fish health pathogens are likely to flourish if the fish stock is compromised in any way. Consideration must be given to fish health issues during the planning stage of these industries, including a single-year class management strategy that could be coordinated between numerous offshore sites for the total production volume. These considerations are important from the outset, especially when developing logistics to mitigate the complexities inherent in offshore aquaculture. Another consideration for future siting and existence of offshore aquaculture is the degree of access by other users and eventual implications related to use conflicts following the occurrence of a fish health issue.

8. The additional distance from shore also creates the potential for new fish health issues that are not presently experienced in near shore aquaculture. Added distance increases the costs associated with traveling to and from offshore grow-out sites. These costs must be recovered by industry and considered during the planning stage. Added distance will also affect the frequency and regularity of monitoring fish health at distant and exposed locations. This issue might be mitigated through adoption of suitable technologies that allows distance surveillance, such as underwater camera systems and telemetry feedback and control.

CONCLUSIONS

Developing innovative technologies to mitigate offshore aquaculture logistics in the absence of a system design strategy would be remiss. Without effective and safe integration of all components, the entire system would likely prove to be too inefficient to support economically feasible aquaculture in the offshore environment. Operating within the Gulf of Mexico, the Offshore Aquaculture Consortium has developed numerous individual components—a lift-boat Aquaculture Support Vessel, a single-point mooring, an autonomous feeder, and a cage/mooring monitor—that meet the demands of foreseeable issues associated with operating a farm in a distant and harsh environment. Offshore aquaculture operations can now be considered through use of these engineering innovations.

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CHAPTER 5

GENETIC IDENTIFICATION OF FISH HARVESTED FROM OFFSHORE AQUACULTURE: AN EXAMPLE INVOLVING RED DRUM, *SCIAENOPS OCELLATUS*, FROM THE NORTHERN GULF OF MEXICO

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ABSTRACT

A total of 31 nuclear-encoded microsatellites and an ~ 370 base pair fragment from the 'control' region of mitochondrial (mt)DNA were employed to resolve potential forensic issues relating to legal sale of red drum (*Sciaenops ocellatus*) harvested from offshore aquaculture operations in the northern Gulf of Mexico. Exclusion analyses demonstrated that only 16 microsatellites (13 if mtDNA was employed) were necessary to exclude a sample of 101 'wild' red drum from Biloxi Bay, Mississippi, as having been produced by broodfish in a hatchery near Corpus Christi, Texas; the probability of incorrectly assigning a 'wild' fish as having been produced by the broodfish ranged from 2.58×10^{-19} to 1.33×10^{-27}. Probabilities that the most common, hatchery-produced 'composite' genotype would occur in the sample from Biloxi Bay ranged from 1.38×10^{-27} to 2.98×10^{-42}. All probability values were several orders of magnitude smaller than the reciprocal of the total number of adult red drum (10^6–10^7) estimated to occur in the northern Gulf of Mexico. Comparison of results with and without mtDNA indicated that it would be more cost effective to first sequence individuals for the mtDNA fragment and then determine the number of individuals that needed to be assayed for microsatellite genotypes. The study demonstrated that unequivocally distinguishing red drum spawned from broodstock obtained offshore of Corpus Christi, Texas, from the 'wild' stock in Biloxi Bay, Mississippi, is fairly straightforward, given (i) a sufficient number of polymorphic (variable), independent genetic markers, (ii) the genotypes of the broodfish, and (iii) a survey of allelic variation at the genetic markers among representatives of the 'wild' stock. The three 'requirements' essentially would be the same for any offshore aquaculture operation where legal sale of the cultured species could be an issue.

INTRODUCTION

Offshore aquaculture industries marketing 'game fish' species will require methods to identify or distinguish unequivocally harvested products from 'wild' stocks in order to ensure legal sale and alleviate potential conflicts. Identification needs at the market place could arise when fish are harvested (should certification prior to sale be necessary), stored on ice or frozen, or sold or served as fillets. It also may be necessary from time to time to identify escapees from different aquaculture impoundments relative to ownership. Identification methods must thus be accurate and reproducible, capable of deployment on whole fish or fillets (perhaps even when fillets are in the skillet), and have sufficient power to

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identify unambiguously the origin (parentage) of individuals from the same species or population (or even the same hatchery).

Forensic methods used historically to identify origin of animals or animal products have almost exclusively been 'genetic' and primarily have involved analysis of proteins (AOAC 1984; Kim and Shelaf 1986). The most commonly used methods have been electrophoresis (of soluble proteins), high performance liquid chromatography, immunological procedures that rely on antibody-recognition, and isoelectric focusing (Ashoor et al. 1988; Berger et al. 1988). Advantages to using proteins, especially protein electrophoresis, were simplicity, relatively low cost, and low initial start-up costs. However, analysis of proteins is limited generally to tissues that are either fresh or have been frozen fairly soon after procurement. In addition, the relative proportion of hypervariable protein-coding markers (loci) is fairly low in most fishes (Ward et al. 1994) making it very difficult to identify origin of individuals without screening an inordinately large number of different proteins. Direct analysis of genomic DNA polymorphism as a means to discriminate origin of individuals is preferable for a number of reasons. First, DNA is the genetic material and homologous DNA sequences are essentially the same in all tissues and cells of an individual, meaning that any available tissue can be utilized. Second, the information content of genomic or mitochondrial DNA considerably exceeds that of proteins as a large panel of polymorphic markers can be accessed straightforwardly from a reasonably good DNA extract. Third, DNA is remarkably stable and has been successfully extracted from fossilized or mummified tissue (Paabo et al. 1988, 1989) and from meat that has been partially cooked (Bartlett and Davidson 1992; Forrest and Carnegie 1994). Finally, because the approach typically used today to assay DNA markers is based on polymerase chain reaction or PCR amplification (White et al. 1989), the quantity of tissue needed for DNA analysis is far less than that typically required for protein analysis.

The statistical issues involved in DNA analysis to identify parentage (i.e., in this case to discriminate hatchery-produced fish from 'wild' fish) are straightforward, and conceptually were outlined in NRC (1996) and Evett and Weir (1998). Assuming that alleles (forms of genes) and genotypes (allele combinations or genetic constitution) of broodstock in a hatchery are known, and that sufficiently powerful genetic markers are available, genetic profiles can be established that permit unquestionable certification that a given fish was *not* generated from that broodstock or unquestionable certification that a given fish *could* have been generated by that broodstock. The converse, 'proving' that a given fish did *not* come from a 'wild' stock cannot be ascertained unequivocally, but can be stated in terms of acceptable probability levels. Genetic data used forensically might indicate, for example, that there is a probability of 1 that a given fish *could* have originated from known broodstock but that the probability that the same fish was sampled at random from a 'wild' stock was less than one in a billion. Explicit statistical methods of parentage analysis were reviewed recently by Jones and Ardren (2003). Of the methods reviewed, the most appropriate for forensic issues is *exclusion* analysis, where Mendelian expectations are used to reject particular parent—offspring hypotheses. The approach is optimized when the number of candidate parents is small and the genetic markers employed are hypervariable (Jones and Ardren 2003).

In this chapter, we demonstrate the use of hypervariable genetic markers to discriminate hatchery-produced from 'wild' red drum (*Sciaenops ocellatus*). The initial design of the Offshore Aquaculture Consortium (OAC) project was to use red drum as the 'test' species for an offshore aquaculture operation in the northern Gulf of Mexico. Fingerling red drum were to be obtained from hatcheries operated by the Texas Parks and Wildlife Department (TPWD) and ultimately placed into the OAC Ocean Spar Sea Station offshore of Ocean Springs, Mississippi, for grow-out trials. Accordingly, we employed a suite of PCR primers for hypervariable loci in red drum and genotyped the broodfish in one of the TPWD hatcheries and a sample of 'wild' red drum from Biloxi Bay, Mississippi. The hypervariable markers used were 31 nuclear-encoded microsatellites and an ~ 370 base pair fragment from the 'control' region of mitochondrial (mt)DNA. The former (microsatellites) are abundant, short stretches of DNA composed of di-, tri-, or tetranucleotide arrays that are embedded in unique DNA, inherited in a Mendelian fashion, and distributed evenly throughout chromosomes (Wright 1993). Microsatellites are ideal for forensic application because of high levels of polymorphism, codominant inheritance, and Mendelian segregation of alleles (Weber and May 1989; Wright 1993). In addition, because identification of each microsatellite is via amplification, using specific polymerase chain-reaction (PCR) primers, there are few problems associated with homology of alleles from distinct loci (Wright and Bentzen 1994). Mitochondrial (mt)DNA is a haploid genetic molecule inherited through the female parent, meaning that mtDNA, provided there is sufficient polymorphism, can be useful in excluding mother-offspring relationships. Prior studies of red drum mtDNA (Gold et al.1999; Seyoum et al. 2000) had revealed extensive variability of mtDNA among 'wild' red drum; nucleon diversities (the probability that any two fish sampled at random will *differ* in mtDNA genotype) were > 95%, meaning that nearly all female broodstock could be expected to differ in mtDNA genotype from one another and from most 'wild' fish. The specific objectives of the project were to generate a suite of hypervariable DNA markers specific for red drum and then demonstrate how these markers could be employed to distinguish hatchery-produced red drum from 'wild' red drum in Mississippi waters. In a more general way, the project was to serve as a model in terms of using genetic data to resolve forensic issues relating to legal sale of marine products from offshore aquaculture operations.

MATERIALS AND METHODS

Relative small pieces (~ 2–3 cm^3) of upper lobe of the caudal fin were removed from sires (males) and dams (females) in each of nine brood tanks at the CCA/CPL Marine Development Center in Corpus Christi, Texas (hereafter, *Broodstock*). Each brood tank contained two sires and three dams (45 fish total). Fin clips were fixed and preserved in 95% ethanol. Heart tissues, frozen in liquid nitrogen, from a total of 102 age 0 red drum sampled from Biloxi Bay, Mississippi, were kindly provided by J. Franks of the Gulf Coast Research Laboratory in Ocean Springs, Mississippi (hereafter, *Biloxi Bay*). DNA from all individuals was isolated and purified using methods outlined in Gold and Richardson (1991).

Microsatellites were generated from a genomic library of red drum DNA via standard methods described fully in O'Malley et al. (2003). Briefly, size-selected DNA fragments (200–1,200 base pairs in length) were ligated into cloning vectors and transformed into competent *Escherichia coli* cells. Clones were hybridized with mixtures (cocktails) of synthetic oligonucleotide probes to identify those containing candidate microsatellites. Clones that gave a positive hybridization signal were then sequenced. PCR primers were designed from sequences flanking candidate microsatellites. Optimization of PCR protocols for each designed primer pair was carried out on a panel of DNA from 10–12 individuals. PCR primer sequences, repeat sequence, and optimal annealing temperature for the 31 microsatellites used in the project are given in Appendix Table 1. Details of PCR amplification may be found in O'Malley et al. (2003).

A fragment of ~370 base pairs of the mitochondrial DNA control region was amplified in 50 ml reactions. Each reaction contained 1x reaction buffer (10 mM Tris-HCl, pH 8.5, 50 mM KCl, 1.5 mM $MgCl_2$), 200 µM of each dNTP, 0.5 µM of each primer, 2.5 U *Taq* polymerase, approximately 100 ng of template DNA, and ultrapure water. Thermal cycling conditions were: initial denaturation at 94°C (30 sec), 30 cycles of denaturation at 94°C (10 sec), annealing at 55°C (15 sec), and polymerization at 72°C (45 sec). Amplification (and sequencing) primers used were those developed by Seyoum et al. (2000): L15943 (5'-GTAAACCGGATGTCGGGGGTTAG-3') and H16484 (5'-GGAACCAGATACCAGGAATAGT-TCA-3'). Amplification products were purified for sequencing with Montage-96 PCR filter plates (Millipore Inc.) and double-stranded products were sequenced in both directions. Sequencing reactions contained the following (total volume of 10 µl): 1 µl BigDye version 3.0 reaction mix (Applied Biosystems Inc.), 1.5 µl 5x sequencing dilution buffer (400 mM Tris-HCl, pH 9.0, and 10 mM $MgCl_2$), 0.32 µM primer, approximately 50 ng template DNA, and ultrapure water. Cycling conditions were: initial denaturation at 96°C (30 sec), 40 cycles of 96°C (10 sec), 55°C (15 sec), and 60°C (4 min). Sequencing products were purified via precipitation with 95% ethanol and 3 M sodium acetate, washed with 70% ethanol, and dried. Electrophoresis and base-calling were performed with an Applied Biosystems Prism 310 capillary sequencer. Sequences were edited and vector-trimmed with Sequencher (GeneCodes, Inc.).

Genetic variability for nuclear-encoded microsatellites was measured as number of alleles, allelic richness (a measure of the number of alleles independent of sample size), and gene diversity. Genetic variability for mtDNA was measured as number of haplotypes, nucleon diversity (the probability that two individuals will differ in mtDNA haplotype), and nucleotide diversity (the average number of pairwise nucleotide changes per site). Gene and nucleon diversity were estimated after Nei (1987). Deficiency/excess of heterozygotes (F_{IS}) at each nuclear-encoded locus within each sample was estimated via the *f* statistic of Weir and Cockerham (1984). Estimates of allelic richness and gene and nucleon diversity and F_{IS} (*f*) were obtained using F-STAT version 2.9.3.2 <http://www.unil.ch/izea/softwares/fstat.html>. Tests for conformance of genotype proportions (nuclear-encoded loci) to Hardy-Weinberg (HW) equilibrium expectations employed an unbiased estimate of Fisher's exact-test statistic calculated by a Markov-chain procedure (5,000 dememorizations, 500 batches and 5,000 iterations per batch). Genotypic disequilibrium between pairs of nuclear-encoded loci also was tested via exact tests (same Markov-chain parameters as above). Tests of HW and genotypic disequilibrium were carried out using GENEPOP 3.3 (Raymond and Rousset 1995). Homogeneity of allele (genic) and genotype distributions between samples (*Broodstock* versus *Biloxi Bay*) was tested via exact tests (as described above and using GENEPOP). Homogeneity of mtDNA haplotype distributions between samples was assessed via the F_{ST} analogue in ARLEQUIN; the probability that the F_{ST} analogue = 0 was assessed by an exact test (as described above and using ARLEQUIN).

For exclusion analysis, genotype comparisons at the 31 microsatellites were made between *Broodstock* ($n = 45$) and *Biloxi Bay* ($n = 102$). Because there were two sires and three dams in each of the nine TPWD broodtanks, there were a total of 54 different sire x dam combinations possible. As each microsatellite in an offspring has two alleles, one contributed by the sire and one contributed by the dam, genotype comparisons and subsequent exclusion of incompatible individuals from *Biloxi Bay* were based on expected Mendelian segregation from all 54 sire x dam (broodstock) combinations. Any individual from *Biloxi Bay* failing to meet this criterion was excluded and not assigned as an offspring from any of the sire x dam possibilities in *Broodstock*. This analysis essentially asks how many microsatellites are required to exclude the 102 *Biloxi Bay* fish as not having been offspring produced from the TPWD broodfish. Exclusion analysis was carried out using the program PROBMAX-2 (Danzmann 1997; Ferguson and Danzmann 1998). Exclusion analysis, using mtDNA, was even more straightforward. Only 20 of the fish in *Biloxi Bay* possessed an mtDNA haplotype found among the 27 dams from *Broodstock*, automatically excluding the remaining 79 *Biloxi Bay* fish from which mtDNA sequences were recovered as having been produced in the TPWD hatchery. Genotype comparisons, as above, for the 31 microsatellites were then carried out on the 20 *Biloxi Bay* fish with mtDNA haplotypes the same as those found among *Broodstock* dams.

We also estimated exclusion probabilities for each microsatellite and for mtDNA. Exclusion probabilities estimate the probability of individual markers to exclude a given relationship (i.e., a sire x dam cross) based on the number of alleles at the marker and the number of independent markers used in the data set (Gerber et al. 2000). The basic probability formula (after Grundel and Reetz 1981) for excluding parental pairs is:

$$P = 1 + \sum[p_i^2(2 - p_i)]^2 - 2[\sum p_i^2(2 - p_i)]^2 + 4(\sum p_i^3)^2 - 4\sum p_i^6$$

where p_i represents allele frequencies at a given microsatellite. The P value represents the probability that the allele frequency set, estimated from the 102 *Biloxi Bay* fish, will exclude any individual parental pair chosen at random. The value $[1 - P]$ represents the probability of making a mistake and not excluding a pair of non-parents. Estimates of $[1 - P]$ were combined over all microsatellites and mtDNA by multiplying the $[1 - P]$ values from each independent genetic marker.

RESULTS

Summary data of microsatellite variation within the two samples are presented in Appendix Table 2. All 31 microsatellites were polymorphic. Number of alleles sampled per microsatellite averaged 12.6 (*Broodstock*) and 15.0 (*Biloxi Bay*) and ranged from three (*Soc*444, *Broodstock*) to 32 (*Soc*428, *Biloxi Bay*). Allelic richness generally paralleled number of alleles. Gene diversity (expected heterozygosity) per microsatellite averaged 0.793 (*Broodstock*) and 0.787 (*Biloxi Bay*) and ranged between 0.457 (*Soc*156, *Broodstock*) and 0.954 (*Soc*44, *Biloxi Bay*). Microsatellite variability in both samples compares favorably with values reported for 32 other fish species (DeWoody and Avise 2000), where the average number of alleles per microsatellite was 13.1 and the average heterozygosity was 0.63. The microsatellites were considerably more variable (polymorphic) than genes encoding proteins. Ward et al. (1994), for example, reported an average heterozygosity of 0.059 for allozyme loci of 57 marine species.

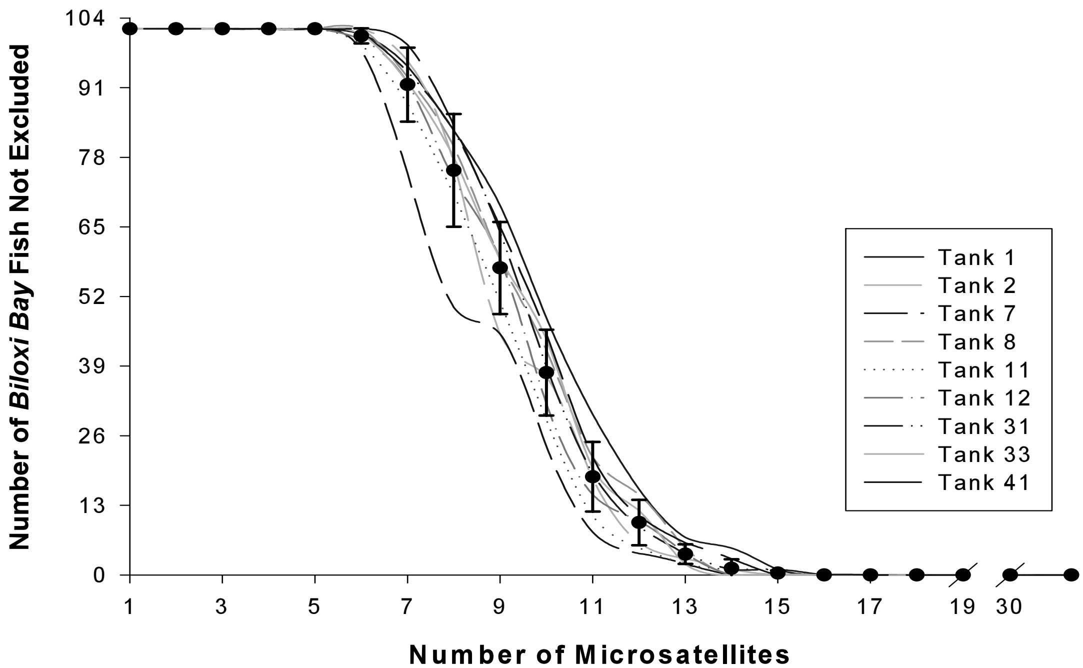
Tests of conformity to Hardy-Weinberg equilibrium expectations, following sequential Bonferroni correction (Rice 1989), were significant for microsatellites *Soc*44, *Soc*201, *Soc*243, *Soc*401, *Soc*404, and *Soc*412 in *Biloxi Bay* and for microsatellites *Soc*404 and *Soc*412 in *Broodstock*. In all but one of these (*Soc*243, *Biloxi Bay*), the inbreeding coefficient (F_{IS}) was positive, indicating a deficit in heterozygotes and possibly reflecting the presence of null alleles. All tests of pairwise genotypic disequilibrium were non-significant ($P > 0.05$) following sequential Bonferroni correction.

A total of 90 unique mtDNA haplotypes (sequences) were detected (Appendix Table 3). These included 29 haplotypes from 45 individuals in *Broodstock* and 73 haplotypes from 99 individuals in *Biloxi Bay*. Twelve haplotypes were common to both samples. The number of polymorphic sites were 52 (*Broodstock*) and 67 (*Biloxi Bay*). Nucleon diversities were 0.963 ± 0.0.016 (*Broodstock*) and 0.992 ± 0.003 (*Biloxi Bay*), and nucleotide diversity values were 0.027 ± 0.002 in both *Broodstock* and *Biloxi Bay*.

Exact tests of homogeneity in allele (genic) distributions between the two samples were significant prior to Bonferroni correction at seven of the 31 microsatellites; only one microsatellite (*Soc*412) remained significant following Bonferroni correction. Similar results were obtained in exact tests of genotype distributions. Fisher's method of combining probabilities from independent (exact) tests of all 31 microsatellites revealed a significant difference ($P = 0.000$) between samples in both allele and genotype distributions. Removal of those microsatellites whose genotype proportions were not in Hardy-Weinberg equilibrium (including *Soc*412) did not change these results appreciably. However, the overall F_{ST} (microsatellites) of 0.003 between samples was of borderline significance ($P = 0.050$), while the distribution of mtDNA haplotypes between samples was homogeneous ($F_{ST} = 0.010$, $P = 0.272$).

Results of the exclusion analysis (microsatellites only) are shown in Fig. 1. Each plot represents the number of individuals from the *Biloxi Bay* sample (*y* axis) that were *not* excluded as offspring from each of the nine broodtanks relative to the number of microsatellites (*x* axis) incorporated into the analysis. The nine plots represent each of the nine broodtanks and the six possible sire x dam combinations in each broodtank. As shown, exclusion profiles for each of the nine broodtanks are fairly similar and only 16 of the 31 available microsatellites were necessary to exclude all 102 fish from *Biloxi Bay* as having been produced from any of the sire x dam combinations in *Broodstock*. Inclusion of mtDNA reduced the number of microsatellites needed to exclude all *Biloxi Bay* fish from 16 to 13 (Fig. 2). However, largely because mtDNA in red drum is highly polymorphic, 77 of the 99 *Biloxi Bay* fish genotyped for mtDNA possessed a haplotype not found among *Broodstock* dams. Thus, the 13 microsatellites were needed for exclusion of only 22 individuals.

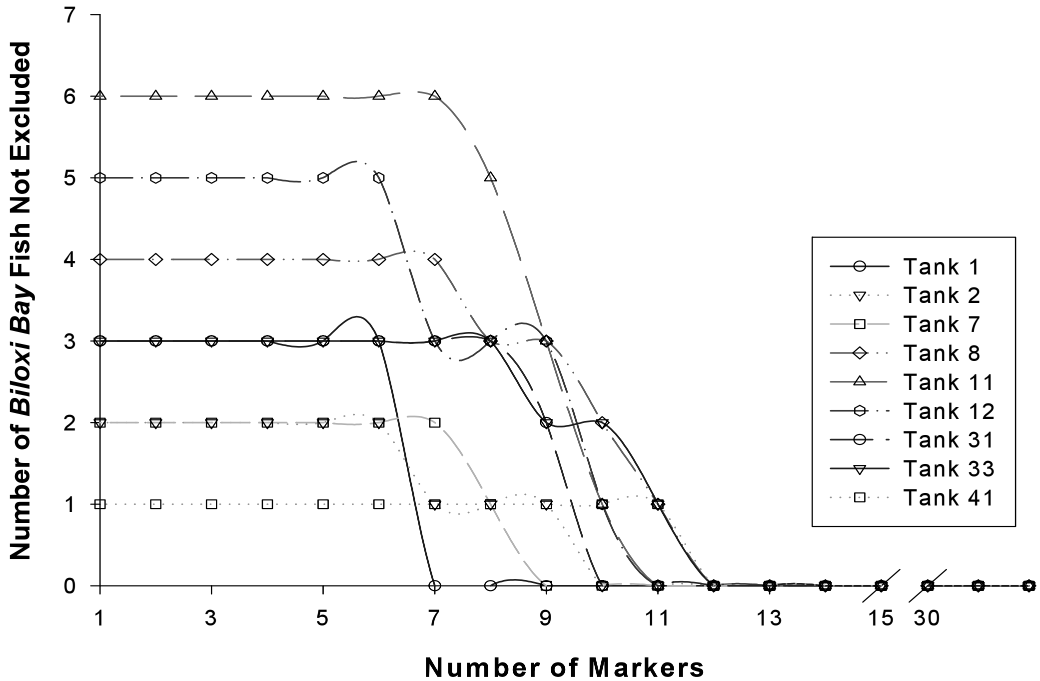
Fig. 1. Exclusion profiles: the number of *Biloxi Bay* fish not excluded (*y* axis) relative to the number of microsatellites required for exclusion (*x* axis). Each plot represents one of nine broodtanks, with six possible sire x dam combinations in each broodtank. Averages and standard deviations (*y* error bars) are indicated.



The heterozygote deficiency observed at five of the microsatellites (*Soc*44, *Soc*201, *Soc*401, *Soc*404, and *Soc*412), if due to null alleles, could potentially generate 'typing errors' and negatively impact genotype exclusion tests (Pemberton et al. 1995; Taylor et al. 1997; Marshall et al. 1998). Errors in 'parental' genotypes (*Broodstock* fish, in this case) can be critical, as they can potentially impact comparisons with every potential 'offspring' genotype; genotyping errors in 'offspring' (*Biloxi Bay* fish, in this case) will only impact assignment of each individual mistyped. PROBMAX-2 enables the user to specify the number of microsatellites at which mistyping may occur. The program then matches genotypes at the remaining microsatellites with all possible combinations of microsatellite alleles. A standard error rate of 5%, for example, would allow for mismatches at two of the 31 microsatellites used here. Incorporating a 5% error rate did not affect the outcome of exclusion analysis, as all *Biloxi Bay* fish were still successfully excluded. Repeated PROBMAX-2 runs with different error rates demonstrated that a typing error rate of nearly 48% (up to 15 microsatellites) could be considered without affecting the exclusion of all *Biloxi Bay* fish.

Exclusion analysis also was carried out without the microsatellites where genotype proportions did not conform to Hardy-Weinberg expectations in either *Broodstock* or *Biloxi Bay*. The results were the same as exclusion profiles when all 31 microsatellites were employed; 16 microsatellites were necessary without mtDNA to exclude all 102

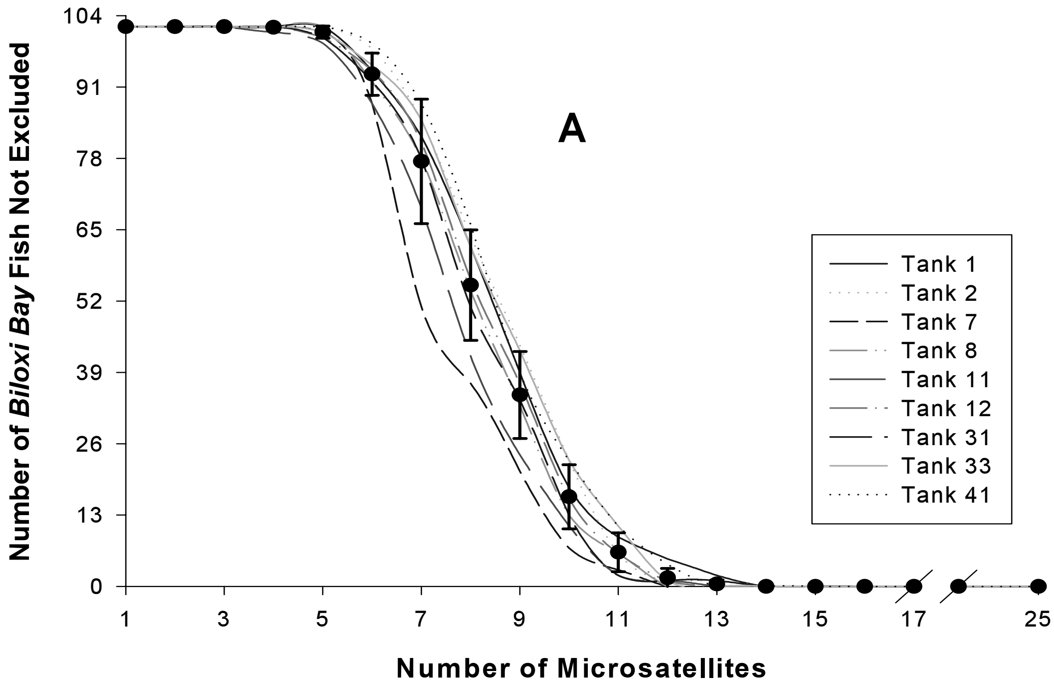
Fig. 2. Exclusion profiles: the number of *Biloxi Bay* fish not excluded (*y* axis) relative to the number of genetic markers (microsatellites and mtDNA) required for exclusion (*x* axis). Each plot represents one of nine broodtanks, with six possible sire x dam combinations in each broodtank.



Biloxi Bay fish (Fig. 3a), while 13 microsatellites were (again) needed when mtDNA was included (Fig. 3b).

Parental pair exclusion probabilities (*P* values) for each microsatellite are given in Table 1. Each *P* value represents the probability that allele frequencies estimated from the 'wild' fish in *Biloxi Bay* will exclude any individual parental pair sampled at random. *P* values for the 31 microsatellites are listed in the table from the largest to the smallest parental-exclusion probability. The highest *P* value (0.980479) is for *Soc*44 and means that ~ 98% of all potential sire x dam combinations are excluded; conversely, the lowest *P* value (0.411053) is for *Soc*206 and means that only ~ 41% of all potential sire x dam combinations are excluded. These exclusion probabilities can then be used to estimate the probability of not excluding a pair of non-parents (simply estimated as [1 – *P*]). The value [1 – *P*] represents the probability of incorrectly assigning a 'wild' fish as having been produced by any possible sire x dam combinations. Assuming the microsatellites are inherited independently, the estimates of [1 – *P*] can be combined to yield a cumulative probability. The values for [1 – *P*] and the cumulative probabilities also are given in Table 1. Using all 31 microsatellites, the cumulative probability of incorrectly assigning one of the 'wild' fish from *Biloxi Bay* to a particular pair of parents is 3.38×10^{-26}. Removing the six microsatellites that failed to conform to Hardy-Weinberg genotype expectations in either sample reduced the probability of incorrect assignment to 2.58×10^{-19}.

Fig. 3. Exclusion profiles with microsatellites failing to conform to Hardy-Weinberg equilibrium expectations (*Soc*44, *Soc*201, *Soc*243, and *Soc*401, *Soc*404, *Soc*412) omitted. (A) Microsatellites (25) only; (B) Microsatellites (25) and mtDNA. Axes are as in Figs. 1 and 2. Averages and standard deviations (y error bars) are indicated for microsatellites (A).



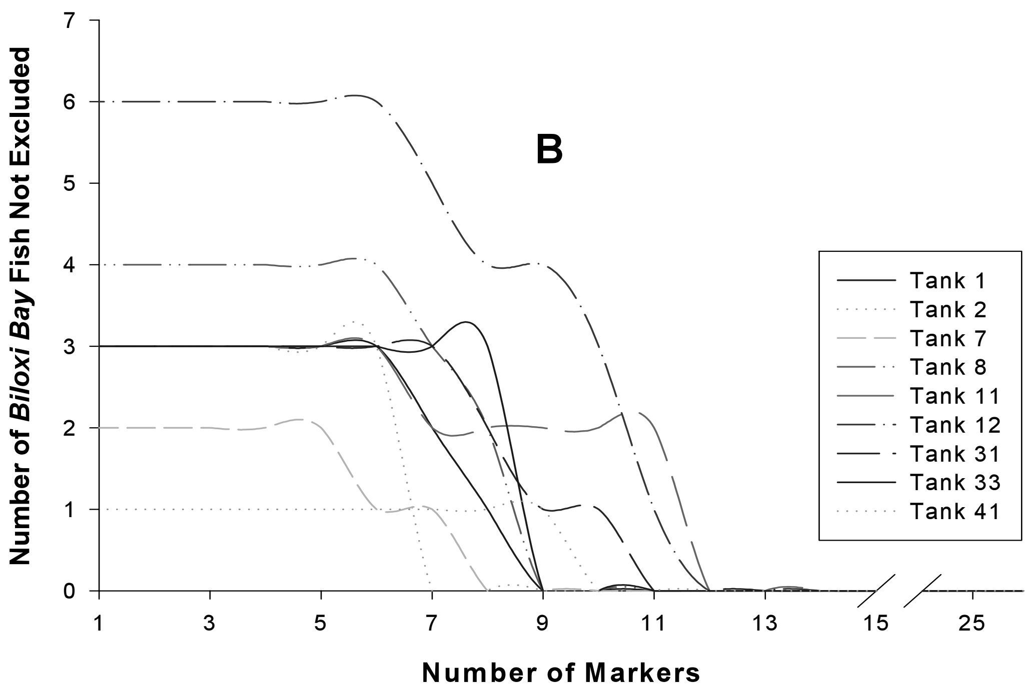


Table 1. Parental pair exclusion probabilities (*P* values) and cumulative probability of incorrectly assigning a *Biloxi Bay* fish [1 – *P*] as having been produced by any sire x dam combination. Probabilities are based on 31 microsatellites. Individual microsatellites are ranked from highest to lowest parent pair exclusion probability.

Microsatellite	Parent Pair (*P*)	Cumulative (1 – *P*)	Microsatellite	Pair Parent (*P*)	Cumulative (1 – *P*)
*Soc*44	0.980479	1.95 x 10^{-2}	*Soc*445	0.814598	1.44 x 10^{-19}
*Soc*428	0.980179	3.87 x 10^{-4}	*Soc*138	0.808236	2.76 x 10^{-20}
*Soc*404	0.980162	7.68 x 10^{-6}	*Soc*433	0.806873	5.32 x 10^{-21}
*Soc*412	0.955382	3.42 x 10^{-7}	*Soc*410	0.790577	1.11 x 10^{-21}
*Soc*99	0.947407	1.80 x 10^{-8}	*Soc*201	0.737766	2.93 x 10^{-22}
*Soc*19	0.937484	1.13 x 10^{-9}	*Soc*417	0.737483	7.67 x 10^{-23}
*Soc*423	0.925199	8.42 x 10^{-11}	*Soc*400	0.721149	2.14 x 10^{-23}
*Soc*402	0.921417	6.62 x 10^{-12}	*Soc*415	0.670224	7.06 x 10^{-24}
*Soc*401	0.9087 7	6.04 x 10^{-13}	*Soc*243	0.655686	2.43 x 10^{-24}
*Soc*416	0.883978	7.01 x 10^{-14}	*Soc*11	0.633953	8.16 x 10^{-25}
*Soc*83	0.873138	8.89 x 10^{-15}	*Soc*140	0.566945	3.54 x 10^{-25}
*Soc*419	0.871818	1.14 x 10^{-15}	*Soc*156	0.484788	1.82 x 10^{-25}
*Soc*85	0.854858	1.65 x 10^{-16}	*Soc*60	0.454885	9.93 x 10^{-26}
*Soc*407	0.850088	2.48 x 10^{-17}	*Soc*444	0.422665	5.73 x 10^{-26}
*Soc*432	0.826472	4.30 x 10^{-18}	*Soc*206	0.411053	3.38 x 10^{-26}
*Soc*424	0.819807	7.75 x 10^{-19}			

Parental pair exclusion probabilities (*P*) and 'incorrect assignment' probabilities [1 – *P*] when mtDNA is included are given in Table 2. Inclusion of mtDNA decreased the cumulative probability of incorrect assignment (all 31 microsatellites) to 1.33 x 10^{-27}. Removing the six microsatellites that failed to conform to Hardy-Weinberg genotype expectations in either sample increased the cumulative probability of incorrect assignment to 9.34 x 10^{-21}.

To further illustrate the power of the exclusion analysis approach, we also generated exclusion profiles (with and without mtDNA) that were based on the 486 possible sire x dam combinations had all 18 sires been crossed randomly with all 27 dams. Only 19 of the 31 microsatellites were necessary to exclude all *Biloxi Bay* fish in the absence of mtDNA data, while only 15 microsatellites were necessary when mtDNA data were included (Fig. 4). The situation where all possible pairwise combinations of broodfish are used to generate progeny is, of course, unlikely, given the facility requirements to hold this many adult red drum. However, the exclusion analysis profiles generated demonstrate quite adequately the power of exclusion analysis.

The foregoing demonstrated first, that all of the 'wild' fish sampled from Biloxi Bay could be excluded unequivocally as having been produced by the TPWD broodstock; and second, that the probability of misidentifying one of the 'wild' fish as having been produced by the broodstock ranged between 2.58 x 10^{-19} and 1.33 x 10^{-27}, depending on whether 25 or 31 microsatellites, with and without mtDNA, were used. However, supposing that a fish was *not* excluded as having come from *Broodstock*, the question arises as to whether it *could* have come from the 'wild' population. The 'genetic' approach to this question would be to ask how likely it would be to encounter a hatchery-produced genotype in the 'wild' population. To address this question, we computed the expected frequency of

Table 2. Parental pair exclusion probabilities (*P* values) and cumulative probability of incorrectly assigning a *Biloxi Bay* fish [1 – *P*] as having been produced by any sire x dam combination. Probabilities are based on 31 microsatellites and mitochondrial (mt)DNA. Individual genetic markers are ranked from highest to lowest parent pair exclusion probability.

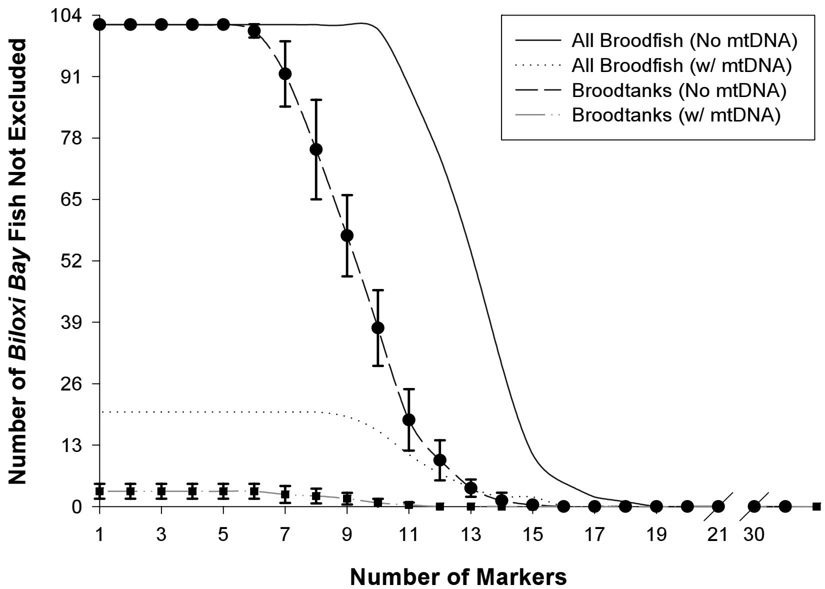
Marker	Parent Pair (*P*)	Cumulative (1 – *P*)	Marker	Parent Pair (*P*)	Cumulative (1 – *P*)
*Soc*44	0.980479	1.95×10^{-2}	*Soc*424	0.819807	2.80×10^{-20}
*Soc*428	0.980179	3.87×10^{-4}	*Soc*445	0.814598	5.19×10^{-21}
*Soc*404	0.980162	7.66×10^{-6}	*Soc*138	0.808236	9.96×10^{-22}
MtDNA	0.963855	2.77×10^{-7}	*Soc*433	0.806873	1.92×10^{-22}
*Soc*412	0.955382	1.24×10^{-8}	*Soc*410	0.790577	4.03×10^{-23}
*Soc*99	0.947407	6.51×10^{-10}	*Soc*201	0.737766	1.06×10^{-23}
*Soc*19	0.937484	4.07×10^{-11}	*Soc*417	0.737483	2.77×10^{-24}
*Soc*423	0.925199	3.04×10^{-12}	*Soc*400	0.721149	7.73×10^{-25}
*Soc*402	0.921417	2.39×10^{-13}	*Soc*415	0.670224	2.55×10^{-25}
*Soc*401	0.908767	2.18×10^{-14}	*Soc*243	0.655686	8.78×10^{-26}
*Soc*416	0.883978	2.53×10^{-15}	*Soc*11	0.633953	3.21×10^{-26}
*Soc*83	0.873138	3.21×10^{-16}	*Soc*140	0.566945	1.39×10^{-26}
*Soc*419	0.871818	4.12×10^{-17}	*Soc*156	0.484788	7.17×10^{-27}
*Soc*85	0.854858	5.98×10^{-18}	*Soc*60	0.454885	3.91×10^{-27}
*Soc*407	0.850088	8.96×10^{-19}	*Soc*444	0.422665	2.26×10^{-27}
*Soc*432	0.826472	1.55×10^{-19}	*Soc*206	0.411053	1.33×10^{-27}

the most common 'composite' genotype in each of the nine broodtanks by multiplying the observed frequencies of the most common observed genotype at each independent genetic marker. We then asked what would be the probability of recovering the most-common, hatchery-produced 'composite' genotype from the population in Biloxi Bay, based on the observed allele frequencies at each genetic marker in the sample from Biloxi Bay. The probabilities of finding a fish with the most common, hatchery-produced genotype (by broodtank) in Biloxi Bay are given in Table 3. These probabilities, by broodtank, ranged from 1.38×10^{-27} (Tank 41, 25 microsatellites, without mtDNA) to 2.98×0^{-42} (Tank 33, 31 microsatellites, with mtDNA). All other genotypes produced from the TPWD broodstock would thus occur among fish from Biloxi Bay at even lower (expected) frequencies. It is an important point to note that the inverse of the highest probability estimate (1.38×10^{-27}) is ~20 orders of magnitude larger than the estimated number of 6×10^6 (lower and upper-bound 90% confidence intervals of 4.4×10^6 and 7.7×10^6) adult red drum in the northern Gulf of Mexico (Nichols 1988; Mitchell and Henwood 1999).

DISCUSSION

The exclusion analyses and parental-pair exclusion probabilities indicated, respectively, that (i) only 16 microsatellites (13 if mtDNA was employed) were necessary to exclude all of the red drum sampled from Biloxi Bay as having been produced by TPWD broodfish, and (ii) the probability of incorrectly assigning a *Biloxi Bay* fish as having been produced by TPWD broodfish ranged from 2.58×10^{-19} (25 microsatellites in HW equilibrium) to 1.33×10^{-27} (all 31 microsatellites and mtDNA). Probabilities (with and without mtDNA) that the most-common, hatchery-produced 'composite' genotype would occur in the sample from Biloxi Bay ranged by broodtank from 1.38×10^{-27} to 2.98×10^{-42}.

Fig. 4. Exclusion profiles estimated with all possible combinations of 18 ♂♂ and 27 ♀♀ (486 total) or with the 54 possible combinations in the nine broodtanks (each broodtank with 2 ♂♂ and 3 ♀♀). Axes are as in Figs. 1 and 2. Averages and standard deviations (y error bars) are indicated for broodtanks (no mtDNA).



All of the probability values are several orders of magnitude smaller than the reciprocal of the total number of adult red drum (10^6–10^7) estimated to occur in the northern Gulf of Mexico (Nichols 1988; Mitchell and Henwood 1999).

In part because genotyping expenses, including labor, increase as a function of the number of genetic markers employed, we estimated the minimum number of genetic markers that would be appropriate for the case at hand. We began with the premise that the minimum number of markers would be 16

Table 3. Probabilities for each of nine broodtanks of finding a fish with the most common, hatchery-produced genotype in the 'wild' population from Biloxi Bay. Values are given for all 31 microsatellites (with and without mitochondrial DNA), and for the 25 microsatellites in Hardy-Weinberg equilibrium (with and without mitochondrial DNA).

	31 Microsatellites		25 Microsatellites	
Broodtank	**No MtDNA**	**With MtDNA**	**No MtDNA**	**With MtDNA**
Tank 1	1.38×10^{-38}	4.19×10^{-40}	8.41×10^{-30}	2.55×10^{-31}
Tank 2	2.27×10^{-38}	6.89×10^{-40}	4.28×10^{-27}	1.30×10^{-28}
Tank 7	8.03×10^{-37}	1.62×10^{-38}	7.76×10^{-28}	1.57×10^{-29}
Tank 8	9.53×10^{-40}	2.89×10^{-41}	3.81×10^{-30}	1.15×10^{-31}
Tank 11	2.45×10^{-38}	4.94×10^{-40}	1.42×10^{-28}	2.87×10^{-30}
Tank 12	2.60×10^{-34}	7.88×10^{-36}	1.43×10^{-26}	4.37×10^{-28}
Tank 31	1.54×10^{-36}	4.68×10^{-38}	2.80×10^{-28}	8.49×10^{-30}
Tank 33	1.48×10^{-40}	2.98×10^{-42}	6.64×10^{-31}	1.34×10^{-32}
Tank 41	1.83×10^{-37}	1.84×10^{-39}	1.38×10^{-27}	1.39×10^{-29}

microsatellites alone or 13 microsatellites plus mtDNA, given that 100% of the red drum sampled from Biloxi Bay were excluded with either marker set. Sequencing ~ 370 base pairs of DNA on an individual-by-individual basis would be more expensive and time consuming than genotyping an additional three microsatellites, particularly if the latter were multiplexed efficiently. However, inclusion of mtDNA alone in this situation resulted in exclusion of 77 of 99 *Biloxi Bay* fish (~ 78%), meaning that only 22 fish needed to be genotyped at 13 microsatellites for 100% exclusion, i.e., in this example, it would be more cost effective to sequence mtDNA fragments, then determine the number of individuals that needed to be assayed for microsatellite genotypes.

For probability levels of either incorrect assignment of *Biloxi Bay* fish as having come from *Broodstock* or for finding in Biloxi Bay the most common 'composite' genotype produced from the broodstock, we suggest that values of 10^{-10} or 10^{-15} would be more than sufficient to insure legal sale and avoid/alleviate potential conflicts. These values are still orders of magnitude smaller than the reciprocal of the estimated number of adult red drum in the northern Gulf of Mexico and are well within the range (10^{-9}–10^{-15}) of match-probability estimates generated for the 13 microsatellite markers validated for forensic use in humans (Chakraborty et al. 1999). The minimum number of microsatellites (from all 31 assayed) needed to attain probabilities of 10^{-10} and 10^{-15} of incorrectly assigning a fish from Biloxi Bay as having come from *Broodstock* were seven and twelve, respectively, without mtDNA, and six and ten, respectively, with mtDNA. Removing the six microsatellites that failed to conform to Hardy-Weinberg genotype expectations in either sample increased the minimum numbers to eight and fifteen (without mtDNA) and seven and thirteen (with mtDNA). The latter thirteen microsatellites are the same 13 microsatellites (plus mtDNA) needed for 100% exclusion. The number of microsatellites (with and without mtDNA) needed to obtaining probabilities of 10^{-10} and 10^{-15} that the most common, hatchery produced 'composite' genotype would occur in the sample from Biloxi Bay ranged by broodtank from three (several broodtanks and with mtDNA) to ten (two broodtanks and without mtDNA). Because different microsatellites were 'informative' across broodtanks, we estimated the minimum number of microsatellites needed over all nine broodtanks. For all 31 microsatellites, the minimum number to obtain probabilities of 10^{-10} and 10^{-15}, respectively, were six and ten (without mtDNA) and five and nine (with mtDNA); for just those microsatellites whose genotypes were in Hardy-Weinberg proportions, the minimum numbers were seven and twelve (without mtDNA) and six and ten (with mtDNA).

The foregoing demonstrates that unequivocally distinguishing red drum spawned from broodstock obtained offshore of Corpus Christi, Texas, from the 'wild' stock in Biloxi Bay, Mississippi, is fairly straightforward, given (i) a sufficient number of polymorphic (variable), independent genetic markers, (ii) the genotypes of the broodfish, and (iii) a survey of allelic variation at the genetic markers among representatives of the 'wild' stock. In the example documented here, thirteen microsatellites and a fragment of mtDNA sufficed to exclude 100% of sampled 'wild' fish from Biloxi Bay as having come from the broodstock, while the probabilities of (i) incorrectly assigning a 'wild' fish as having come from the broodstock, and (ii) finding the most common 'composite' genotype produced from the broodstock in the 'wild' were greater than 10^{-15}. The three 'requirements' essentially would be the same for any offshore aquaculture operation where legal sale of the cultured species could be an issue. Two other issues remain, however, in terms of the broader applicability of the approach in both red drum and other marine fish species that might be cultured in offshore facilities.

The first issue is the applicability of the findings relative to offshore aquaculture of red drum at other localities in the northern Gulf of Mexico or elsewhere (e.g., the southeast coast of the U.S.). Several previous studies of spatial genetic variation among red drum along both the northern Gulf Coast and the U.S. South Atlantic Coast (Gold et al. 1999; Seyoum et al. 2000; Gold and Turner 2002) have shown that differences in microsatellite and mtDNA allele frequencies accumulate primarily as a function of geographic distance between geographic localities. Consequently, the number of genetic markers needed for forensic exclusion would likely be inversely related to the geographic distance between the location where broodfish were obtained and the location of the offshore aquaculture facility. The minimum number of markers required could then be estimated following a survey of the 'wild' stock at the locality for the same markers used to genotype the broodfish. One advantage in the case of offshore aquaculture of red drum (as opposed to other species) is that the genetic markers and the conditions for their assay already have been developed and tested (this paper).

The second issue is the applicability of findings here to other species. In brief, the approach taken here essentially would be the same for any species of interest. For most marine fish species, appropriate genetic markers, including primer sequences for PCR amplification, would likely need to be generated. The two other species of interest to the OAC were red snapper (*Lutjanus campechanus*) and cobia (*Rachycentron canadum*). Virtually no genetic data are available for cobia, meaning that genetic markers for this species would need to be generated *de novo*. Both microsatellite (Gold et al. 2001) and mitochondrial DNA (Garber et al. 2004) markers have been developed for red snapper and employed in studies of geographic variation. Levels of variability in red snapper microsatellites were considerably less than those found in red drum. Observed heterozygosity (20 microsatellites) among red snapper sampled from four localities in the northern Gulf of Mexico averaged 0.542–0.609 (Gold et al. 2001), as compared to heterozygosities of 0.793 (*Broodstock*) and 0.787 (*Biloxi Bay*) for red drum studied here. Alternatively, Garber et al. (2004) sequenced an ~ 300 base pair fragment of the mtDNA control region from 140 red snappers from the northern Gulf of Mexico and found a nucleon diversity of 1.00 (each individual possessed a different mtDNA genotype). The lower levels of variability in red snapper microsatellites may indicate that more microsatellites than needed for red drum will likely need to be employed for forensic application in red snapper.

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APPENDIX

Table 1. PCR primer sequences (forward, top; reverse, bottom), repeat sequence (of the cloned allele), and annealing temperature (AT) for 31 microsatellites used to genotype (i) red drum broodstock at the CCA/CPL Marine Development Center in Corpus Christi, TX, and (ii) age 0 red drum sampled from Biloxi Bay, MS.

Micro-satellite	PCR primer sequence (5'→3')	Repeat sequence	AT
*Soc*11	GCCGAGTCACGAAGGAACAGAGAA		
	TGTCGTCTCATCTATCTCCATCTC	$(GA)_{11}$	62
*Soc*19	GGGTACAACTAAACAGACACAATA		
	TTTGAAAATGTTCCTGTGAATCAC	$(GATA)_{16}$	58
*Soc*44	GAGGGTGACGCTAACAGTTGA		
	CACAGCTCCACTCTGATATG	$(CA)_{22}$ $(GT)_5$	62
*Soc*60	TCTATTGAAGCCTGTAAGTTAGTT		
	CAAGGAAGGAGTGGGGAATGACAA	$(AGG)_8$	56
*Soc*83	TGCTGTAATTGAAAAGCAGTGTAC		
	AGCGGAACTAGAATTGGTTTTATA	$(TG)_{19}$	56
*Soc*85	TTTTGGACCTACACTAGAGTAGC		
	CGTGGGAGACTAGCGATGTAGAT	$(AC)_{17}$	58
*Soc*99	CACCCACTGACACACACATACAC		
	GGAACCAATATGTCTGCCATGAT	$(CA)_{29}$	62
*Soc*138	CTGGAGCTTTTCCCTTTCTGT		
	TGGGAGGAGAAGGCAGGAAGG	$(TGTC)_6$	58
*Soc*140	GGTGCAAACACAGCCATACAGT		
	GCAAAATCGAAGACCGAGTTTAG	$(CTGT)_8$	56
*Soc*156	CCTCTCCTTTCTCCATCAGTGC		
	AGCCCGGCTGTCATCTCCTGTA	$(CCT)_6$ $(TCC)_4$	58
*Soc*201	GGAGGAACTGATGAGGGCAGTGT		
	GCACAACACACCTCGCTATATC	$(CCT)_6$	58
*Soc*206	GTTTCCCACATCCCCCAACC		
	AGTTTGGTCGCTTTAAAGGC	$(GCAC)_5$	58
*Soc*243	GACGGGGATGCCATCTGC		
	AATGCGAAAAAGACGAAACAGT	$(CCT)_9$	56
*Soc*400	TGCCATTGTCATTCTACAGAGC		
	TTATAGTGGGGTGAGTGTTTGA	$(CA)_{19}$	52
*Soc*401	ACGTCTTAATCGGTCTCTGTCC		
	ATCTCTGTGTGAAAGGAAAACA	$(TG)_{14}$	52
*Soc*402	CATATTTAACGAGCGACATAGC		
	AAACAGATGAAGCACCTGGACT	$(CA)_{20}$	52
*Soc*404	AGACCCTTTTGTTGATTTCATA		
	ATGACTGCACCATTTCAAAAAG	$(TG)_{23}$	52
*Soc*407	AAAGTCTGCCTCTTACAGCTTC		
	GAGTTAAAGCGTGTGCTAGTCC	$(CA)_{13}$	56
*Soc*410	GTACCAAGTCAGCCAGTGTCAG		
	TCTCTGTGTCCCTCTGTGTTTG	$(TG)_{17}$	56

Appendix Table 1. continued.

Micro-satellite	PCR primer sequence (5'→3')	Repeat sequence	AT
*Soc*412	CACAGAAACTCAGCTCGAGACC AGGAAGAATGTACAAGGTGTTC	$(AC)_{13}$	49
*Soc*415	CTCAGCACCCTCAGACATATGG CACAAGTTAAGTGGTATCGAGT	$(TG)_{15}$	52
*Soc*416	CTCGATACCACTTAACTTGT ATCGACATAATCTGGCACCA	$(GA)_{38}$	49
*Soc*417	CTTACGTGATAAAGTGTGGGTGA ATATGCCAGTAATCCACCGAAG	$(AC)_{24}$	49
*Soc*419	ATTTAGCCAACTGCTCCGCTCA GAGTGCGTGGTGTAGGGGGGTA	$(AC)_{20}$	56
*Soc*423	GTCACCGCACCATGATGGAGAT TACCACTTACACTCAGCAGGTG	$(CA)_{26}$	54
*Soc*424	CACTCTTCATCCCTCACTCGTC TTCGATGGGTGACAGCGTCAGG	$(CA)_{15}$	56
*Soc*428	GACATCGCATTTGTCTACAGAGTCG AACTCCCAGTCATAATATCCCTTT	$(TG)_{38}$	53
*Soc*432	TTTAGGCTACGTCTGGAGGCACA GTGTGTTTGAGGGTCAGCGTAC	$(AC)_{16}$	52
*Soc*433	AGTACGCTGACCCTCAAACACA TTCTCTTTGCCTCCTTTTTCCCTGA	$(TG)_{16}$	52
*Soc*444	TGAACTAATCCAGCCACAGATG CACAGCCGATTAAAGAGAGGGAAT	$(TG)_{17}$	
*Soc*445	ATACAAAGGGACTCTCATACTCTC TTTTAATCCCATTACAGCTTT	$(TCC)_{10}$	

Appendix Table 2. Summary statistics at 31 nuclear-encoded microsatellites in two samples of red drum (Sciaenops ocellatus). N = sample size, #A = number of alleles, AR = allelic richness, H_E = gene diversity (expected heterozygosity), P_{HW} = probability of conformity to Hardy-Weinberg genotypic expectations, and F_{IS} = inbreeding coefficient.

Sample		***Broodstock***	***Biloxi Bay***	Sample		***Broodstock***	***Biloxi Bay***
*Soc*11	N	45	102	*Soc*19	N	45	102
	#A	10	11		#A	15	16
	AR	9.86	8.01		AR	14.82	14.18
	H_E	0.729	0.664		H_E	0.909	0.908
	P_{HW}	0.709	0.932		P_{HW}	0.024	0.774
	F_{IS}	–0.006	–0.019		F_{IS}	0.071	0.050
*Soc*44	N	43	99	*Soc*60	N	45	102
	#A	23	28		#A	5	7
	AR	23.00	24.51		AR	4.96	5.59
	H_E	0.941	0.954		H_E	0.577	0.591
	P_{HW}	0.371	**0.000***		P_{HW}	0.752	0.407
	F_{IS}	0.036	0.195		F_{IS}	0.114	0.021
*Soc*83	N	45	102	*Soc*85	N	45	102
	#A	13	14		#A	14	14
	AR	12.73	12.95		AR	13.91	12.40
	H_E	0.835	0.850		H_E	0.880	0.832
	P_{HW}	0.687	0.413		P_{HW}	0.102	0.764
	F_{IS}	–0.037	0.066		F_{IS}	0.065	-0.014
*Soc*99	N	45	101	*Soc*138	N	45	101
	#A	22	23		#A	12	13
	AR	21.73	19.31		AR	11.90	10.78
	H_E	0.934	0.913		H_E	0.829	0.812
	P_{HW}	0.663	0.251		P_{HW}	0.207	0.991
	F_{IS}	0.000	0.045		F_{IS}	–0.073	–0.024
*Soc*140	N	45	102	*Soc*156	N	45	102
	#A	4	7		#A	4	5
	AR	4.00	6.21		AR	3.96	4.09
	H_E	0.629	0.622		H_E	0.457	0.591
	P_{HW}	0.280	0.794		P_{HW}	0.018	0.007
	F_{IS}	–0.237	–0.040		F_{IS}	–0.166	0.037
*Soc*201	N	43	102	*Soc*206	N	45	102
	#A	10	12		#A	6	5
	AR	10.00	10.05		AR	5.95	4.63
	H_E	0.703	0.739		H_E	0.554	0.541
	P_{HW}	0.401	**0.000***		P_{HW}	0.028	0.083
	F_{IS}	0.107	0.257		F_{IS}	–0.044	0.039

Appendix Table 2. continued.

Sample		*Broodstock*	*Biloxi Bay*	Sample		*Broodstock*	*Biloxi Bay*
*Soc*243	N	45	102	*Soc*400	N	45	102
	#A	5	7		#A	8	10
	AR	4.96	5.81		AR	7.91	8.84
	H_E	0.762	0.726		H_E	0.729	0.742
	P_{HW}	0.244	**0.000***		P_{HW}	0.688	0.663
	F_{IS}	0.037	–0.094		F_{IS}	0.146	0.088
*Soc*401	N	45	101	*Soc*402	N	45	100
	#A	12	16		#A	15	17
	AR	11.86	13.79		AR	14.77	14.55
	H_E	0.859	0.882		H_E	0.885	0.885
	P_{HW}	0.447	**0.000***		P_{HW}	0.250	0.039
	F_{IS}	0.147	0.270		F_{IS}	0.046	–0.051
*Soc*404	N	45	102	*Soc*407	N	45	100
	#A	24	34		#A	10	12
	AR	23.68	28.54		AR	9.91	10.29
	H_E	0.915	0.952		H_E	0.852	0.844
	P_{HW}	0.006	**0.001***		P_{HW}	0.250	0.001
	F_{IS}	0.150	0.135		F_{IS}	–0.069	0.123
*Soc*410	N	45	100	*Soc*412	N	45	100
	#A	14	16		#A	24	26
	AR	13.86	12.87		AR	23.51	22.31
	H_E	0.810	0.753		H_E	0.916	0.921
	P_{HW}	0.131	0.014		P_{HW}	**0.000***	**0.000***
	F_{IS}	0.122	0.031		F_{IS}	0.102	0.175
*Soc*415	N	45	102	*Soc*416	N	45	99
	#A	12	18		#A	16	18
	AR	11.86	13.61		AR	15.86	16.75
	H_E	0.717	0.636		H_E	0.862	0.837
	P_{HW}	0.556	0.140		P_{HW}	0.370	0.149
	F_{IS}	0.070	0.029		F_{IS}	0.150	0.070
*Soc*417	N	45	102	*Soc*419	N	45	100
	#A	11	13		#A	11	14
	AR	10.90	10.61		AR	10.91	10.89
	H_E	0.765	0.740		H_E	0.860	0.857
	P_{HW}	0.258	0.152		P_{HW}	0.888	0.705
	F_{IS}	–0.017	–0.034		F_{IS}	–0.060	0.055
*Soc*423	N	45	101	*Soc*424	N	45	102
	#A	18	19		#A	13	19
	AR	17.69	16.22		AR	12.95	15.29
	H_E	0.891	0.894		H_E	0.850	0.780
	P_{HW}	0.110	0.018		P_{HW}	0.315	0.028
	F_{IS}	0.003	0.092		F_{IS}	0.007	0.082

Appendix Table 2. continued.

Sample		Broodstock	Biloxi Bay	Sample		Broodstock	Biloxi Bay
*Soc*428	N	45	101	*Soc*432	N	45	102
	#A	27	32		#A	9	10
	AR	26.77	26.66		AR	8.91	8.74
	H_E	0.957	0.953		H_E	0.817	0.828
	P_{HW}	0.249	0.204		P_{HW}	0.871	0.165
	F_{IS}	0.001	0.065		F_{IS}	–0.061	0.112
*Soc*433	N	45	101	*Soc*444	N	45	102
	#A	10	12		#A	3	5
	AR	9.91	10.21		AR	3.00	4.47
	H_E	0.837	0.804		H_E	0.509	0.555
	P_{HW}	0.188	0.195		P_{HW}	0.526	0.183
	F_{IS}	–0.035	0.003		F_{IS}	–0.179	0.046
*Soc*445	N	45	101				
	#A	10	11				
	AR	9.96	9.80				
	H_E	0.815	0.795				
	P_{HW}	0.132	0.006				
	F_{IS}	0.045	0.153				

* Significant following Bonferroni correction (in boldface).

Appendix Table 3. Distribution of mitochondrial (mt)DNA haplotypes (sequences) in two samples of red drum (*Sciaenops ocellatus*). Data are from 369 base pairs of the mtDNA control region. GenBank Accession Numbers (in sequence) are AY 578986–AY 579075.

Haplotype	*Broodstock*	*Biloxi Bay*	Total	Haplotype	*Broodstock*	*Biloxi Bay*	Total
1	7	3	10	46	0	1	1
2	1	0	1	47	0	1	1
3	1	0	1	48	0	1	1
4	1	0	1	49	0	4	4
5	1	0	1	50	0	1	1
6	1	3	4	51	0	1	1
7	2	0	2	52	0	1	1
8	2	1	3	53	0	1	1
9	2	1	3	54	0	1	1
10	4	2	6	55	0	1	1
11	2	0	2	56	0	1	1
12	1	0	1	57	0	1	1
13	1	1	2	58	0	2	2
14	4	3	7	59	0	1	1
15	1	1	2	60	0	1	1
16	1	0	1	61	0	5	5
17	1	0	1	62	0	1	1
18	1	3	4	63	0	1	1
19	1	0	1	64	0	1	1
20	1	0	1	65	0	1	1
21	1	0	1	66	0	1	1
22	1	0	1	67	0	1	1
23	1	2	3	68	0	1	1
24	1	1	2	69	0	1	1
25	1	0	1	70	0	1	1
26	1	0	1	71	0	1	1
27	1	0	1	72	0	1	1
28	1	1	2	73	0	1	1
29	1	0	1	74	0	1	1
30	0	1	1	75	0	1	1
31	0	1	1	76	0	1	1
32	0	1	1	77	0	1	1
33	0	1	1	78	0	1	1
34	0	2	2	79	0	1	1
35	0	1	1	80	0	1	1
36	0	2	2	81	0	1	1
37	0	1	1	82	0	1	1
38	0	2	2	83	0	1	1
39	0	1	1	84	0	1	1
40	0	3	3	85	0	2	2
41	0	2	2	87	0	1	1
42	0	1	1	87	0	1	1
43	0	1	1	88	0	1	1
44	0	2	2	89	0	1	1
45	0	1	1	90	0	1	1
				Total	29	73	90

CHAPTER 6

ENVIRONMENTAL ISSUES ASSOCIATED WITH OFFSHORE AQUACULTURE & MODELING POTENTIAL IMPACT

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ABSTRACT

Real and perceived aquaculture environmental impacts that must be considered prior to expansion to open ocean locations include: 1) benthic carbon loading, 2) water column nutrification, 3) stimulation of harmful algal blooms, and 4) escapement and implications to wild populations. A simulation model was developed for predicting the benthic impacts from offshore cage culture. The model simulates the impact of feed and feces from one cage on a 600 m^2 area on the seafloor using total organic carbon (TOC) as an indicator. A Gaussian error was added to all variable means to represent variation about central tendencies. Cobia, red snapper, and red drum were the cultured species. We also considered depths of 20, 40, and 60 m between feces and feed point of release from the cage and the seafloor. Variables associated with management scenarios and fish biology were held constant throughout simulation runs. Cobia culture resulted in the least impact on TOC accumulation. Cages operated at 40 m depth resulted in 20% less TOC accumulation than those operated at 20 m. Operations at 60 m resulted in an accumulation of TOC of over 60% less of that from 40 m. Additional research is necessary to validate model results with data collected from operating open ocean aquaculture ventures prior to industry usage of the simulation model for site selection and management planning purposes.

INTRODUCTION

Cage culture is practiced in coastal bays, fjords, and lochs in numerous countries throughout the world. Due to increasing seafood demand and coastal expansion bottlenecks, coastal aquaculture areas are becoming increasingly burdened. To alleviate space constraints, cage aquaculture has been recently pressured to move offshore for grow-out. Limits to coastal expansion, additionally, are associated with potential environmental impacts by aquaculture. Some environmental impacts might be minimized by operating in more exposed locations, adding to the pressure for cage aquaculture to move to open and deeper sites.

No aquaculture industry presently exists offshore in U.S. federal waters within the United States Exclusive Economic Zone (EEZ). Introducing a new use for the offshore EEZ presents significant challenges for appropriate aquaculture site selection. Numerous users of the EEZ are established, including the commercial and recreational fishing industry, the oil and gas industry (minerals rights and future exploration), shipping (established channels), military zones (national defense and training), and dumping zones. Existing uses potentially limit access to appropriate

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grow-out sites, especially when considering the environmental and oceanographic criteria for optimal sites. Additionally, offshore aquaculture sites may also have production limits prior to negatively impacting the environment, thereby decreasing economic potential to investors.

ENVIRONMENTAL IMPACTS FROM OFFSHORE AQUACULTURE

Real and perceived aquaculture environmental impacts that must be considered prior to expansion to open ocean locations include: 1) benthic carbon loading, 2) water column nutrification, 3) stimulation of harmful algal blooms, and 4) escapement and implications to wild populations. Adoption of a thorough site selection process and suitable technologies that minimize effects will relieve many concerns related to environmental impacts.

Benthic impacts associated with waste solids accumulation can be attributed to poor site selection, management decisions, site overproduction, or some combination of these. Numerous studies throughout the world have documented the benthic impact associated with fish farming (Table 1; from Costa-Pierce and Bridger 2002). Most of the studies in Table 1 monitored environmental impacts associated with near shore and protected aquaculture sites. Owing to greater residual current, potentially deeper water, and greater assimilative capacity in open ocean conditions (Gowen and Edwards 1990), benthic impacts from exposed aquaculture operations are anticipated to be less than comparable sized near shore operations. Having decreased impact allows for larger size farms with more fish for grow-out. However, even exposed aquaculture sites would eventually reach an assimilative carrying capacity that could result in harm to the environment, if nutrient inputs exceed an acceptable threshold. Two reports of monitoring open ocean aquaculture sites in the U.S. have provided no evidence of benthic impact from open ocean operations (Bybee and Bailey-Brock 2003; Grizzle et al. 2003). Bybee and Bailey-Brock (2003) further illustrated the results of optimizing farm practices during the development phase of the project with comparable results observed over two consecutive years despite doubling fish density and feed. However, caution should be taken when interpreting these results as neither study may be indicative of actual results that would be attained from commercial operations. Only after monitoring commercial fish farming efforts in the open ocean can more accurate conclusions be drawn regarding benthic impact from exposed site applications.

Water quality impacts are mostly related to the addition of nutrients from feeding and fish excretion. Introduction of excess nutrients, particularly dissolved inorganic nitrogen, in the marine environment may result in algal blooms that can deleteriously affect aquaculture (discussed later in this section). Increased nutrient loading will also result in eventual depletion of oxygen in the surrounding water. This could increase stress in the cultured stock and result in fish health deterioration to arise with subsequent mortality leading to devastating economic losses. In exposed open ocean conditions, rapid removal of farm wastes and large volumes of water passing through a farm site resulting in large dilution of wastes will likely mitigate effects on water quality. However, open ocean farms will exist at enormous operational scale, thereby resulting in much larger quantities of dissolved nutrients into the environment, warranting extensive environmental monitoring programs.

Table 1. Degree of benthic 'halo' region impact associated with aquaculture operations.

Study	Benthic Impacts Reported
Mattsson and Linden (1983)	Species composition changed up to 20 m away from mussel farm
Brown et al. (1987)	Species composition changed up to 15 m away from cage edge
Gowen et al. (1988)	Species composition changed up to 30-40 m away from cages
Lumb (1989)	Impacts restricted to within 50 m of cage edges and dependent on seabed type
Ritz et al. (1989)	Macrofaunal community under the farm adopted an undisturbed condition 7 wk post-harvest of farm stock
Kupka-Hansen et al. (1991)	Species composition changed up to 25 m away from cages
Weston (1990)	Farm effects on sediment chemistry evident up to 45 m from the farm; species composi tion changed at least to 150 m away from cages
Johannessen et al. (1994)	No influence of fish farming could be detected 250 m away from cages
Krost et al. (1994)	Affected area extended 3-5 m from the fish farm margin
Wu et al. (1994)	Impacted area extended to 1000 m with industry using trash fish as feed and poor water flushing exists
McGhie et al. (2000)	Farm wastes largely restricted to area beneath sea cages; most of the sediment organic input from feces; and 12-month fallowing period sufficient to return site to pre-farm oxic conditions
Morrisey et al. (2000)	Large temporal & spatial variabilities depending on water velocities; recovery times esti mated between 3-12 years
Dominguez et al. (2001)	No affect on physical and chemical sediment characteristics due to fish farm operation in high average water current velocity (6 cm/s) site.

Further deterioration of water quality can result from extreme loading to the benthic environment, which could result in production of hydrogen sulphide affecting fish health and performance of the farm. Such a situation might occur in coastal aquaculture sites that have low rates of flushing and high farm waste deposition. Comparable situations are unlikely in more exposed locations, although farm operators need to be aware of this possibility given the large scale of operation expected off-shore. Hydrogen sulphide effects to farm stock may be minimized by siting cages in locations that allow a water depth in excess of 10 m between the bottom of the cage and seabed at low tide (Gowen and Edwards 1990). This depth allows sufficient exposure of the gas bubbles to the water column to oxidize the hydrogen sulphide gas, removing its toxicity.

Fish farming will result in increased nutrients in the surrounding environment. However, most studies to date have concluded that aquaculture sited in preferable locations for optimal fish health will not result in increased abundance of phytoplankton species (Parsons et al. 1990; Pridmore and Rutherford 1992). In fact, Arzul et al. (2001) reported inhibited phytoplankton growth when in the presence of excretion from selected finfish species (sea bass and salmon). These results were in stark contrast to the excretion from shellfish species (oysters and mussels), which stimulated phytoplankton growth rates.

Aquaculture escapees have been cited to demonstrate ecological, disease and genetic interactions with wild fish stocks in the vicinity of the aquaculture operations. Escapees are also particularly troublesome to the aquaculture entrepreneur as they represent a loss of stock value from the farm. Myrick (2002) discussed escapement of cultured species while Bridger and Garber (2002) specifically reviewed the salmonid escapement occurrence, implications, and solutions for mitigation. Salmonid escapees—specifically steelhead trout—have been observed to remain in the vicinity of aquaculture cages following escapement to the wild and displayed a homing response to aquaculture facilities if escapement occurred away from established aquaculture sites (Bridger et al. 2001). These results indicate a much lower risk from escapement to wild stocks than portrayed by environmental NGOs. Further, using biological cues to attract escapees allows development of recapture strategies to return escapees to cages for additional growth and decrease economic losses possible. Genetic impacts from escapees are considered an issue within salmon populations because of the species having geographically isolated populations within individual river systems that can be negatively impacted through the introduction of exotic genetic material. Cobia, red snapper, and red drum are all genetically considered panmixic and therefore regulated as one genetic stock throughout a fishery region. This population structure differs considerably from the salmonid case and greatly reduces the potential impact of genetic pollution from aquaculture escapees. Regardless, the most logical approach to mitigate impacts of escaped aquaculture fish is prevention. Appropriately designed aquaculture cages that can sustain the oceanographic loads anticipated in the open ocean will lower the probability for escapement.

PREDICTING BENTHIC IMPACT

Benthic impacts from feed and fish feces may be a function of site selection, management decisions, and site overproduction. Offshore aquaculture site selection and overproduction might be assessed by using numerical models, as is done in other fields, such as engineering, weather prediction, or economics. Numerical models might become a cornerstone in aquaculture to determine environmental impacts and farm siting. The incorporation of environmental impact assessment models, however, will fall largely on the extension community to provide the technology transfer to the new industry.

Numerous authors have discussed the mechanics and relationships involved in modeling benthic impacts from fish farm wastes (e.g., Hargrave 1994). Complex hydrodynamic models have been developed for specific regions (Panchang et al. 1997), but are unlikely to be general. DEPOMOD is a more generic, end-user benthic impact model developed for the Scottish cage culture industry (Cromey et al. 2002) using changes in species population composition to determine impacts. Although generic to the sea loch systems in Scotland, DEPOMOD may have limitations for its use in siting farm operations and management in the open ocean and outside Scotland. The Simulation for Environmental Impact (SEI) model used in this study was created to provide a tool that can be integrated into the development of an offshore aquaculture industry for appropriate site selection, optimal environmental management decisions, and application of medicated feed in exposed or offshore environments (Riedel and Bridger 2003).

THE SIMULATION FOR ENVIRONMENTAL IMPACT

SEI is intended to be a tool for the offshore aquaculture industry to help determine best farm locations (based upon oceanographic conditions) and stations for environmental monitoring of farm-related impact. SEI may also aid in determining more efficient farm management practices. Specific objectives for developing SEI were to:

1. predict potential environmental impacts measured by benthic carbon loading associated with various environmental and fish farm management scenarios;

2. develop a graphical user interface tool that extension professionals may use to assist the industry in determining off-shore aquaculture sites and management strategies to minimize detrimental environmental impacts; and,

3. provide the industry with advanced statistical diagnostic tools to assist with environmental monitoring and potential future diversification of activities, such as application of medicated feed.

Although SEI is intended to use TOC to indicate impact, other impact metrics may also be used depending upon the exact reason for using SEI, such as other chemical compounds or indices for species health or diversity. In Scotland, mathematical models have been accepted by regulatory agencies for farm site selection and monitoring medicated discharges from cage operations (Singleton and Rosie 2003). We, however, advise against relying solely on SEI to make regulatory and critical management decisions.

SEI has the look and feel of most Windows-based commercial software packages in that it consists of a menu-driven window with dialog boxes (Fig. 1). SEI is user friendly and has a visual interface to aid in exploring and interpreting various fish farm management scenarios. It also allows more complex spatial analyses through output of a text file ready to be imported into most data analysis software.

MODEL DESCRIPTION

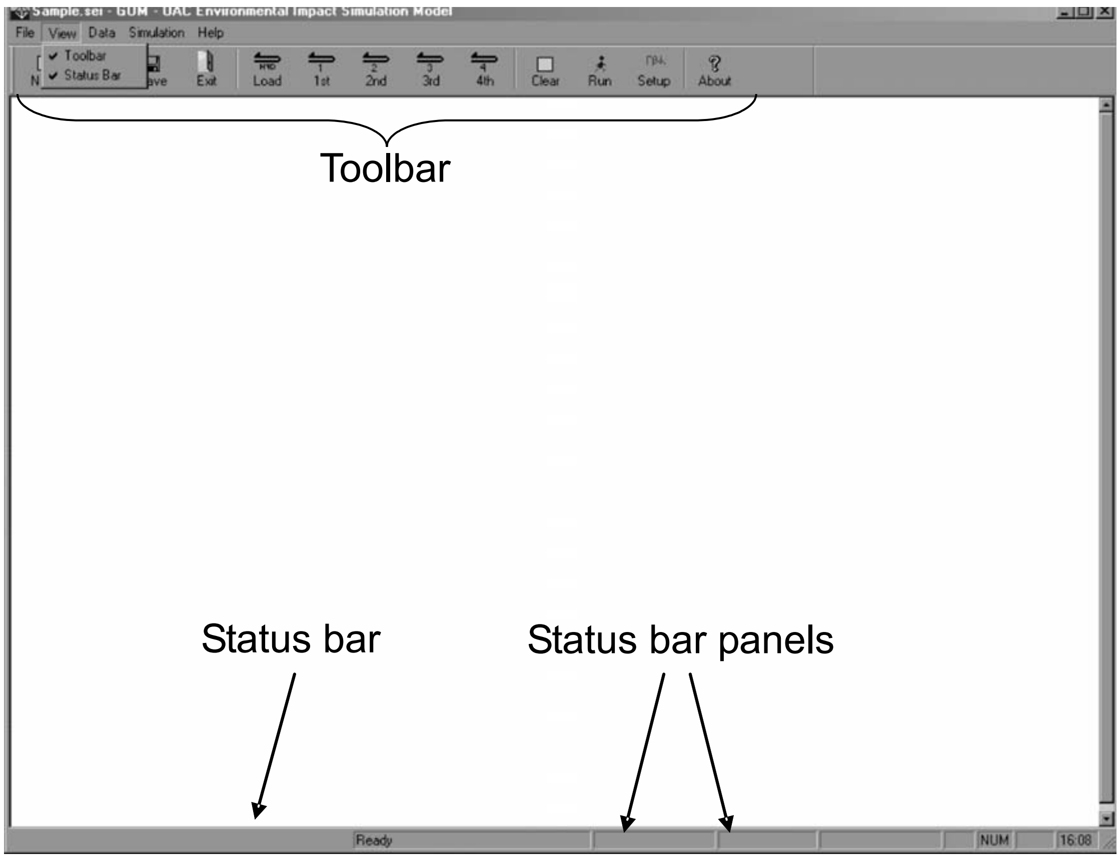
SEI was designed to simulate the fate of individual feces and feed pellets (referred to as pellets hereto forth) after their exit to the open water from the physical bounds of a fish cage. SEI simulates each pellet individually during one day for the duration of up to a year. Simulating individual pellets makes the program more realistic than approaches dealing with average pellets over extended time periods. While this approach is more realistic it also increases the computational complexity of the model and time required to process the fate of all pellets exiting the fish cage.

The underlying model in SEI is based upon a suite of variables that represent processes within the cage, in the open water, and in the sediment (Fig. 2). In the end, SEI only simulates the effects of pellets exiting the cage on the sediment.

SEI simulations are based on uniform and Gaussian random numbers. Computer routines may be executed many times during each simulation due to the potentially high number of pellets released by the simulated fish cage. To minimize sequential autocorrelations, SEI avoids linear congruential methods (Devroye 1986; Knuth 1997) for generating random numbers, compromising speed in favor of accuracy.

All estimates of spread around mean values of the variables in SEI are assumed normally distributed. Uniform deviates for generating normal deviates follow the algorithm by Park and Miller (Press et al. 1997). The period of that algorithm is estimated at approximately 2.1×10^9, which is below the number of random values we generated in any simulation scenario. Generation of normal random

Fig. 1. The SEI program has the look and feel of most Windows-based commercial software packages in that it consists of a menu-driven window with dialog boxes.

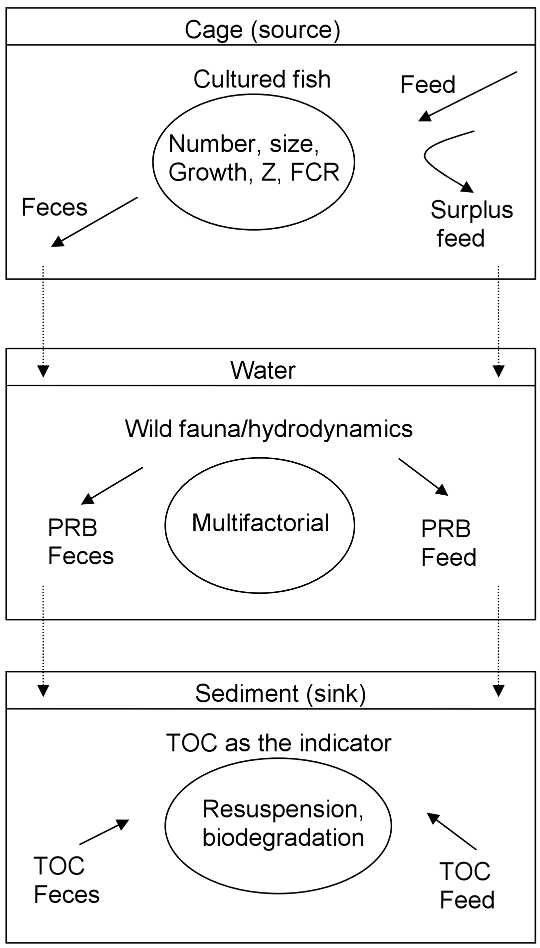


deviates followed the algorithm developed by Box and Muller (Bratley et al. 1987).

Variables within SEI for calculating the number of pellets leaving the cage into the open ocean reflect fish biomass and the management practices of the farm. The fish density per cage, fish average monthly weight, and fish mortality estimates fish biomass. Biomass, in turn, will affect fish feces production and wasted feed, which are the only factors in SEI contributing to sediment total organic carbon (TOC) accumulation. Fish mortality is estimated by a negative exponential function (Ricker 1975). Fish feces production is estimated according to Findlay and Watling (1994) and wasted feed according to Silvert (1994).

SEI uses local hydrology data, pellet settling speed, and the probability of pellets reaching the sediment to simulate the fate of pellets between the cage and the ocean floor. Hydrology data are ocean current speed and direction for the time the pellet is settling to the bottom. That time is determined from data on pellet settling speed and depth of the farm site. Hydrology data also includes the coefficient of variation for both current speed and direction. The coefficient of variation is used

Fig. 2. Simulation for Environmental Impact model components and driving variables of processes determining total organic carbon accumulation on sediment below a fish cage.



for adding a random component to the current acting on the settling pellet.

TOC in the top 5 cm of sediment is the impact indicator used within SEI. We used a 600 x 600 m impact grid because over 95 % of the pellets land on that area, given the hydrodynamic characteristics of our test site. To compromise accuracy and simulation time, we used a 1 m^2 patch (grid cell) on the impact grid as the minimum area of impact.

Once the pellet is on the bottom, SEI indirectly estimates pellet attrition due to resuspension or consumption. Attrition estimates are calculated as the TOC ratio between values from the previous and present months. The ratio is used to adjust impact downward. As an example, if the TOC ratio between the previous and present month is 2 (previous month with twice TOC), the estimated impact from pellets is adjusted to half. No adjustments are made if the ratio is one or smaller.

SEI considers sediment type by using the weight of a patch of sediment 1 m^2 x 5 cm. Weight was used as a surrogate for sediment compaction and fractionation. High weights imply compact sediments, which is less sensitive to the weight of an incoming settling pellet.

Accumulation of TOC in the sediment is calculated by SEI when the sediment TOC is less than the TOC in the pellet. Conversely, a decrease in sediment TOC is calculated when the sediment TOC is above that of the pellet. Accumulation of total organic carbon on sediment is modeled with the second-order equation:

$$y = TOC_{max} * (1 - e^{(K*W)})$$

where TOC_{max} is the asymptotic TOC value (maximum of sediment, feces, and pellet TOC values), K is the curve steepness (weight of TOC from pellet / weight of TOC in sediment), and W is the weight of pellet units fallen on that specific grid cell.

Attrition of TOC from the sediment is modeled using the exponential decay model:

$$y = e^{-W}$$

where W is as above.

SIMULATION SCENARIOS AND DRIVING VARIABLES

We chose a simulation reference site that was comparable to the Offshore Aquaculture Consortium (OAC) research site off Mississippi. The simulation reference site was located near a gas platform 40 km offshore. Simulation data for farm management were informed by economic modeling results presented by Posadas and Bridger (this volume). Posadas and Bridger (this volume) investigated the economic feasibility of offshore aquaculture in the northern Gulf of Mexico with cobia, red snapper, and red drum serving as likely candidate species. Cobia had an anticipated growth rate of 729 g/mo and an initial stocking density of 6 fish/m^3; red snapper had an anticipated growth rate of 46 g/mo and an initial stocking density of 67 fish/m^3; and, red drum had an anticipated growth rate of 100 g/mo and an initial stocking density of 33 fish/m^3. All three scenarios using 12–3,000 m^3 cages proved to be economically feasible and were, therefore, used in our simulations. We also added an estimate of 20% mortality to determine fish losses occurring at a fish farm and a starting stocking size of 10 g for all species (Posadas and Bridger, this volume).

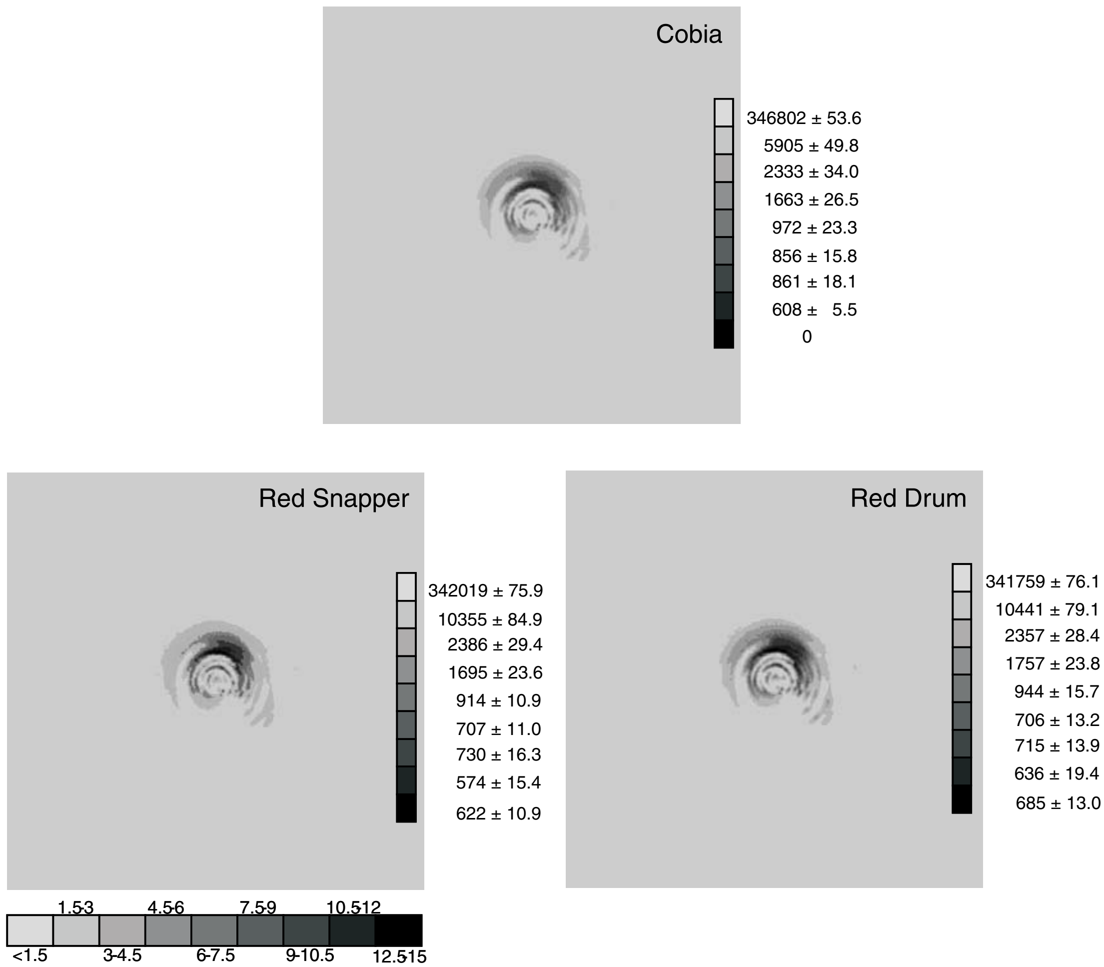
We considered the feed and feces leaving the cage to be the only source for impact on the sediment. The driving variables within the cage were average weight for a month of an individual fish, fish number in a cage, and food conversion ratio. Food conversion ratio was used to determine the amount of feed lost from the cage (Silvert 1994). The driving variables within the open water compartment were current speed and direction, and water depth. Current speed and direction were obtained from the National Ocean Service for 2001 at a reference site in the vicinity of the OAC research site. The coefficients of variation for current speed and direction were calculated from direct measurements with a current meter from our site during January and July 2001. Variation was obtained from thirty current speed and direction readings one minute apart at 5 m depth. The likelihood for the feed pellets to reach the bottom was set to 0.1 and for the feces pellet to 0.04 (Findlay and Watling 1994). The amount of feed given was fixed at 4% body weight, settling speed for feces was 10 cm/s and for feed pellets was 7.5 cm/s (Chen et al. 1999), and feces TOC was fixed at 12% and feed TOC was fixed at 15%. Sediment TOC was fixed at 0.9% and the weight of a 1 m^2 x 5 cm parcel was fixed at 150 kg. Grow-out times were nine months for cobia (March to December), and twelve months for red snapper and red drum (Posadas and Bridger, this volume).

ANALYTICAL APPROACH

Model output data was analyzed for the three species scenarios independently using ordinary kriging to represent TOC magnitude and extent on the impact grid. A spherical semi-variogram model was applied because it best fit the error structure of the data. An anisotropic model was also applied because of the presence of a directional component in the water circulation data for the year 2001 at our simulated location. To allow for visualization, TOC values were categorized into ranges. Nine equal sized ranges represented TOC values between 0 and 15.

To keep the scenarios comparable among species, simulations for cobia during an entire year was used but the impact was adjusted at each grid cell to 75% of that for the entire year. This adjustment was to correct the year-long simulation results to the expected nine month period (March–December) for cobia

Fig. 3. Effects of species farmed on the total organic carbon accumulation below a 3000 m^3 cage. Numbers down the scale bars are mean area (m^2) ± one standard deviation.



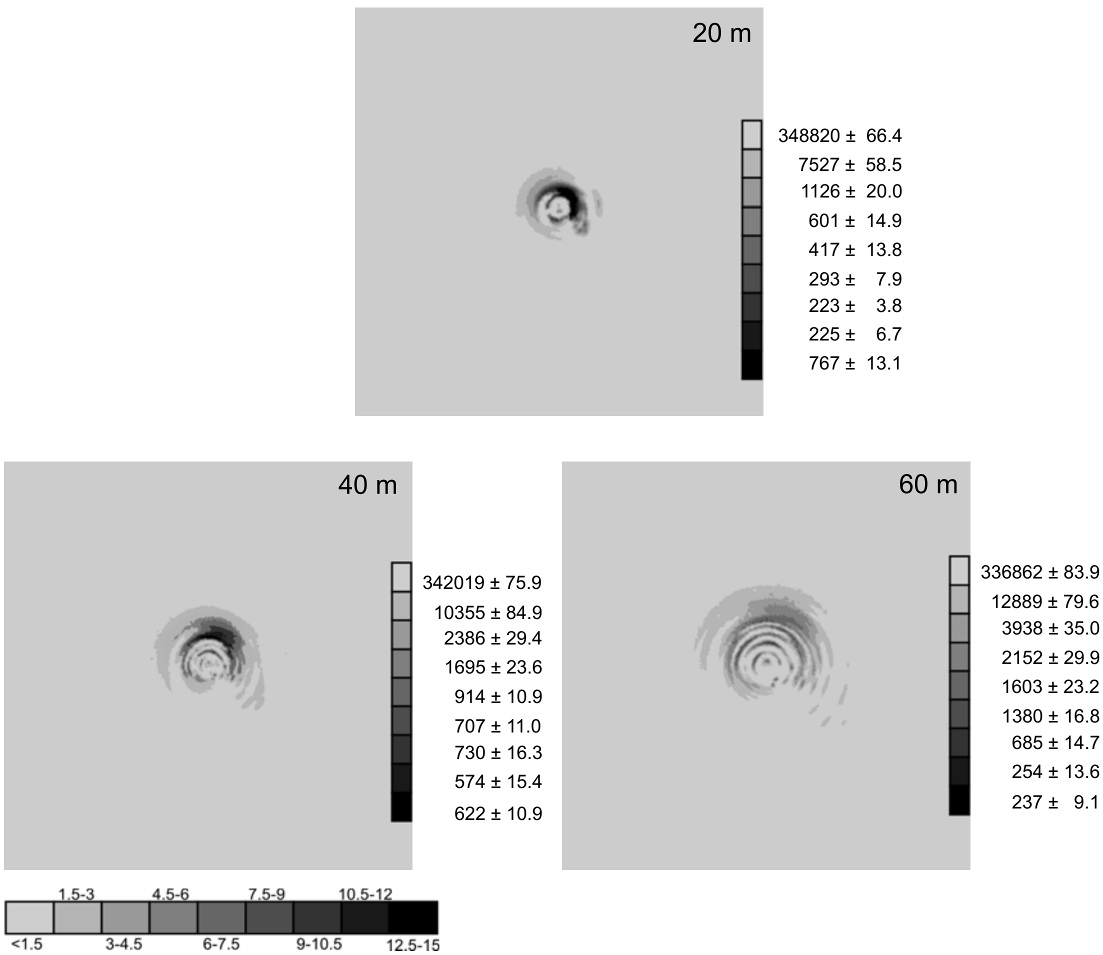
grow-out. The model was run over the twelve months to keep the circulation patterns identical among the cultured species.

RESULTS

The maximum possible TOC level, the TOC level at saturation, given the simulation data above is 15% (maximum among TOC sources). Lytle and Lytle (1982) report TOC levels of highly polluted areas in the Mississippi Sound of 10% and above. The level of TOC from our maximum range may, therefore, be considered environmentally detrimental.

Cobia produced the least impact among the three species, followed by red snapper, and red drum (Fig. 3). Red snapper and red drum had comparable effects on sediment TOC, even though the growth rate for red drum was twice that from red snapper. The area above 12% TOC for red drum was less

Fig. 4. Effect of depth on the total organic carbon accumulation on sediment below a red snapper 3000 m^3 cage. Numbers down the scale bars are mean area (m^2) ± one standard deviation.



than 1%, being possibly environmentally sustainable at the simulated depth.

The effect of depth on TOC accumulation demonstrates the potential for open ocean cage culture when environmental effects from that activity are detrimental in coastal areas. Our simulated results illustrated a 20% reduction in the TOC area above 12% when running the simulation from 20 to 40 m. We, however, observed a 62% reduction when running the simulation from 40 to 60 m (Fig. 4). Open ocean areas adequate for cage culture may be in deeper than 60 m, which may further assure that environmental impacts of that activity may be minimal when in deep, open ocean sites.

CONCLUSIONS

Environmental impacts from cage culture may include benthic carbon loading, water column nutrification, and stimulation of algal blooms. We only considered accumulation of TOC, which is a surrogate for a broad range of possible effects. A potential way to reduce the impacts of TOC accumulation on sediment, aside from site selection, is fallowing. When the impacts of multiple cages become environmentally unsustainable, one may consider setting aside a farm site for the duration of several months to a year. Appropriate site selection coupled with fallowing, particularly with respect to depth, may enable farms to operate in areas small enough to avoid user conflicts, yet have an enough number of cages to be profitable.

Benthic impacts from feed and fish feces are a function of site selection, management decisions, and site overproduction, which are variables not well understood in the yet incipient industry of cage culture in the offshore environment. The use of environmental impact assessment models may shed light into those variables to assure that the offshore cage culture industry is able to cohabit with all other industry sectors exploiting ocean resources. The incorporation of such models will initially fall largely on the extension community to provide the technology transfer and necessary advice to the new industry. Appropriate site selection and optimal environmental management decisions are essential to keep offshore cage culture a viable option for fish production. Models such as the one presented here are tools for making unbiased and effective decisions toward that goal. Additional research is necessary to validate model results with data collected from operating open ocean aquaculture ventures prior to industry usage of the simulation model for site selection and management planning purposes.

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CHAPTER 7

ECONOMIC FEASIBILITY & IMPACT OF OFFSHORE AQUACULTURE IN THE GULF OF MEXICO[1]

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ABSTRACT

An offshore aquaculture industry in the Gulf of Mexico will never exist if this innovative business venture does not make economic sense. To more fully understand the economic potential of offshore aquaculture, that can also be effectively managed as determined by OAC researchers, we created a model to analyze the OAC hypothetical offshore aquaculture production system. This model is based on present expectations of technology and logistics mitigation of offshore grow-out, biology of suitable species, recommended usage and costs of inputs, and established ex-vessel fish prices. Simulation results of each candidate species (i.e., cobia, red snapper, and red drum), with enhanced market value and improved growth rates over wild fishery data, and twelve cages having fish stocked at 30 kg/m^3 indicated a favorable investment project with positive net present value and internal rates of return. Given these favorable results, we conducted further economic analyses to determine the potential economic impact of an offshore aquaculture industry on the local economy. The operation of a 12-cage offshore production system would produce an additional annual regional economic output reaching more than U.S. $9 million and provide additional employment for at least 262 persons.

INTRODUCTION

Total seafood consumption has been steadily growing in the U.S. Even if per capita consumption remained unchanged at 6.8 kg/yr, a 1% increase in the U.S. population growth alone would add more than 18 x 10^6 kg to the demand for seafood each year. The domestic fishery can no longer supply additional landings of most wild caught species without endangering the resources. Increases in domestic demand will have to be met either through increased aquaculture production or increased imports. More than 2/3 of the seafood consumed in the U.S. is imported resulting in more than U.S. $8 billion deficit in the nation's seafood trade balance (USDC 2003). Many species heavily imported are currently being overexploited worldwide causing further need to become dependent on domestic aquaculture production.

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Economic benefits from aquaculture production accrue not only to those directly involved in the industry but contribute to increased employment and revenue of the entire region through multiplier effects. Aquaculture can also supplement domestic fisheries, increase seafood production, and provide stability for the seafood industry. A successful approach to solving many present domestic fishery problems is through the development of intensive aquaculture programs in the United States, such as the farm raised catfish industry centered in the Mississippi Delta region. Aquaculture has been established in the U.S. for more than 100 yr, but it remains relatively undeveloped in comparison to the rest of the world. While farmed seafood contributes more than 25% by weight to world seafood production, U.S. production is less than 3% of world aquaculture production. In recent years, however, U.S. production has grown to more than 371,000 metric tons (mt; USDC 2003).

Coastal and offshore aquaculture frequently involves new species, product forms, and production technologies. During the last decade, several species have been raised along the Gulf of Mexico including catfish, baitfish, gamefish, soft shell crab, crawfish, red drum, hybrid striped bass, tilapia, alligators, freshwater prawns, oysters, and carp. Because research and development efforts have been focused on production, little attention has been paid to linking aquaculture with existing support services or to developing needed infrastructure. Essential seafood services such as processing, storage, transportation, financing, insurance, and personnel training already exist in the coastal region.

Determination of cost projections for offshore aquaculture production systems is useful to determine the viability of such operations under present and future economic conditions. Information on production costs allows economists and scientists to discuss major contributing cost factors with a goal of focusing future research efforts toward reducing these costs and increasing profitability. Engle (1989) stated that profitability is difficult to measure for new technologies not yet adopted on a commercial scale. It is precisely at this point in the development of an innovation, however, that information relative to the economics of the new technology is most useful. Cost estimation provides information on the production efficiency of the new technology and as a base for future comparisons. Careful assessment of benefits arising from the new technology leads to the estimation of potential revenues. Once the benefits and costs associated with the new technology are determined, revenues can be compared with costs by using enterprise budgets (Posadas and Dillard 1997; Posadas 2000). The profit motive of fish farmers to adopt a technology would be met if the expected marginal benefits were equal to the estimated marginal costs of constructing and operating new systems. Every fish farmer, lender, and investor is concerned with the employment of scarce capital to its most productive use.

Our economic research efforts have focused on the potential of offshore aquaculture of candidate finfish species in the Gulf of Mexico. Specifically, we attempted to determine the:

1. economic feasibility of offshore aquaculture in the Gulf of Mexico at the individual farm scale under different economic and biological scenarios;

2. economic impact of an emerging offshore aquaculture industry and existing

fish harvesting and processing industry on the regional economy; and,

3. most efficient means to transport commercial quantities of fingerlings to a distant offshore aquaculture site from an economic perspective.

ECONOMIC FEASIBILITY OF OFFSHORE AQUACULTURE

Methods

A hypothetical commercial offshore aquaculture production system (COAPS) is constructed based on present information of offshore grow-out technology and biology of suitable species in the Gulf of Mexico. Numerous researchers have indicated that existing oil and gas structures may be utilized for open ocean aquaculture platforms (Stickney 1999). Owing to expected constraints (i.e., dependence, sub-optimal structure, liability, cost, and inappropriate site selection for aquaculture), however, an alternative approach should be considered for the future of offshore aquaculture in the Gulf of Mexico (Bridger and Goudey, this volume). Therefore, the hypothetical offshore fish farm presented consists of an Aquaculture Support Vessel (ASV) and appropriate offshore cages. The ASV, which is presently under consideration, is envisioned as a mobile offshore support structure that can be used to adjust deployment of the sea cages. It may also serve as offshore quarters for the crew (1 supervisor and 3 farm crew/shift), storage for feed and supplies, and transport for fish to be harvested.

Based on present OAC experience, the 3000-m^3 cages are deployed 40 km offshore, in water at least 24 m deep, and able to hold 20–30 kg/m^3 of market-size fish (Bridger and Costa-Pierce 2002). The base model scenario has six cages. Two service boats are used at the offshore farm for daily operations, maintenance, and harvesting. A supply boat and crew are hired to transport fingerlings, farm crew, and supplies, on an operation determined basis. Initially, fingerlings are purchased from commercial nurseries located within the region, which in the future may be integrated in the aquaculture operation. Slow sinking marine species feed is bought in bulk from nearby commercial feed manufacturing plants. An additional harvesting crew is employed to harvest fish from each cage on a regular basis. Office staff (1 manager and 2 office staff) housed in a building located in a 0.8-hectare land-based facility undertakes initial marketing of fish.

An enterprise budget is created for the hypothetical base COAPS, including investment requirements, operating costs, and net returns. Initial investment requirements for COAPS are based on OAC scientist and industrial partner specifications. Total costs of COAPS include both operating and ownership costs. Operational expenditures are based on estimated input usage and costs. Input usage is based on recommended management practices and biological knowledge of candidate finfish species. Ownership costs include depreciation, investment interest, management, and insurance for fish stock and equipment. For the hypothetical base model using six offshore cages (BASE6), gross returns are estimated from the average established ex-vessel prices of all candidate finfish species combined and expected annual yields. Candidate species considered are red drum (*Sciaenops ocellatus*), red snapper (*Lutjanus campechanus*), and cobia (*Rachycentron canadum*). The BASE6 cages are stocked with 10-g fingerlings to give a final stocking density of 20 and 30 kg/m^3 of market-sized fish in

9 mo. Deviations from this base model included specific candidate species models using 6 and 12 cages/operation, increasing the price by $1/kg over the established ex-vessel price of each candidate species, improving fish growth through optimal farm management, and combined growth improvement and price increase scenarios. Presently, provisions for the costs of the permitting process and environmental monitoring are not included in the model. Further, the logistical problem of transporting feed and market-size fish has not been adequately examined at this stage. A comparison of three methods to transport fingerlings is provided below. Net returns from all COAPS simulations consisted of the difference between gross returns and total costs.

Investment analysis provides a mechanism for comparing alternative investment opportunities (Gittinger 1982; Robison and Barry 1996). It is recognized, however, that it will be difficult to extrapolate experimental data for purposes of doing investment analysis of hypothetical commercial-scale fish farming operations (Posadas 1998). A wide range of risks is involved in grow-out culture in the Gulf of Mexico associated with the uncertainty in output and prices. Output risks may include complete or partial loss of the crop due to natural disasters (e.g., hurricanes), poor survival, slow growth, lack of fingerlings, and technical malfunction. Risks associated with prices may arise from competition with wild harvests, imports, and land-based production. It is important to recognize that at this stage of offshore technology development, the various risks involved need to be managed in order to reduce their negative effects on the economic viability of this emerging industry.

In order to determine the economic viability of base COAPS models and their derivatives, three investment indicators are evaluated under different critical technical, biological, and economic scenarios. The net present value (NPV) is the sum of the discounted annual net benefits of an investment project (Shang 1990). If NPV > 0, the project is economically feasible; it is not feasible if NPV < 0; and, it is a break-even situation if NPV = 0 (Shang 1990). Internal rate of return (IRR) is the discount rate that makes the present value of the annual net benefits of an investment project equal to zero (Shang 1990). The decision rule used in determining the economic feasibility of an investment project using the IRR method is as follows: if IRR ≥ cost of capital (r), accept the project; otherwise, reject the project (Shang 1990). The payback period (PP) estimates the number of years to recover the initial investment out of the expected annual net income before any allowance for depreciation (Shang 1990).

Results and Discussion

Three candidate finfish species are considered for culture in the hypothetical COAPS. Cobia (*Rachycentron canadum*) has been successfully cultured in ponds and cages in Taiwan and can be grown to 7 kg in one year (I-Chiu Liao, Director General, Taiwan Fisheries Research Institute, personal communication). Phelps et al. (2000) showed that red snapper (*Lutjanus campechanus*) grew at a rate of 1.23 g/d in experimental 0.051 m^3 cages located in Gulf Shores, Alabama. Red drum (*Sciaenops ocellatus*) has been cultured in ponds and offshore cages in the Gulf of Mexico and reached 1 kg in 12 mo (Holt 2000).

The initial enterprise budget model (BASE6) for the hypothetical COAPS requires an initial fixed investment of $2.89 x 10^6 consisting of $1.50 x 10^6 for the ASV, $0.96 x 10^6 for six cages/mooring and associated equipment (i.e., net cleaners), $0.33 x

Table 1. Initial fixed investment in a base COAPS with 6-cages.

Item	Total Cost ($)	Per m^3 ($)	% of Total
Land and Permitting			
Land, base camp	80,000	4	3%
Sub-total	80,000	4	3%
Onshore Support Facilities			
Buildings, trailers	100,000	6	3%
Trucks/Service vehicle	50,000	3	2%
Fish transport vehicle	100,000	6	3%
Sub-total	250,000	14	9%
Offshore Operations			
Cages[1], moorings, feed distribution	900,000	50	31%
Aquaculture Service Vehicle	1,500,000	83	52%
Net cleaners	60,000	3	2%
Vessel (> 50', small outboard)	100,000	6	3%
Sub-total	2,560,000	142	89%
TOTAL	2,890,000	161	100%

[1]growing area is 3,000 m^3/cage.

10^6 for land and onshore support facilities, and \$0.10 x 10^6 for service vessels (Table 1). On average, initial fixed investment on a COAPS is \$161/m^3 of growing area. With stocking density of 30 kg/m^3, an operating capital of \$1.28 x 10^6 is needed to finance the cost of repair and maintenance, fuel and oil, fingerlings, feed, labor, supply boat and crew, harvesting and hauling, liability insurance, and miscellaneous expenses (Table 2).

Given the base model assumptions, an estimated 0.54 x 10^6 kg, 2.11-kg fish can be produced every 9-mo of offshore grow-out period. The estimated average cost of production is \$4.286/kg, consisting of \$2.641 and \$1.645/kg average variable and fixed costs, respectively. The major cost items are labor (22%), feed (20%), fingerlings (17%), repair and maintenance (13%), and supply boat (10%) for operating costs; and, depreciation (42%), farm management (25%), insurance on fish stocks and equipment (17%), and interest on investment (16%) for fixed costs (Table 2). At an average established ex-vessel price of \$4.25/kg whole, fresh on ice, annual net return is \$–0.02 x 10^6, payback period is indefinite, and net present value and internal rate of return are negative for the BASE6 model using 30 kg/m^3 stocking density (Table 3). A lower stocking assumption of 20 kg/m^3 produced similar economically unfavorable simulation results.

The BASE6 scenario can be considered as a benchmark for further economic and environmental analysis of COAPS under different technical, biological, and economic circumstances. At gross feed conversion (FCR) of 1.5:1.0, estimated total feed consumption was 0.54 and 0.81 thousand metric tons/crop for the 20 and 30 kg/m^3 stocking densities, respectively. The number of fingerlings needed was 213.66 and 320.40 thousand pieces/crop for the 20 and 30 kg/m^3 stocking densities, respectively.

Species-specific evaluations were generated by applying best available information on growth rate and established ex-vessel price of

Table 2. Total annual costs and returns of a base COAPS[1] with 6 cages using stocking density of 30 kg/m^3.

Item	Total Cost ($)	Per m^3 ($)	Per kg ($)	% of Total
Gross receipts	2,297,952	766	4.255	
Variable Costs				
Repair and maintenance	188,500	63	0.349	13%
Fuel & oil	30,000	10	0.056	2%
Fingerlings	240,300	80	0.445	17%
Feed	283,537	95	0.525	20%
Labor	312,500	104	0.579	22%
Harvesting & hauling	47,626	16	0.088	3%
Liability insurance	30,000	10	0.056	2%
Supply boat	144,000	48	0.267	10%
Miscellaneous	54,000	18	0.100	4%
Operating interest	95,735	32	0.177	7%
Total variable costs	1,426,197	475	2.641	100%
Income above variable costs	871,754	291	1.614	
Fixed Costs				
Depreciation	377,000	126	0.698	42%
Farm management	218,750	73	0.405	25%
Interest on investment	144,500	48	0.268	16%
Insurance on stocks & equipment	148,118	49	0.274	17%
Total fixed costs	888,368	296	1.645	100%
Total Costs	2,314,565	772	4.286	
Net Returns	(16,614)	(6)	(0.031)	

1- stocking size - 10 g/fish; stocking density - 17.8 fish/m^3; growth rate - 233 g/mo; gross feed conversion - 1.5 kg of feed per kg of fish; survival rate - 80%; capital outlay - $2.89 M; ex-vessel price - $4.25/kg; grow-out period - 9 mo; harvest size - 2.11 kg/fish.

the three candidate finfish species to the BASE6 model. Simulation results using both stocking densities, 20 and 30 kg/m^3, showed that none of the three species has economic potential (Table 4). Since it is still under development, it is assumed that one ASV unit can adequately provide support services to 12 offshore cages and accommodate 12 persons during regular aquaculture and rotating harvesting operations. With 12 offshore cages, the average initial fixed investment decreases accordingly to $107/m^3 of growing area. By expanding growing capacity to 12 cages/operation, simulation results using the higher stocking density indicated that cobia is an economically viable species for offshore culture in the Gulf of Mexico (Table 5).

The culture of red snapper and red drum using commercial offshore cages and the ASV in the Gulf of Mexico is not economically feasible given the current biological information, cost structure of the offshore production technology, and established ex-vessel market prices of the selected species. Both base and expanded model simulation results indicated that the two proposed investment projects are not favorable (PP = indefinite, IRR < 0 and NPV < 0; Tables 4 and 5).

The economic and biological constraints to finfish offshore aquaculture in the Gulf of Mexico could be adequately managed to promote the growth of this emerging industry. Economic feasibility of offshore grow-out of

Table 3. Simulation results of base COAPS model with 6 cages (BASE6) using two stocking densities.

Item	Unit	20 kg/m^3	30 kg/m^3
Model Assumptions[1]			
Stocking density	fish/m^3	11.87	17.80
Model Description			
Harvest size	kg/fish	2.11	2.11
Fingerlings required	1,000 pc	213.66	320.40
Fish production	1,000 mt	0.36	0.54
Feed required	1,000 mt	0.54	0.81
Model Results			
Net returns	$M	(0.55)	(0.02)
Payback period	yr	∝	∝
NPV	$M	< 0	< 0
IRR	%	< 0	< 0
Investment Decision		Infeasible	Infeasible

1- stocking size - 10 g/fish; growth rate - 233 g/mo; gross feed conversion - 1.5 kg of feed per kg of fish; survival rate - 80%; capital outlay - $2.89 M; ex-vessel price - $4.25/kg; grow-out period - 9 mo.

the selected species can be enhanced by a combination of revenue-enhancing and cost-reducing measures, including improvement in fish growth and market development. Changes in ex-vessel prices influence the economic feasibility of offshore aquaculture in the Gulf of Mexico. The most recent reported commercial landings of red drum, red snapper, and cobia in the Gulf of Mexico were valued at an average ex-vessel price of $3.75, $4.50, and $4.25/kg, respectively.

Simulation results of the ENHANCED MARKET models led to mixed investment decisions should prices received be $1.00/kg higher than the reported ex-vessel prices, *ceteris paribus*. The ENHANCED MARKET base model results indicated that only the proposed 6-cage COAPS at higher stocking density for cobia in the Gulf of Mexico would be economically feasible (Table 6). Simulation results on the ENHANCED MARKET base models for red snapper and red drum, however, indicated that the use of the proposed 6-cage COAPS for these species would not be economically viable (Table 6). With expanded growing capacity of 12-cages/operation, all three species have the potential of being economically viable at the higher ex-vessel price ($1.00/kg more) and higher stocking density (30 kg/m^3; Table 7).

A moderate improvement (25%) in fish growth rate does not have any significant effects on the economic viability of the offshore culture of the three species in the Gulf of Mexico, *ceteris paribus*. An increase in fish growth rates by 25% and the corresponding reduction in stocking density in order to maintain the maximum biomass of market-size fish at 20 and 30 kg/m^3, *ceteris paribus*, is not sufficient to enhance economic performance of the 6-cage COAPS as shown by the simulation results of the IMPROVED GROWTH models (Table 8). The expansion of the growing capacity to 12 cages/operation at both stocking densities did not improve the economic potential of red snapper and red drum grow-out culture in the Gulf of Mexico (Table 9).

The combined effects of IMPROVED GROWTH and ENHANCED MARKET models on the aquaculture of individual candidate

Table 4. Simulation results of COAPS candidate species base models with 6 cages (SPECIES6) using two stocking densities.

Item	Unit	COBIA6		SNAP6		DRUM6	
		20 kg/m^3	30 kg/m^3	20 kg/m^3	30 kg/m^3	20 kg/m^3	30 kg/m^3
Model Assumptions[1]							
Stocking density	$fish/m^3$	4.75	7.13	55.06	82.60	27.49	41.24
Growth rate	g/mo	583.00	583.00	37.00	37.00	80.00	80.00
Ex-vessel price	$/kg	4.25	4.25	4.50	4.50	3.75	3.75
Model Description							
Harvest size	kg/fish	5.25	5.25	0.45	0.45	0.97	0.97
Fingerlings used	1,000 pc	85.00	128.34	991.08	1,468.80	494.82	742.23
Fish production	1,000 mt	0.36	0.54	0.36	0.54	0.36	0.54
Feed required	1,000 mt	0.54	0.81	0.54	0.81	0.54	0.81
Model Results							
Net returns	$M	(0.65)	(0.17)	(0.20)	(0.95)	(1.05)	(0.73)
Payback period	yr	∝	∝	∝	∝	∝	∝
NPV	$M	<0	<0	<0	<0	<0	<0
IRR	%	<0	<0	<0	<0	<0	<0
Investment Decision		Infeasible	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible

1- stocking size - 10 g/fish; gross feed conversion - 1.5 kg of feed per kg of fish; survival rate - 80%; capital outlay - $2.89 M; grow-out period - 9 mo for cobia and 12 mo for red snapper and red drum.

Table 5. Simulation results of COAPS candidate species expanded models with 12 cages (SPECIES12) using two stocking densities.

Item	Unit	COBIA12		SNAP12		DRUM12	
		20 kg/m^3	30 kg/m^3	20 kg/m^3	30 kg/m^3	20 kg/m^3	30 kg/m^3
Model Assumptions[1]							
Stocking density	$fish/m^3$	4.75	7.13	55.06	82.60	27.49	41.24
Growth rate	g/mo	583.00	583.00	37.00	37.00	80.00	80.00
Ex-vessel price	$/kg	4.25	4.25	4.50	4.50	3.75	3.75
Model Description							
Harvest size	kg/fish	5.25	5.25	0.45	0.45	0.97	0.97
Fingerlings used	1,000 pc	171.00	256.68	1,982.16	2,973.60	989.64	1,484.46
Fish production	1,000 mt	0.72	1.08	0.72	1.08	0.72	1.08
Feed required	1,000 mt	1.08	1.62	1.08	1.62	1.08	1.62
Model Results							
Net returns	$M	(0.13)	0.83	(1.14)	(0.64)	(0.84)	(0.19)
Payback period	yr	∝	4.70	∝	∝	∝	∝
NPV $M	<0	3.17	<0	<0	<0	<0	
IRR %	<0	29.24	<0	<0	<0	<0	
Investment Decision		Infeasible	**Feasible**	Infeasible	Infeasible	Infeasible	Infeasible

1- stocking size - 10 g/fish; gross feed conversion - 1.5 kg of feed per kg of fish; survival rate - 80%; capital outlay - $3.85 M; grow-out period - 9 mo for cobia and 12 mo for red snapper and red drum.

Table 6. Simulation results of COAPS candidate species ENHANCED MARKET base models with 6 cages using two stocking densities.

		COBIA6		SNAP6		DRUM6	
Item	**Unit**	**20 kg/m^3**	**30 kg/m^3**	**20 kg/m^3**	**30 kg/m^3**	**20 kg/m^3**	**30 kg/m^3**
Model Assumptions[1]							
Stocking density	fish/m^3	4.75	7.13	55.06	82.60	27.49	41.24
Growth rate	g/mo	583.00	583.00	37.00	37.00	80.00	80.00
Ex-vessel price	$/kg	5.25	5.25	5.50	5.50	4.75	4.75
Model Description							
Harvest size	kg/fish	5.25	5.25	0.45	0.45	0.97	0.97
Fingerlings used	1,000 pc	85.50	128.34	991.08	1,486.80	494.82	742.32
Fish production	1,000 mt	0.36	0.54	0.36	0.54	0.36	0.54
Feed required	1,000 mt	0.54	0.81	0.54	0.81	0.54	0.81
Model Results							
Net returns	$M	(0.31)	0.34	(0.86)	(0.44)	(0.71)	(0.21)
Payback period	yr	∝	8.54	∝	∝	∝	∝
NPV $M	<0	0.83	<0	<0	<0	<0	
IRR	%	<0	17.04	<0	<0	<0	<0
Investment Decision		Infeasible	**Feasible**	Infeasible	Infeasible	Infeasible	Infeasible

1- stocking size - 10 g/fish; gross feed conversion - 1.5 kg of feed per kg of fish; survival rate - 80%; capital outlay - $2.89 M; grow-out period - 9 mo for cobia and 12 mo for red snapper and red drum.

Table 7. Simulation results of COAPS candidate species ENHANCED MARKET expanded models with 12 cages using two stocking densities.

		COBIA12		SNAP12		DRUM12	
Item	**Unit**	**20 kg/m^3**	**30 kg/m^3**	**20 kg/m^3**	**30 kg/m^3**	**20 kg/m^3**	**30 kg/m^3**
Model Assumptions[1]							
Stocking density	fish/m^3	4.75	7.13	55.06	82.60	27.49	41.24
Growth rate	g/mo	583.00	583.00	37.00	37.00	80.00	80.00
Ex-vessel price	$/kg	5.25	5.25	5.50	5.50	4.75	4.75
Model Description							
Harvest size	kg/fish	5.25	5.25	0.45	0.45	0.97	0.97
Fingerlings used	1,000 pc	171.00	256.68	1,982.16	2,973.60	989.64	1,484.64
Fish production	1,000 mt	0.72	1.08	0.72	1.08	0.72	1.08
Feed required	1,000 mt	1.08	1.62	1.08	1.62	1.08	1.62
Model Results							
Net returns	$M	0.57	1.87	(0.45)	0.39	(0.15)	0.84
Payback period	yr	6.92	2.09	∝	9.94	∝	4.63
NPV	$M	1.70	8.87	<0	0.76	<0	3.24
IRR	%	20.78	59.08	<0	14.97	<0	29.63
Investment Decision		**Feasible**	**Feasible**	Infeasible	**Feasible**	Infeasible	**Feasible**

1- stocking size - 10 g/fish; gross feed conversion - 1.5 kg of feed per kg of fish; survival rate - 80%; capital outlay - $3.85 M; grow-out period - 9 mo for cobia and 12 mo for red snapper and red drum.

Table 8. Simulation results of COAPS candidate species IMPROVED GROWTH base models with 6 cages using two stocking densities.

		COBIA6		SNAP6		DRUM6	
Item	**Unit**	**20 kg/m^3**	**30 kg/m3**	**20 kg/m^3**	**30 kg/m^3**	**20 kg/m^3**	**30 kg/m^3**
Model Assumptions[1]							
Stocking density	fish/m^3	3.80	5.70	44.49	66.74	22.04	33.06
Growth rate	g/mo	729.00	729.00	46.00	46.00	100.00	100.00
Ex-vessel price	$/kg	4.25	4.25	4.50	4.50	3.75	3.75
Model Description							
Harvest size	kg/fish	6.57	6.57	0.56	0.56	1.21	1.21
Fingerlings used	1,000 pc	68.40	102.60	800.05	1,201.20	396.72	595.08
Fish production	1,000 mt	0.36	0.54	0.36	0.54	0.36	0.54
Feed required	1,000 mt	0.54	0.81	0.54	0.81	0.54	0.81
Model Results							
Net returns	$M	(0.64)	(0.16)	(1.04)	(0.72)	(0.97)	(0.61)
Payback period	yr	∝	∝	∝	∝	∝	
NPV	$M	<0	<0	<0	<0	<0	<0
IRR	%	<0	<0	<0	<0	<0	<0
Investment Decision		Infeasible	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible

1- stocking size - 10 g/fish; gross feed conversion - 1.5 kg of feed per kg of fish; survival rate - 80%; capital outlay - $2.89 M; grow-out period - 9 mo for cobia and 12 mo for red snapper and red drum.

species in the Gulf of Mexico are encouraging (Tables 10 and 11). With a simultaneous improvement in fish growth (25%) and price increase ($1/kg), the three candidate species are economically viable at the higher stocking density (30 kg/m^3) and 12 cages in operation (Table 11). With 12 cages in operation, only the culture of cobia is economically viable at the lower stocking density (20 kg/m^3).

Summary

In order to achieve the objectives of this study, several activities were conducted leading to the evaluation of the economic potential of finfish offshore grow-out in the Gulf of Mexico. A hypothetical commercial offshore aquaculture production system (COAPS) was developed based on present information on offshore grow-out technology in the Gulf of Mexico. The projected costs and returns of COAPS were estimated based on recommended management practices, biological knowledge of targeted candidate finfish species, estimated input usage and prices, and established ex-vessel fish prices. Simulation models were developed to evaluate the economic viability of COAPS under different economic and biological scenarios relating to the grow-out of selected species in the Gulf of Mexico.

Simulation results suggested encouraging but limited investment options regarding the culture of cobia, red snapper, and red drum in the Gulf of Mexico, given the biological and economic assumptions of the models. The offshore grow-out of cobia in the Gulf of Mexico is economically feasible when using a 12-cage operation and stocking at the higher density or prices received are $1.00/kg more than reported ex-vessel prices. A simultaneous $1.00/kg increase in prices received, 12-cage growing capacity, and higher stocking density would make offshore grow-out of red snapper and red drum in the Gulf of Mexico economically feasible.

These simulation results are considered preliminary since the models are based on

Table 9. Simulation results of COAPS candidate species IMPROVED GROWTH expanded models with 12 cages using two stocking densities.

Item	Unit	COBIA12		SNAP12		DRUM12	
		20 kg/m^3	30 kg/m^3	20 kg/m^3	30 kg/m^3	20 kg/m^3	30 kg/m^3
Model Assumptions[1]							
Stocking density	fish/m^3	3.80	5.70	44.49	66.74	22.04	33.06
Growth rate	g/mo	729.00	729.00	46.00	46.00	100.00	100.00
Ex-vessel price	$/kg	4.25	4.25	4.50	4.50	3.75	3.75
Model Description							
Harvest size	kg/fish	6.57	6.57	0.56	0.56	1.21	1.21
Fingerlings used	1,000 pc	136.80	205.20	1,601.64	2,402.46	793.44	1,190.16
Fish production	1,000 mt	0.72	1.08	0.72	1.08	0.72	1.08
Feed required	1,000 mt	1.08	1.62	1.08	1.62	1.08	1.62
Model Results							
Net returns	$M	(0.97)	0.87	(0.82)	(0.17)	(0.68)	0.05
Payback period	yr	∝	4.49	∝	∝	∝	∝
NPV	$M	<0	3.39	<0	<0	<0	<0
IRR	%	<0	30.45	<0	<0	<0	1.84
Investment Decision		Infeasible	**Feasible**	Infeasible	Infeasible	Infeasible	Infeasible

1- stocking size - 10 g/fish; gross feed conversion - 1.5 kg of feed per kg of fish; survival rate - 80%; capital outlay - $3.85 M; grow-out period - 9 mo for cobia and 12 mo for red snapper and red drum.

Table 10. Simulation results of COAPS candidate species combined ENHANCED MARKET and IMPROVED GROWTH base models with 6 cages using two stocking densities.

Item	Unit	COBIA6		SNAP6		DRUM6	
		20 kg/m^3	30 kg/m^3	20 kg/m^3	30 kg/m^3	20 kg/m^3	30 kg/m^3
Model Assumptions[1]							
Stocking density	fish/m^3	3.80	5.70	44.49	66.74	22.04	33.06
Growth rate	g/mo	729.00	729.00	46.00	46.00	100.00	100.00
Ex-vessel price	$/kg	5.25	5.25	5.50	5.50	4.75	4.75
Model Description							
Harvest size	kg/fish	6.57	6.57	0.56	0.56	1.21	1.21
Fingerlings used	1,000 pc	68.40	102.60	800.82	1,201.32	396.72	595.08
Fish production	1,000 mt	0.36	0.54	0.36	0.54	0.36	0.54
Feed required	1,000 mt	0.54	0.81	0.54	0.81	0.54	0.81
Model Results							
Net returns	$M	(0.29)	0.36	(0.70)	(0.20)	(0.63)	(0.09)
Payback period	yr	∝	8.09	∝	∝	∝	∝
NPV	$M	<0 0.93	<0	<0	<0	<0	
IRR	%	<0	17.90	<0	<0	<0	<0
Investment Decision		Infeasible	**Feasible**	Infeasible	Infeasible	Infeasible	Infeasible

1- stocking size - 10 g/fish; gross feed conversion - 1.5 kg of feed per kg of fish; survival rate - 80%; capital outlay - $2.89 M; grow-out period - 9 mo for cobia and 12 mo for red snapper and red drum.

hypothetical or “best guess” scenarios. Further research is required to discover new markets for selected species, verifying biological assumptions of the models, and solving logistical problems involved in the construction and operation of an offshore production system in the Gulf of Mexico. To achieve sustainability, the costs of monitoring and maintaining a suitable environment surrounding the offshore operation should be considered in later evaluations.

ECONOMIC IMPACT OF OFFSHORE AQUACULTURE

Methods

The potential economic impact of operating a single COAPS, consisting of a single ASV and 12 offshore aquaculture cages, as previously described, was estimated by using IMPLAN Professional 2.0 Software and the 2000 Gulf of Mexico States IMPLAN data files, including Florida, Alabama, Mississippi, Louisiana and Texas. These impact planning software and data files facilitated the estimation of economic impacts with the use of the most appropriate multipliers (MIG 1999).

Two series of economic impact estimates were prepared for the offshore aquaculture industry. The first series of estimates included those associated with the initial investment expenditures that would be incurred during the establishment or construction year. The second series of estimates covered those annual expenditures that would be incurred in operating the COAPS. Offshore aquaculture production facilities would also enhance both commercial and recreational fishing opportunities in the nearby waters by serving as a fish aggregating device (Costa-Pierce and Bridger 2002). Additional production of the candidate species would also increase processing and distribution activities in both existing and new processing and distribution plants.

The COAPS sector was represented by the “Miscellaneous Livestock ” IMPLAN sector 9 which corresponded to the 1987 Bureau of Economic Analysis (BEA) Standard Industrial Classification (SIC) codes 0271 and 0272 (MIG 1999). The commercial seafood processing sector involves plants engaged in primary wholesale and processing activities. IMPLAN sector “Prepared Fresh or Frozen Fish or Seafood, 98” corresponded to the 1987 BEA-SIC code 2092 (MIG 1999). Commercial harvesting is represented by IMPLAN sector 25, which corresponded to the 1987 BEA-SIC code 0910 (MIG 1999). The ex-vessel values of the Gulf of Mexico commercial fishing sector were retrieved from the NMFS (2004) website.

Extrapolating a potential offshore aquaculture industry from these hypothetical COAPS models is difficult. Several key economic and marketing issues need to be addressed when projecting an industry-wide economic impact of offshore aquaculture from multiple COAPS, each consisting of 12-cages. There is no published inventory of suitable offshore areas for offshore aquaculture operations that lack conflicts with present and future users of these marine resources. Reliable information to predict the reaction of the domestic market to further product supplies of the cultured species arising from offshore aquaculture and imports from foreign producers are nonexistent. Public perceptions, legal and political mind-sets, and environmental constraints associated with offshore aquaculture, required to make the investment climate more favorable, have also not been addressed. Finally, present regulations affecting the harvesting, production and marketing of the candidate species in both state and fed-

Table 11. Simulation results of COAPS candidate species combined ENHANCED MARKET and IMPROVED GROWTH expanded models with 12 cages using two stocking densities.

Item	Unit	COBIA12 20 kg/m³	COBIA12 30 kg/m³	SNAP12 20 kg/m³	SNAP12 30 kg/m³	DRUM12 20 kg/m³	DRUM12 30 kg/m³
Model Assumptions[1]							
Stocking density	fish/m³	3.80	5.70	44.49	66.74	22.04	33.06
Growth rate	g/mo	729.00	729.00	46.00	46.00	100.00	100.00
Ex-vessel price	$/kg	5.25	5.25	5.50	5.50	4.75	4.75
Model Description							
Harvest size	kg/fish	6.57	6.57	0.56	0.56	1.21	1.21
Fingerlings used	1,000 pc	136.80	205.20	1,601.64	2,402.64	793.44	1,190.16
Fish production	1,000 mt	0.72	1.08	0.72	1.08	0.72	1.08
Feed required	1,000 mt	1.08	1.62	1.08	1.62	1.08	1.62
Model Results							
Net returns	$M	0.59	1.91	(0.13)	0.87	0.02	1.09
Payback period	yr	6.59	2.05	∝	4.52	250.24	3.60
NPV	$M	1.86	9.09	<0	3.36	<0	4.58
IRR	%	21.68	60.14	<0	30.27	0.33	36.93
Investment Decision		**Feasible**	**Feasible**	Infeasible	**Feasible**	Infeasible	**Feasible**

1- stocking size - 10 g/fish; gross feed conversion - 1.5 kg of feed per kg of fish; survival rate - 80%; capital outlay - $3.85 M; grow-out period - 9 mo for cobia and 12 mo for red snapper and red drum.

eral waters represent potential constraints every grower, lender or investor will have to consider prior to entrance into this novel aquaculture sector.

Results and Discussion

Impact of Initial Investment in a Single COAPS

The initial investment expenditures that would be incurred in establishing a single COAPS with 12 cages during its establishment year would generate additional output of economic goods and services valued at U.S. $6.84 million. Associated with this added economic activity would be an increase in the derived demand for 197 workers. The expected increase in labor income, which consists of employee compensation and proprietor's income, would reach U.S. $2.17 million. Indirect business tax collections are estimated at $210,870 (Table 12). Federal income tax collections would include $231,000 from personal income taxation and $59,000 from corporate income taxation.

Annual Impact of Operating a Single COAPS

A single COAPS with 12 cages stocked with either of the candidate species would require different levels of input usage, primarily fingerlings and feed (Table 11). Annual fish production would be 1.08 x 10^3 metric tons for all three species. Differences in ex-vessel prices would generate varying levels of annual fish sales: cobia—$5.67 x 10^6, red snapper—$5.94 x 10^6, and red drum—$5.13 x 10^6.

The economic impact to the Gulf of Mexico region, using the annual fish sales expected from the single COAPS with 12 cages, was measured using four indicators: output of goods and services, employment, labor income, and indirect business taxes (Table 13). Using the same 2000 Gulf of Mexico IMPLAN model, additional output produced would range from $9.1 x 10^6 to $10.2 x 10^6. The number of jobs created would be between 262–289 positions. The single COAPS would generate additional pro-

Table 12. Summary of economic impact of initial investment expenditures on a single COAPS using 12 cages incurred during the establishment year.

Item	Output ($\$ \times 10^6$)	Employment (jobs)	Labor Income ($\$ \times 10^6$)	Indirect Business Taxes $\$ \times 10^3$
Direct	3.85	156	1.17	46.33
Indirect	1.59	24	0.49	74.67
Induced	1.40	17	0.51	89.86
Total	6.84	197	2.17	210.86

prietor income and employee compensation ranging from $2.9 x 10^6 to $3.2 x 10^6. Annual indirect business taxes associated with the added output produced by a single COAPS would amount to at least $281,000. This tax collection does not include personal income taxation that could be collected from employment and ownership of the COAPS. Federal and state personal income tax collections from households would amount to $340,000 and $11,000, respectively. Tax collections from corporate profits would reach $87,000 and $4,000 for federal and state taxing authorities, respectively.

Impact of Current Commercial Fish Harvesting

Commercial harvesting of the candidate species is limited by state and federal regulations. Recent domestic commercial landings valued at ex-vessel prices exceeded U.S. $10 million. Using the same 2000 Gulf of Mexico IMPLAN model, the commercial landings valued at U.S. $12.4 million could have created an economic impact in the region amounting to U.S. $20.1 million output of goods and services if it were all landed in the Gulf of Mexico. A total of 628 jobs could have been created and a combined income of workers and proprietors could reach U.S. $10.3 million. Business establishments would also remit indirect business taxes amounting to $856.7 x 10^3 (Table 14).

Impact of Current Commercial Foodfish Processing

The 64 Gulf of Mexico processing plants engaged in the primary processing and wholesaling of foodfish handled a total plant-gate value of foodfish products amounting to U.S. $52.7 million in 2000 (NMFS 2004). By using the same 2000 Gulf of Mexico IMPLAN model, total economic impact of commercial foodfish processing reached U.S. $80.8 million. This sector also provided 769 jobs and generated U.S. $17.6 million in labor income for the region. Indirect business taxes collected from this sector amounted to U.S. $1.3 million (Table 15).

Sectoral Economic Linkages

The direct effects created by establishing and operating a single COAPS with 12 cages would generate indirect and induced effects. Indirect effects consist of the inter-industry effects of the input-output analysis. Induced effects consist of the impact of household expenditures in input-output analysis (MIG

Table 13. Summary of annual economic impact of a single COAPS using 12 cages stocked with candidate species under enhanced market and improved growth conditions.

	Output ($\$ \times 10^6$)			Employment (jobs)			Labor Income ($\$ \times 10^6$)			Indirect Business Taxes ($\$ \times 10^3$)		
Item	COBIA	SNAPPER	DRUM	COBIA	SNAPPER	DRUM	COBIA	SNAPPER	DRUM	COBIA	SNAPPER	DRUM
Direct	5.7	5.7	5.1	229	232	208	1.7	1.7	1.6	68.1	69.0	61.7
Indirect	2.3	2.4	2.1	35	36	32	0.7	0.7	0.6	109.8	111.2	99.5
Induced	2.1	2.1	1.9	25	25	22	0.7	0.8	0.7	132.2	133.8	119.7
Total	10.1	10.2	9.1	289	293	262	3.1	3.2	2.9	310.1	314.0	280.9

Table 14. Summary of annual economic impact of combined commercial fish harvesting of cobia, red snapper, and red drum in the Gulf of Mexico, 2000.

Item	Output ($ x 10^6)	Employment (jobs)	Labor Income ($ x 10^6)	Indirect Business Taxes ($ x 10^3)
Direct	12.4	586	7.6	389.9
Indirect	0.9	8	0.3	33.6
Induced	6.7	34	2.5	433.2
Total	19.0	628	10.4	856.7

Table 15. Summary of annual economic impact of commercial foodfish processing in the Gulf of Mexico, 2000.

Item	Output ($ x 10^6)	Employment (jobs)	Labor Income ($ x 10^6)	Indirect Business Taxes ($ x 10^3)
Direct	52.7	338	7.3	318.1
Indirect	17.0	297	6.3	1,009.4
Induced	11.1	133	4.0	0.7
Total	80.8	768	17.6	1,328.2

1999). The sum of the direct, indirect, and induced effects is equal to the total economic impact measured in terms of output ($), jobs, labor income ($), and tax collections ($). The indirect or inter-industry linkages would mostly occur among the agriculture (27%), manufacturing (23%), trade (14%), and transportation, communication and public utilities (TCPU = 14%) sectors (Fig. 1). Additional indirect linkages could be expected from the services (8%), and finance, insurance and real estate (FIRE = 7%) sectors. The induced effects associated with increased household expenditures would be mostly observed among the services (30%), trade (24%) and FIRE (23%) sectors (Fig. 2). The manufacturing and TCPU sectors would share some of the induced effects (9%) generated by added household spending.

Fig. 1. Percent distribution of indirect annual economic impact of a single COAPS using 12 cages stocked with candidate species under enhanced market and improved growth conditions.

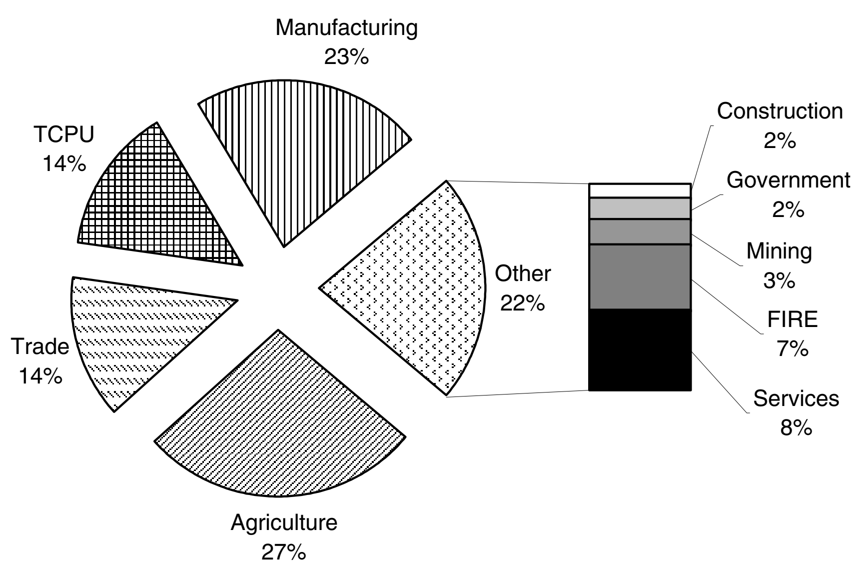
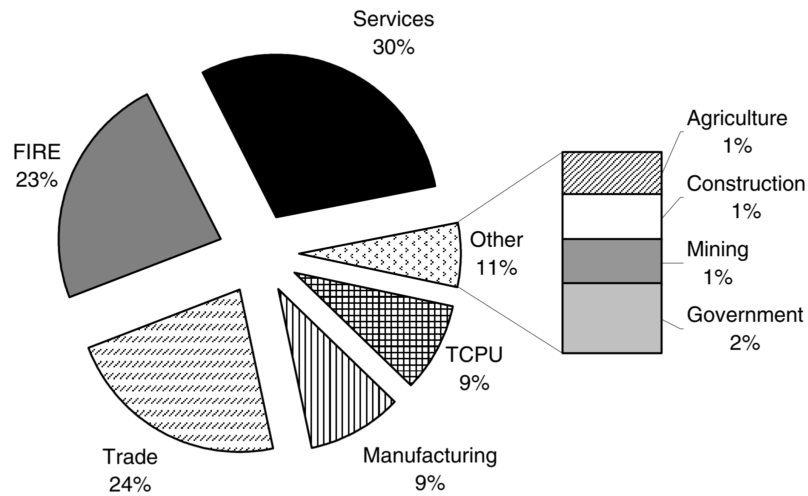


Fig. 2. Percent distribution of induced annual economic impact of a single COAPS using 12 cages stocked with candidate species under enhanced market and improved growth conditions.



ECONOMIC CONSIDERATIONS RELATED TO FINGERLING TRANSPORT

As alluded to earlier, the logistical problem of transporting feed and market-size fish has not been adequately examined. We have compared the economic inputs required for different methods to transport fingerlings to a distant offshore aquaculture site. These methods include: a) hauling fingerlings in live-haul trucks from the hatchery/nursery, transferring these fish to barge tanks thereby keeping the fingerlings safely on deck during the offshore transport, and a final transfer to the awaiting cage (LHT); b) craning fingerling tanks from a flatbed truck to a barge deck thereby eliminating one fingerling handling step while maintaining safe transport offshore (FBT); and, c) transporting fingerlings dockside and transferring them to individual offshore cages and towing fingerlings in the cage to the distant offshore aquaculture site thereby eliminating the need to transfer fingerlings to the cage offshore.

Both LHT and FBT are estimated to require a total of 12 hours for each transport trip. Cage towing is expected to be much slower than transporting fish offshore in tanks placed on the vessel deck. In total, cage towing transport is estimated to require 22 hours per trip (Table 16). Initial investment on equipment required to transport fingerlings would reach up to $11,844 per system (Table 17). There are no allocations for the purchase of livehaul trucks or flatbed trucks since they are assumed to be available for rent or lease on a per trip or mileage basis. Similar assumptions were made for cranes at the dock and barge. Due to these assumptions, the annual costs of fingerling transport consisted mostly of operating expenses (Table 18). Annual transport costs would range from $101,500 for the FBT and towing option to $116,075 for the LHT and barge transport option.

The method that results in the least fingerling mortality during transport would be the ultimate choice. Both trucking options that involve transporting fingerlings offshore by cage towing require much greater duration of

Table 16. Methods of transporting fingerlings from nursery ponds to offshore cages and anticipated hours required to complete each phase of transport.

Method	Hours
Using Livehaul Truck (LHT) and Barge	
Load fingerlings in LHT compartments at the nursery	2.00
Haul fingerlings in LHT to dock	2.00
Unload fingerlings to livehaul tanks on board barge	2.00
Transport livehaul tanks on board barge to offshore cages	4.00
Unload fingerlings from livehaul tanks to offshore cages	2.00
Total	12.00
Using Flatbed Truck (FBT) and Barge	
Load fingerlings in livehaul tanks on board FBT at the nursery	2.00
Haul fingerlings in livehaul tanks on board FBT to dock	2.00
Crane LH tanks from FBT to barge	2.00
Transport livehaul tanks on board barge to offshore cages	4.00
Unload fingerlings from livehaul tanks to offshore cages	2.00
Total	12.00
Using LHT or FBT and Cage Towing	
Load fingerlings to LHT or FBT at the nursery	2.00
Haul fingerlings to LHT or FBT to dock	2.00
Unload fingerlings from LHT or FBT to cages at dock	2.00
Tow cages to offshore farm site	16.00
Total	22.00

time thereby increasing the risk involved with the operation. Cage towing operations also would be limited to defined shipping channels close to shore along much of the Gulf of Mexico. This further increases operational risks through heightened potential for interactions with other marine traffic. Finally, cages towed to the offshore site must be immediately connected to the mooring system. However, cage connection would be jeopardized if surface conditions are not optimal. This risk would only be mitigated if cages are maintained at the offshore site and the fingerlings transported to moored cages. Both the LHT and FBT options are identical when comparing duration for transport and capital equipment investment and quite comparable with regards to associated operational costs. However, use of the LHT option requires additional handling of individual fingerlings (required to transfer fingerlings from the pond to LHT and from LHT to barge tanks) compared with FBT (required only to transfer fingerlings from the pond to livehaul tanks on the FBT but having each livehaul tank transferred to the barge with a crane). One less handling step involved with the FBT option will greatly reduce operational stress to the fingerlings and therefore the most optimal means to transport fingerlings to offshore aquaculture cages.

CONCLUSIONS

The culture of cobia, red snapper and red drum using commercial offshore cages and the proposed aquaculture support vessel in the Gulf of Mexico has limited economic potential given the present biological information, cost structure of the offshore production technology, and established ex-vessel market prices. Only cobia can be considered a viable candidate species for offshore culture using either six or 12 cages. The economic and biological constraints to offshore aquaculture of these species in the Gulf of Mexico, however, could be adequately managed to promote the growth of this emerging industry. Economic feasibility of offshore grow-out of the selected species can be enhanced by a combination of revenue-enhancing and cost-reducing measures, including improvement in fish growth and market development. With improved growth and enhancement of market prices, the offshore culture of red snapper and red drum

Table 17. Capital equipment investment requirements for fingerling transport.

Item	Description	LHT and Barge ($)	FBT and Barge ($)	LHT and Towing ($)	FBT and Towing ($)
Live transport tanks	268 gal	9,444	9,444	0	9,444
Pure oxygen tanks	Units	100	100	0	100
Regulators, hoses and airstones	Units	100	100	0	100
Oxygen meter	W/4m cable	800	800	800	800
Water pump	10 hp	1,000	1,000	1,000	1,000
Corrugated water hoses	100 ft each	400	400	400	400
Total		11,844	11,844	2,200	11,844
Assumptions					
Total fingerlings stocked	#/crop	1,200,000	1,200,000	1,200,000	1,200,000
Fingerlings transported	#/trip	100,000	100,000	100,000	100,000
Average fingerling size	g/fish	10	10	10	10
Total fingerling weight	lb/trip	2,205	2,205	2,205	2,205
Livehaul tank stocking rate	lb/gal	1	1	1	1
Number of transport trips	trips/crop	12	12	12	12
Number of crops per year	crops/yr	1	1	1	1

in 12 offshore cages could be considered economically viable.

The annual economic impact to the Gulf of Mexico region of a single offshore aquaculture production system consisting of 12 cages would consist of additional economic output ranging from \$9.1 x 10^6 to \$10.2 x 10^6. In comparison, current commercial harvesting of the three candidate species in the Gulf of Mexico, which are limited by state and federal regulations, created a total economic impact in the region amounting to \$20.1 x 10^6. The subsequent primary processing and wholesaling of all food fish species in the Gulf of Mexico created a total economic impact reaching \$80.8 x 10^6.

Table 18. Total costs associated with fingerling transport.

Item	LHT and Barge ($)	FBT and Barge ($)	LHT and Towing ($)	FBT and Towing ($)
Variable Costs				
Crane services	0	12,000	0	0
Trucking services	28,800	14,400	28,800	14,400
Barge services	72,000	72,000	72,000	72,000
Pure oxygen	1,200	2,400	0	1,200
Labor	1,440	1,440	2,640	2,640
Fuel for pumps	101	50	50	50
Repair and maintenance	538	538	365	538
Interest on operating capital	10,408	10,283	10,386	9,083
Total variable costs	114,487	113,111	114,241	99,911
Fixed Costs				
Depreciation	996	996	340	996
Interest on investment	592	592	110	592
Total fixed costs	1,588	1,588	450	1,588
Total costs	116,075	114,700	114,691	101,500

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CHAPTER 8

FISH HEALTH MANAGEMENT FOR OFFSHORE AQUACULTURE IN THE GULF OF MEXICO

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ABSTRACT

Since its inception, aquaculture has developed into a major industrial complex, a major component of which is cage culture. Along with the growth, however, problems arose. Translocations of animals and diseases, as well as concerns over environmental effects limited the growth of the industry. The concept of fish health management whereby the host, pathogen, and environment are proactively managed to maximize the optimal conditions for sustained growth and health of both the fish and the environment was developed to facilitate the movement of animals and the growth of the industry. Fish Health Management Plans typically include requirements for training of personnel; protocols for site selection, maintenance, feeding, water quality, containment, and biosecurity; techniques for routine monitoring and assessment; maintenance of records; protocols for diagnosing and treating illness; and, protocols for demonstrating or reporting the health status of the stock. Implementation of the concept requires a regulatory framework, coordination by the government, and active participation by producers and user groups. In the Gulf of Mexico (GOM), no cage culture industry exists. If an industry is to develop, federal and state regulations must be developed and coordinated, the framework for fish health management specific to the disease issues relevant in the GOM must be developed, and issues specific to the physical environment in the GOM must be explored. In the context of the potential risk to aquaculture operations dealing with the most likely candidate species—red snapper (*Lutjanus campechanus*), red drum (*Sciaenops ocellatus*), and cobia (*Rachycentron canadum*)—we review the state of knowledge on potential disease-causing organisms in the GOM and comment on some GOM-specific physical parameters with the potential to impact fish health in an aquaculture operation. A template for a process of developing an aquaculture operation in the GOM within the context of fish health management is presented.

INTRODUCTION AND DEVELOPMENT OF AQUACULTURE

Originally conceived in the mid-1800s as a way to apply centuries-old subsistence techniques to the support of collapsing wild fisheries, modern aquaculture, driven by the increased demand for fish products from a growing population and technological advances, has developed into a major industrial complex. By 1995, aquaculture operations worldwide were producing approximately 28 million metric tons of product worth in excess of U.S. $40 billion (Subasinghe et al. 1998; Stickney 2000). Over the last decade, facilitated by intensification in existing facilities, expansion into new facilities/areas, and diversification into new products, aquaculture has been the fastest growing sector of food production (Subasinghe et al. 2001). Such record growth, however, has come with a price. Nonindigenous animals have been translocated, diseases have been transported along with the animals, and new diseases requiring new diagnostic techniques have emerged.

Massive mortalities in wild Australian pilchards in 1995 and 1998 were linked to a herpesvirus in imported frozen fish used to feed southern bluefin tuna and other fishes held in netpens (Ward et al. 2001a, b). Whirling disease was introduced to North America through frozen fish imported from Europe (Markiw 1992). Infectious Salmon Anemia emerged as a significant pathogen in the mid-1980s in Norway and has subsequently caused mortalities throughout the North Atlantic basin. Indeed, in many parts of the world disease has become the primary constraint to the sustainability and growth of the industry (Subasinghe et al. 1998). China, traditionally the world's largest aquaculture producer, for example, lost almost its entire shrimp farming industry to viral diseases in the early 1990s (Lotz 1997). In addition, the impacts of waste feed, overuse of chemicals, and excretory effluent have become a major concern not only because of their effects on the environment but also because of their effects on the culture animals themselves. However, concomitant with the emergence of problems and concerns, sophisticated diagnostic techniques and increased scientific rigor has been brought to bear to deal with these issues.

Realizing the potential of the industry and the importance of moving animals for the continued development of the industry and the demonstrated risks, scientists, government officials, fishers, aquaculturists and businesspeople began to appreciate the need for coherent regulation and management. Beginning in the 1970s, the risks were becoming apparent. As such, Canada, for example, designated the Department of Fisheries and Oceans (DFO) as the agency solely responsible for managing and regulating aquaculture. In 1977, DFO implemented a set of Fish Health Protection Regulations. Those regulations, originally developed specifically for salmonids, were intended to prevent the spread of known infectious diseases through controlling the movement of live fish, eggs, and fish products. Under the regulations presently in effect, transfer is permitted only from sources with a history of inspections demonstrating the absence of the specified pathogens. Briefly, this is accomplished through ministry-appointed officials (public or private) qualified to certify, via a Fish Health Certificate, facilities or animals free of the specified pathogens. Fish Health Certificates are issued only if facilities are inspected in accordance with a Manual of Compliance produced as part of the regulations. The Manual specifies, among other things, the diseases that must be inspected for and the appropriate diagnostic procedures. Local Fish Health Officers, also appointed by the ministry, issue the appropriate Import Permits based on the presence of a valid Fish Health Certificate from the source and other data provided by the importer and exporter (DFO 2003). Various revisions since 1977 have incorporated information on new diseases and advances in procedures, as well as amendments to deal with other finfish species and the emergence of new diseases. Since their implementation, the standards have successfully prevented the introduction of previously undetected diseases and confined those known to limited geographical areas. Presently, a proposal to develop a National Aquatic Animal Health Partnership is underway to facilitate the involvement of local and private authorities that would allow the regulations to more easily keep pace with advancements in surveillance, biosecurity, international trade, and introduction and transfer requirements. As a result, the Canadian approach is widely respected and provides an excellent working model. In 1995, the Office International des Epizooties (OIE), an international intergovernmental organization of representatives from more than 150 countries aimed at promoting world animal health, began publishing the International Aquatic Animal Health Code and the Diagnostic Manual for Aquatic Animal Diseases based on the same principles enshrined in the Canadian regulations and designed to define the minimum health standards required of international trading partners to avoid the risk of spreading aquatic animal diseases. Among the developments facilitated through the OIE is the movement toward the establishment of scientifically based objective aquatic risk assessment criteria and the Aquatic Animal Health Code (OIE 2003). Also in 1995, the Food and Agriculture Organization of the United Nations developed the Code of Conduct for Responsible Fisheries, which included recommendations to ensure the coexistence of aquaculture with sound environmental, economic, and human health policy.

In the United States, regulations are less centralized and less comprehensive. The framework for aquaculture in the United States is established in the Aquaculture Act of 1980 (and subsequent amendments); however, the Act creates at least two concerns with respect to fish health. First, it specifies no central decision-making authority, and second, it does not explicitly deal with trade issues from a biological perspective. Thus, several federal agencies, in addition to regional and state agencies, with responsibilities in animal health are left to independently operate with perhaps conflicting priorities. To complicate matters, the United States' membership in OIE requires certain procedures and actions. Without some centralized authority, insuring compliance becomes difficult, potentially redundant and, therefore, unnecessarily restrictive.

In 2001, recognizing the maze of conflicting regulations and priorities, the National Aquatic Animal Health Task Force, consisting of representatives from the departments of Agriculture, Interior, and Commerce, was charged with developing procedures for safe, efficient, and effective national and international commerce of aquatic animals and protection of cultured and wild aquatic animals from foreign pests and diseases. Some clarification was provided in 2002 when the Secretary of Agriculture was given the authority to protect and control the health of all livestock including imports and exports of aquatic animals. As of May 2004, however, only the introductory chapters for the National Aquatic Animal Health Plan (NAAHP) have been written and details of the implementation of the Secretary's authority are still being worked out (Amos 2004). In the interim, The American Fisheries Society's Bluebook, first published in 1975, and the OIE's Diagnostic Manual for Aquatic Animal Diseases, first published in 1995 and now in its 3rd edition, have provided a way of standardizing the procedures required to certify the presence or absence of particular pathogens. In addition, some state, local or regional groups have attempted to coordinate activities. The Pacific Northwest Fish Health Protection Committee (2004), for example, coordinates activities of government, academia, and user groups to prevent the importation or transfer of serious salmonid pathogens, as well as promote biosecurity and mitigation of factors conducive to the development of diseases (http://pnfhpc.fws.gov/).

For the Gulf of Mexico (GOM) region, no coordinating organization exists. Most jurisdictions, including Mississippi, provide for the protection and conservation of resources (some even name aquaculture as a permissible activity), but few specifically indicate how fish health issues should be handled. Some jurisdictions, particularly Florida, have adopted basic fish health guidelines that focus on maintaining cultured fish for use in stock enhancement programs at or below the levels of disease organisms found in their wild counterparts (Florida Fish and Wildlife Conservation Commission 2004). At the Gulf Coast Research Laboratory (GCRL), we have adopted the basic Florida guidelines. However, the Florida approach fails to elucidate a mechanism for dealing with emerging diseases or large-scale, intensive culture of organisms in the offshore from seed that may require transport from different facilities, localities, and environments.

In this paper, we will review the concept of fish health management and discuss the components of a Fish Health Management Plan. We will then review fish health issues for the GOM, and speculate on how those issues could be incorporated into a comprehensive strategy for managing large-scale, offshore culture of marine organisms in the GOM.

FISH HEALTH MANAGEMENT

Traditionally, fish health focused on treating the diseases that occurred; however, such an approach requires accepting a high degree of risk. In any outbreak, a certain number of fish will die before the disease is detected and treated (assuming a treatment is available). Even if a treatment is available, unchecked disease progression may lead to a decreased appetite in the stock and reduce the efficacy of available in-feed oral treatments. Profit-making entities cannot always afford to assume a high risk. Thus, approaches to maximizing growth and health have been developed.

Fish Health Management is the concept of proactively regulating the host, pathogen, and environment to maximize the optimal conditions for sustained growth and health. It is based on Snieszko's premise that disease becomes a problem only under the confluence of proper conditions (Snieszko 1974). Pathogens must gain entry into the fish to cause disease or death; therefore, prevention is an important component of a fish health management program. But, pathogens are a normal part of the environment and may exist in a variety of habitats and host organisms. Thus, mitigation of further risk factors such as stress, nutritional or environmental problems that could directly kill fish, impair immune status, or trigger the outbreak of clinical disease is crucial in a health management protocol. Mitigation also includes the development of an understanding of the disease profiles a stock may encounter such that present technology in vaccine development such as genomics and proteomics can be brought to bear to improve preventative aquatic animal health. Ultimately, however, diseases or problems will occur as demonstrated historically with human and agricultural livestock health. As such, a fish health management plan must provide for containing the outbreak or problem in as few fish as possible and reducing the occurrence in the affected fish through the mitigation of offending environmental or husbandry factors, the judicious use of chemotherapeutants, preventative health protocol management, and combinations thereof. Finally, fish health management must balance the risk of the disease and treatment with public health, the environment, and farm economics including risks from and to wild fish.

A TEMPLATE FOR A HEALTH MANAGEMENT PLAN

To achieve these ends, many producers and regulators are requiring that detailed policies and procedures must be established in writing and understood by all involved parties. British Columbia, for example, requires an individualized Fish Health Management Plan for all private and public fish culture facilities in the province as a term and condition of the license (BC MAFF 2004a). As such, standard Fish Health Management Programs typically include requirements for training of personnel; protocols for site maintenance, feeding, water quality, containment, and biosecurity; techniques for routine monitoring and assessment that will identify signs or risks of morbidity and disease at the earliest stage; maintenance of records sufficient to track changes in health and environmental quality; protocols for diagnosing and treating illness; and, protocols for demonstrating or reporting the health status of a stock in accordance with relevant statutes or agreements. Said statutes or agreements may specify certain diseases whose presence or absence must be disclosed. If those diseases are present, continued operation may be contingent upon completion of specified procedures designed to eradicate or contain the disease. Some Fish Health Management Programs also advocate the use of crop insurance to indemnify against loss due to disease.

THE PRACTICE OF FISH HEALTH MANAGEMENT

Fish health management requires knowledge of the source and complete history of each group of animals in the facility/marine site including diagnostic sampling history, feeding records, dive records, environmental and water quality data records, management history, and records of performance, along with some mechanism to convey that information in a timely manner. Routine maintenance includes standard inspection and/or repair of tanks, netpens, pumps, filters, air supply, or any other life support equipment to ensure the containment and well being of the animals. Routine monitoring includes a regular program for testing water quality, inspecting fish (both cultured fish from the netpen and wild animals from adjacent waters) for signs of disease, and periodically collecting samples of moribund fish or random samples of asymptomatic fish for routine diagnostic procedures in certified laboratories in accordance with specified protocols and statistical sampling requirements. Routine husbandry practices include day-to-day management of animals including feeding, cleaning, and removal/disposal of dead or moribund animals. Procedures for the removal and disposal of waste including the bodies of mortalities from the netpens must be specified. Open ocean disposal from facilities, processing plants, and marine cage sites is not acceptable. Adherence to hygiene and biosecurity protocols that limit contact among groups of animals, workers, and equipment, as well as prescribed disinfection/decontamination procedures are required. For operations that use different facilities for different stages in the production process, it is crucial that some quarantine/isolation or disinfection procedure be specified to reduce the risk of translocation of pathogens. Alternatively, single-year-class protocols in which all fish in a facility come simultaneously from the same stock can be implemented. An “all in-all out” agriculture model may be implemented in which all the stock is removed from the facility or contained portion of the facility followed by disinfection of the area prior to introduction of the new or naïve stock.

In preparation for the inevitable, protocols for diagnosis and treatment should be in place. Plans must specify either the party or the qualifications of the party who will diagnose, what procedures will be used, which accredited laboratories will perform the analyses, and who has decision-making authority. Plans must provide access to necessary and allowable chemotherapeutants, as well as instructions on how to use them. Details of treatments must be documented to certify compliance with public health, environmental, and safety standards. In well-established industries or in operations using animals with long culture histories, vaccine administration and/or the use of certified Specific Pathogen Free (SPF) or High Health animals, including the isolation of broodstock in biosecure land-based facilities, may be part of routine protocols. However, the use of vaccines or SPF stocks for animals to be grown in open systems such as netpens guarantees only that the animals exhibit decreased susceptibility to or are uninfected by a particular agent when they are introduced into the netpens. For SPF stock progeny, this may lead to decreased tolerance to endemic watershed pathogens. Thus, standard biosecurity and monitoring protocols are still required.

REGULATORY FRAMEWORK IN THE GULF OF MEXICO

Offshore, open ocean, netpen aquaculture is an emergent industry in the GOM; thus, no regulatory framework or regional body of knowledge on which to base fish health decisions exists. In one sense, this is an advantage. Designing a program from its inception allows for the incorporation of the expertise accrued through the development of similar industries in other places. In another sense, predictability is low and any plan must accept a fair amount of adaptive management.

First and foremost, the regulatory environment must be established. Because the bulk of the operations will be in federal waters, a federal agency must have regulatory authority. The Department of Commerce/ National Oceanic and Atmospheric Administration (NOAA)/National Marine Fisheries Service (NMFS) and the Department of Agriculture/Animal and Plant Health Inspection Service may be the most directly impacted agencies, although the United States Coast Guard, the U.S. Army Corps of Engineers, and the Environmental Protection Agency are affected as well. In Canada the lead aquaculture agency is the Department of Fisheries and Oceans via the Aquaculture Management Directorate, but the role of the Atlantic Canada Opportunities Agency and other federal agencies has been instrumental to the existence of aquaculture in Canada. The NAAHP, when completed, should delineate these roles and set a minimum standard. A regional committee, consisting of representatives from the five GOM states, could collate the regulations of each state and the federal agencies and propose modifications to streamline the regulatory framework and insure compliance with the minimum standards. The participation of and coordination with states is critical because the hatcheries that provide the fish for growout in the netpens are likely to be land-based and in multiple jurisdictions.

As experience with disease issues in the new industry develops, the development of a list of important pathogens, some of which may already be listed as important or notifiable by the OIE, can be developed. This could lead to the development of SPF animals, if considered desirable, through further research by academia and the producers. Also, along with routine monitoring, the temporal and geographic patterns of diseases will become evident. Using this information, a classification system similar to that used by OIE can be established which certifies the absence of certain pathogens in facilities, zones, and regions, thus facilitating the monitored movement of cultured animals.

DISEASE ISSUES IN THE GULF OF MEXICO

Critical to the establishment of feasible regulations and operating procedures is an understanding of disease issues relevant to the GOM. Because the history of culture in the GOM is limited in scope (i.e., mostly for stock enhancement rather than production aquaculture) and geography (only in select localities/jurisdictions supported by public money), the risks associated with disease in large-scale culture must be extrapolated from essentially incidental observations in culture and background knowledge of the diseases known in wild fisheries and in culture facilities in subtropical regions around the world. Some of the disease issues are related to the choice of culture organisms. In the GOM, the red snapper (*Lutjanus campechanus*), the red drum (*Sciaenops ocellatus*), and the cobia (*Rachycentron canadum*) are the most often discussed candidate species; however, species such as the greater amberjack (*Seriola dumerili*) and spotted seatrout (C*ynoscion nebulosus*) also are possibilities. We do not consider the use of non-indigenous species.

The parasites of the likely candidates for culture in the GOM are relatively well known (Overstreet 1978; Shaffer and Nakamura 1989; Blaylock and Overstreet 2003; Blaylock unpublished data). We, however, take a broad view of disease and discuss not only the disease-causing organisms but also other factors that may impair normal function in culture organisms. Further, we will include disease problems that have had major impacts on culture in other sub-tropical areas to expand the baseline understanding of potential problems.

Not all diseases and parasites pose equal risk to an aquaculture operation. Many disease-causing organisms have complicated life cycles requiring more than a single host species. Others have simple life cycles requiring only a single species. Still other diseases are caused by non-infectious agents. Those organisms with simple, direct life cycles are the most likely to cause difficulty in culture operations because the density of animals facilitates close contact and transmission. Thus, most of the concern in aquaculture is typically focused on these organisms. In open ocean netpens, however, complex life cycles can be operating because of the ingress and egress of organisms with water flow and the inhabitation of the netpen itself by ancillary organisms such as resident or migrating fish stocks. Further, the flow of water may expose fish to non-infectious agents. Thus, some disease organisms are known to predictably cause problems. Some problems will arise from known organisms that do not normally cause disease in the wild. Other problems will arise from organisms previously unknown in the wild. In the absence of non-indigenous culture organisms, non-indigenous pathogens should not be problematic unless introduced independently of aquaculture operations (e.g., ballast water).

Algal Blooms

Harmful algal blooms (HABs) generally refer to dense patches of pigmented phytoplankton carried in the current that can mechanically damage fish gills, produce anoxia or oxygen supersaturation in the water column, or produce toxins that affect various organ systems. HABs have become a major economic threat to wild and cultured fishes, which are, of course, confined and cannot escape (Kent and Whyte 1997). A variety of taxonomic groups of algae contain genera and species known to be associated with disease in fish including dinoflagellates, green algae, cyanobacteria, yellow-green algae, blue-green algae, yellow-green algae, prymnesiophytes, rhaphidophyceans, and diatoms (Noga 1995; Kent and Whyte 1997). Mortalities in netpen-reared salmonids around the world have been attributed to at least one representative of each of the listed groups of organisms, and some are known to kill wild and pond-cultured fish of other species or invertebrates in various localities around the world (Noga 1995).

Representatives of all the groups are present in the GOM. Although "red tides," as HABs are often called, occur around the world due to periodic and often unexplained blooms of algae, the warm, relatively shallow water in the northern GOM may be particularly vulnerable to blooms. Some blooms in the GOM, in fact, have been attributed to normally benthic organisms that because of the relatively shallow water were easily suspended into the water column (C. Moncreiff, personal communication). The "dead zone" in the GOM also attests to this vulnerability. Each summer, algae in the warm GOM water bloom in response to the high nutrient input from the Mississippi River and in the process of decaying consume all available oxygen rendering a vast expanse of the GOM relatively uninhabitable. The "dead zone" can cover more than 20,000 km^2 and vary somewhat in its location from year to year (Rabalais et al. 2002). Further, it is possible that nutrient input from netpens could facilitate smaller scale blooms. In addition, oil platforms/rigs and netpens in the GOM could provide habitat that would not normally be available for microorganisms (C. Moncreiff, personal communication). Those organisms would be available to bloom under proper conditions.

Non-infectious Disorders

Non-infectious disorders in the context of this paper include degenerative, metabolic, neoplastic, and behavioral conditions. Fish production operations require handling and transport of fish for the purposes of stocking, grading, treating and vaccinating. Such activities invariably result in some degree of injury and stress, which contributes to the loss of some animals and increases the susceptibility of the fish to pathogens through the physical damage that creates portals of entry. In well-established industries, such as salmonid culture, technology has provided systems with the potential to minimize those risks. In a newly developing industry, those advantages do not exist. Some technology may be transferable or easily adapted from well-established industries, but, initially, producers should expect losses associated with these activities. Each culture species has its own suite of behavioral characteristics. Atlantic salmon, for example, are territorial and will attack their tank or cagemates resulting in injuries that can directly lead to death or facilitate the establishment of pathogens (Speare 1998). Tank-held red snapper also are known for their aggressive tendencies (R. Blaylock, personal observations). For Atlantic salmon, increased density was found to suppress the territorial behavior (but decreased biomass per tank or cage system is desirable from a health viewpoint). Research and trial and error will be required to establish protocols for a new industry.

Environmentally-induced Diseases

Environmentally-induced disorders include problems associated with water chemistry/quality, toxic compounds, and weather. Problems related to oxygen levels in the context of algal blooms already have been discussed. Temperature affects oxygen levels as well, but also affects metabolic rate and the quality of the immune response, both of which may affect the toxicity or pathogenicity of an agent. Further, the reproductive rate of disease organisms generally increases as temperature increases. In the GOM, water temperatures can easily exceed 32°C, and because of the shallow continental shelf, these temperatures can penetrate significantly into the water column. In cooler climates and in deeper water, fish can escape warm surface water by moving to the bottom of the cage, by the lowering of the cage in the water column, or by using deeper nets (Pepper et al. 2003). In such a warm shallow basin that exists in the GOM, the margin for manipulation is narrow.

Toxic compounds can include chemicals used for treatment of diseases, parasites or environmental pollutants, although therapeutic margins for many chemotherapeutants are relatively well known. Petrochemical pollution in the GOM is a possibility given the presence of numerous oil and gas operations. Hydrocarbons are known to cause mortality and affect parasite loads in marine fish (Overstreet 1993 and references therein). Toxicants in crude oil and water-soluble fractions of crude oil are known to induce histopathological changes in fishes from the GOM (Solangi et al. 1982). Stress related to pollutants and toxicants may increase the susceptibility of organisms to secondary infections. Overstreet and Howse (1977) demonstrated that fish stressed by organic waste and already infected with the ciliate *Epistylis* sp. were more likely to suffer from secondary bacterial infections. Water quality issues such as turbidity are important as well because it can result in fouled gills, which can in turn precipitate other disease problems.

Nutritional Diseases

Food-related disorders are common in aquaculture. Fatty livers are common in many farmed fish, though not always pathological, and can be caused by several factors including rancid food, overfeeding, and inappropriate food formulations (Speare 1998). Overfeeding also can promote outbreaks of diseases such as vibriosis, presumably through nutrient loading (Speare 1998). Fast-growing, fat Atlantic salmon in sea cages are more prone to cardiomyopathy and “water belly,” a condition characterized by a stomach distended by saltwater and a thin tunica muscularis and serosa (Speare 1998). Vitamin or other nutrient deficiencies are widely known to cause a variety of physical, behavioral, or growth deformities (Halver 1989; Lasee 1995). In established industries such as salmonid culture, proper food formulations and food conversion ratios are well known, but in fledgling industries those issues must be researched and developed. In the case of the likely candidates for netpen culture in the GOM, standard marine grower feeds are typically used. The information required for feed formulations specific to the likely candidates generally is not available, though more may be known about the nutritional requirements of red drum than the other candidate species (see Gatlin 2000 and references therein).

Neoplasia

Neoplasia is an uncommon but sometimes important issue in fish culture. Neoplasia is a condition in which genetically altered cells “escape” from normal growth regulation and produce some type of abnormal mass independent of normal tissue that persists after the removal of the stimulus that evoked the lesion (Grizzle and Goodwin 1998). Neoplasias occur spontaneously or can be induced by exposure to chemical pollutants or oncogenic viruses. Spontaneous neoplasias are not likely to be problematic for fish culturists. Chemically induced neoplasias, although known to be induced by halogenated compounds and polycyclic aromatic hydrocarbons in wild fish (Grizzle and Goodwin 1998), are not common in commercially cultured fish. However, there is substantial use of cultured fish for laboratory experiments in carcinogenesis. A variety of neoplastic lesions are known from the GOM, including a schwannoma in lutjanids from Florida (see Overstreet 1988 and references therein), but their role as disease-causing organisms in aquaculture in the GOM is unknown. Oncogenic viruses are known to cause problems in commercial fish culture in some instances. Plasmacytoid leukaemia, caused by a retroviral agent, can cause high mortality in netpen-reared chinook salmon (Kent 1997a), and *Oncorhynchus masou* virus causes typically nonlethal cutaneous lesions on a variety of salmonids (Grizzle and Goodwin 1998). Any cutaneous abnormalities could affect the marketability of fish.

Viruses

Viruses have had a major impact on aquaculture and are among the most difficult diseases with which to deal because of the difficulty in recognizing and diagnosing an infection, the ease with which they are transmitted, and the lack of effective treatments. Viral diseases in penaeid shrimp are considered one of the largest obstacles to the growth of shrimp aquaculture (Lotz 1997). Likewise, viruses such as Infectious Salmon Anemia Virus and Nervous Necrosis Virus (Nodaviridae) have had substantial impacts on finfish aquaculture (ARDF 2002; Miller and Cipriano 2003). With the exception of lymphocystis, a chronic and typically benign condition caused by Lymphocystis Virus (Iridoviridae), and an unnamed DNA virus known to cause mortalities in hardhead catfish (*Arius felis*), no fish viruses are known from marine fishes in the GOM. Viruses certainly exist in the GOM; therefore, any aquaculture operation should be prepared for viral diseases. Unfortunately, because we cannot reasonably predict which viruses will cause problems, aquaculture pioneers in the GOM must assume a high degree of risk. Viruses such as Nervous Necrosis Virus (Nodaviridae) have caused problems in a variety of cultured species around the world, including cobia (Chi et al. 2003) and red drum (Oh et al. 2002), and are likely to be problematic in the GOM. Other iridoviruses that have been reported from more than twenty species of marine fish (Leong and Colorni 2002), as well as members of the Togaviridae family and aquareoviruses, could become problematic.

Bacteria

Bacteria also can be devastating in aquaculture both as primary infectious agents and as secondary infectious agents. Vibriosis, furunculosis (*Aeromonas*), Edwardsiellosis, columnaris, and others including rickettsial and chlamydial organisms are well known in fish culture. Commonly cultured fish species in sub-tropical waters of southeast Asia including groupers, lutjanids, carangids, and sciaenids are regularly lost to outbreaks. Representatives of all these types of bacteria and others are known in warmwater marine fish culture and from fish in the GOM. Representatives of *Acinetobacter*, *Aeromonas*, *Photobacterium*, *Pseudomonas*, *Shewanella*, and *Vibrio* as either primary or secondary pathogens from a variety of wild and cultured fishes including red snapper, red drum, and cobia are readily isolated (Overstreet 1978; Florida Fish and Wildlife Conservation

Commission 2004; R. Blaylock, unpublished data). Most respond well to antibiotic treatment if the outbreak is detected early; however, our experience at GCRL is with bath treatments, which, for obvious reasons, would be difficult in netpen aquaculture. Administration of antibiotics through food or intraperitoneal injection are widely accepted techniques. Vaccines for furunculosis and vibriosis in salmonids and cod are now available; therefore, development for use in other fishes is possible. Others are being refined to account for the variability expressed in some disease organisms. *Mycobacterium marinum*, *Streptococcus* spp., and chlamydia-/rickettsia-like organisms are also known from the GOM, but we have not seen evidence of them in our marine fish culture system at GCRL. Their potential role as disease-causing organisms in netpen culture is unknown.

Fungi and Fungi-like Organisms

Fungal infections in fish typically refer to infections by a variety of organisms with a variety of life cycles that are not necessarily related systematically. Historically, however, they have been referred to as fungi; therefore, we consider them together for convenience. Species of *Ichthyophonus* (now classified as a protist) occur in temperate to tropical waters around the world and systemically infect a variety of marine fishes causing severe mortalities both in the wild and in culture (McVicar 1999). Members of *Saprolegnia*, *Aphanomyces* (water mold—now classified as a protist), and other oomycetes infect a variety of fishes and are known to cause ulcerative mycosis, a serious disease in a range of estuarine species (Bruno and Wood 1999). Various deuteromycetes also have been reported to cause disease in wild and cultured fishes (Bruno 1989; Lehmann et al. 1999; Blaylock et al. 2001). In many cases, however, the disease associated with the fungus is assumed to be secondary to an injury or another compromising factor (Blaylock et al. 2001). That assumption may be valid in many cases, particularly in salmonids; but, Noga et al. (1988) and Dykstra and Kane (2000) show how *Aphanomyces* sp. produces primary disease in an estuarine fish. Representatives of all these groups are present in the GOM, but their role as potential pathogens in netpen culture in the GOM is unknown.

Microspora

Members of the phylum Microspora are widely known from fishes but are typically regarded as parasites of invertebrates. In the GOM, microsporidians are known from blue crabs and grass shrimp and less so from fishes (Overstreet 1978). Microsporidians are small, single-celled, intracellular parasites characterized by spores that contain a sporoplasm that extrudes through an everted polar tube into a host cell. Development of the spores of some species, such as those of *Pleistophora*, occurs in groups within a sporophorous vesicle. A host “cyst,” making an infection apparent to the naked eye, encapsulates large numbers of spores that may be directly infective (Blaylock and Overstreet 2003).

Those species that infect fish can cause severe diseases in culture facilities (e.g., *Glugea stephani* in flatfishes, *Microsporidium seriolae* in *Seriola quinqueradiata*, *Loma salmonae* and *Nucleospora salmonis* in salmonids, *Loma morhua* and *Loma branchialis* in cod (Rodriguez-Tovar et al. 2003)); however, they are typically associated with temperate waters (Overstreet 1978; Dyková 1995). In the GOM, microsporidians (mostly unnamed) are known from sciaenids (drums, croaker, spot, and seatrout) and red snapper; but, in the wild, the cysts appear to be relatively innocuous (Overstreet 1978).

Their potential role as pathogens in netpen culture in the GOM is not known. Dyková (1995) believed that young fish suffered more than adults from microsporidians. This is probably especially true for cultured fish, but primarily hypothesized for wild ones.

Apicomplexa

The phylum Apicomplexa includes the coccidians, haemogregarinids, and piroplasmorids. All have representatives in fishes, though coccidians, typically intestinal parasites that can have either direct or indirect life cycles depending on the species, are the most common. Members of *Goussia* and *Eimeria* are known to cause mortality in cultured marine fishes such as cod, haddock, and red drum (Molnár 1995; Johnson 2000). Several species of *Eimeria* and *Calyptospora funduli* from the Gulf killifish are known from the GOM. *Haemogregarina platessa*, a blood parasite requiring a leech, isopod, or argulid vector, is known from the blood of southern flounder and mullet, among others (Becker and Overstreet 1979; Overstreet 1978). The potential role of these parasites as pathogens in netpen aquaculture in the GOM is unknown.

Sarcomastigophora

Sarcomastigophorans, such as members of *Hexamita,* typically occur in the intestines of a wide variety of marine fishes, have a direct life cycle, and are known to kill juvenile, salt-water reared salmonids (Woo and Poynton 1995). *Ichthyobodo*, an ectoparasite that alternates between a free-living stage and a stage parasitic on the epithelial cells, is known to kill flounders in hatcheries in Japan (Urawa et al. 1991). Species of *Cryptobia/ Trypanoplasma* are well-known flagellate pathogens of fishes (hatchery-reared salmonids and wild summer flounders). There is debate, however, on the taxonomy of the group. *Cryptobia* (subgenus *Cryptobia*) are typically ectoparasites or intestinal parasites with direct life cycles. *Cryptobia* (subgenus *Trypanoplasma*), typically containing the pathogenic species, are haematozoic with indirect life cycles requiring a leech vector (Woo and Poynton 1995). *Cryptobia* (*T.*) *salmositica* causes mortalities in salmonids both in culture and in the wild (Woo and Poynton 1995). In the GOM, *Cryptobia (T.) bullocki* is known from the southern flounder and Atlantic croaker (Overstreet 1978; Becker and Overstreet 1979). The parasite is known to kill experimentally infected summer flounder, *Paralichthys dentatus* (Overstreet 1993). The potential role of these parasites as pathogens in netpen aquaculture in the GOM is unknown. Trypansomes such as *Trypanosoma murmanensis* are known to kill experimentally infected cod (Woo and Poynton 1995). Trypanosomes such as *T. mugilicola* are known from mullets and other fishes in the GOM (Becker and Overstreet 1979), but their potential role as disease-causing organisms in aquaculture in the GOM is unknown. Amoebae such as *Paramoeba pemaquidensis* cause mortalities in salmonids in sea cages (Kent 1997b), but their status as disease-causing organisms in the GOM is unknown.

Sarcomastigophora (Dinoflagellida)

One of the most problematic parasites culturists in the GOM must face is the dinoflagellate *Amyloodinium ocellatum*, often considered the single most consequential pathogen in warm water fish culture (Paperna et al. 1981). The parasite alternates between an obligate feeding trophont on the gills and skin and an encysted reproductive tomont in the sediment, on surfaces of nets and tanks, or in the water column. Trophonts attach to epithelial cells and feed on surrounding cells causing hyperplasia, inflammation, and necrosis that disrupts gas exchange in the gills. Species are differentially susceptible to infection, but most fishes are susceptible (Lawler 1980). Wild-caught fishes are infested at a relatively low level that typically does not harm the host in the wild (Blaylock and Overstreet 2003), although mass mortalities in a variety of fishes have been associated with the parasite (Overstreet 1993). However, because each encysted tomont produces 256 infectious dinospores, populations of the parasite can build to dangerous levels if a fish experiences a stress event, which can stimulate the trophonts to drop off and produce the dinospores. This is particularly important for captive fishes because the tank, pond, or netpen concentrates the infective dinospores in proximity to the fish hosts. Red snapper, cobia, and red drum are susceptible. Survivors, although few in our experience if left untreated, can develop some level of resistance to reinfection, and serum from fish immunized with dinospore fractions kills the parasite in cell culture (Noga and Levy 1995); thus, vaccine development may be possible.

Myxozoa

Myxozoans are pluricellular, spore-producing protists, arguably related to cnidarians, that typically alternate between an actinosporean stage in oligochaetes/polychaetes or other invertebrates and a myxosporean stage in teleost hosts. The parasites can be either intercellular or intracellular in a variety of tissues, and they develop in a variety of patterns, often occurring in "cysts" containing many spores or packets of spores that are infective to the alternate host.

Myxozoans are among the most devastating pathogens of cultured fishes. *Kudoa thyrsites* myoliquefies the flesh of infected fish, and may render it unsightly and unmarketable. *Myxobolus cerebralis* infects the cartilage and is responsible for whirling disease in trout. *Ceratomyxa shasta* infects the gall bladder and causes serious mortality in cultured and wild salmonids. Species of *Henneguya*, *Myxidium*, and *Tetracapsula* also are well-known pathogens of fishes. Species of *Myxidium*, *Sphaerospora*, *Ceratomyxa, Myxobolus,* and *Kudoa* are known to debilitate and kill sparids, groupers, mullets, seabass, and cobia in culture (Alvarez-Pellitero and Sitjà-Bobadilla 1993; Leong and Colorni 2002). In the GOM, representatives of *Kudoa*, *Myxobolus*, *Henneguya*, and *Myxidium* are known, but their potential role as pathogens in netpen aquaculture is unknown.

Ciliophora

Representatives of the phylum Ciliophora parasitic in fishes are typically commensals or opportuntistic parasites. These organisms include *Trichodina*, *Epistylis*, *Tetrahymena*, and *Brooklynella*. Many fish harbor a few commensal organisms without effect; however, because the organisms are typically directly transmitted, the stress and confinement of captivity can result in the development of large numbers of commensals which can do extensive damage to the hosts through grazing on or anchoring on epithelial cells and by interfering with gas exchange in the gills (Overstreet 1978; Lom 1995).

Representatives of the cosmopolitan genus *Trichodina* are among the most common organisms found on fish in the GOM (Overstreet 1978). *Brooklynella* is commonly seen in captivity and typically on the gills where it can destroy the gill epithelium of most marine teleosts. Although we have never seen *Brooklynella* in our marine fish culture facilities at GCRL, lutjanids cultured in Martinique have suffered heavy infestations with the parasite (Gallet de Saint Aurin et al. 1990). *Cryptocaryon irritans* is a ciliate with an obligate parasitic feeding stage inhabiting the basal layer of epithelial cells and a free-living, encysted reproductive stage that infests a wide variety of marine fishes producing vesicles on the skin, increased mucus production, and erosion of the gill epithelium. It is known to cause mass mortalities in closed systems such as ponds and aquaria (Overstreet 1993). Groupers and snappers in cage culture are susceptible (Leong 1994). We identified *C. irritans* on wild-caught, tank-held red snapper on one occasion. Colorni (1987) indicates that *C. irritans* in cage culture can be avoided by keeping cages at depths and currents sufficient to prevent contact with the infectious stage.

Monogenea

Monogeneans commonly occur as ectoparasites on the gills and body surfaces of fishes. The different species attach by means of a variety of hooks, anchors, suckers, and clamps located on a posteriorly located haptor. The life cycles of these parasites are typically direct. Some species lay eggs while others bear live young. Eggs hatch into infective oncomiracidia that invade the same or another individual of the host species. Some oncomiracidia are free swimming and some crawl. Viviparous species produce well-developed embryos that directly infest the host but can be passed on to other individuals. Monogeneans are of two general types: sanguiniferous polyopisthocotyleans, usually with multiple attachment structures in the haptor, and tissue grazing monopisthocotyleans, usually with one or two relatively large pairs of anchors and very small marginal hooks in the haptor. Because of the direct life cycle, populations of monogeneans can build rapidly, producing detrimental effects particularly when the host occurs in confined areas.

Among the most devastating of monogeneans in culture conditions are the capsalids. Amberjack, flounder, rockfish, and various groupers and lutjanids in culture in Asia have been seriously affected by several capsalid species (Leong and Colorni 2002). *Neobenedenia melleni*, a species reported from over 100 host species, including several from the GOM can also be devastating (Bullard et al. 2000, 2003). Other monogeneans, such as members of *Haliotrema*, are very common on lutjanids (Leong and Colorni 2002) including the red snapper (R. Blaylock, personal observation), but their role as disease-causing organisms is unclear (Leong and Colorni 2002). At GCRL, we have maintained wild-caught red snapper infested with a species of *Haliotrema* in captivity for extended periods of time without difficulty (R. Blaylock, personal observation).

Cestoidea

Cestodes, or tapeworms, are perhaps the most well known parasites. These flatworms, typically segmented as adults, generally live as adults in the intestinal tracts of a wide variety of animals including fishes and have intermediate stages in other hosts. Eggs of aquatic species develop into stages infective to invertebrates that are in turn consumed by fishes where the parasites can either develop into adults or encyst as metacestodes that are transmitted to other fishes, birds, or mammals. Most marine teleosts do not serve as a definitive host for tapeworms. Rather, in many cases involving fish tapeworms, the metacestode stage that can occur in the flesh is transferred from host to host many times before it develops further or enters the definitive host, a process known as paratenesis.

Juvenile tetraphyllideans inhabiting the cystic duct and intestinal tract comprise several commonly encountered species that belong in a group collectively termed “Scolex polymorphus.” These organisms, while common, probably cause little harm to the host (Blaylock and Overstreet 2003; Overstreet 1978). Other cestodes include the trypanorhynchean metacestodes. Trypanorhynchs are typically found encapsulated in the flesh or viscera and are characterized by four eversible, hook-bearing tentacles. The metacestodes of species of *Otobothrium* and the *Kotorella-Nybelinia* complex are relatively widespread in fishes and apparently cause little harm (Blaylock and Overstreet 2003). Probably the most well known cestode in the GOM is the trypanorhynch *Poecilancistrium caryophyllum*, a larval tapeworm that appears as a chalky, opaque, worm-like object twisted within the flesh of the spotted seatrout, *Cynoscion nebulosus* (Overstreet 1977). Because these parasites are not infective to humans, the greatest problem related to this parasite is an aesthetic issue (Overstreet 1983). The presence of plerocercoids in the flesh makes the fillets unsightly.

Digenea

Digeneans are the most abundant metazoans in marine fishes both in numbers of species and individuals. These parasites are among the most complex of parasitic organisms, requiring multiple hosts to complete their life cycles. Typically, eggs produce miracidia that enter molluscs where they, in turn, produce a sporocyst or in some cases a redia. After what can be several asexual generations in the mollusc, each sporocyst or redia produces many cercaria, which leave the mollusc, infect a second intermediate host, and often encyst as a metacercaria. Metacercariae, encysted, encapsulated, or free, are infective to appropriate definitive hosts. Marine fishes can act as both intermediate and definitive hosts for digeneans (Blaylock and Overstreet 2003).

Although infections by adult digeneans rarely harm the host, some metacercariae such as diplostome metacercariae, when present in high enough numbers, are known to impair or kill freshwater catfish in farms (Coblentz 2000; Overstreet and Curran 2004). An exception is the sanguinicolid digeneans whose adults and eggs inhabit and obstruct the circulatory system of fishes. These flukes are unusual with respect to most digeneans in that their life cycle may use a polychaete rather than a molluscan first intermediate host, lacks a second intermediate host altogether, and lacks an encapsulated metacercaria. Thus, the mere proximity to the intermediate host can facilitate infection (Bullard and Overstreet 2002). Cultured carangids, seabass, groupers, and snappers in Asia are commonly infected with several species, and mass mortalities have been reported in cultured amberjack (Ogawa and Fukudome 1994). In the GOM, several species of bloodflukes are known from a variety of inshore and pelagic fishes (Bullard and Overstreet 2002). Their potential as disease-causing organisms for fish in culture in the GOM is real.

Nematoda

Nematodes can be found in the intestinal tract, viscera, mesentery, and in the tissues. Marine fishes acquire the worms, depending on the species, by consumption of eggs, juveniles, or the intermediate host, often a copepod. Some species are acquired from a paratenic host, one in which development of the parasite does not occur. After one or two molts in the definitive host, nematodes mature and produce eggs or larvae that are in turn shed from the definitive host to infect the appropriate intermediate host where another series of molts occurs. Nematodes are typically dioecious and often markedly sexually dimorphic. In many species, females often constitute the majority of worms observed (Blaylock and Overstreet 2003).

Some nematodes certainly cause pathology (e.g., abdominal adhesions in salmonids caused by species of *Philonema*; see Dick and Choudhury 1995), but few cause overt disease in either wild or cultured fish. Juvenile nematodes, if they are large relative to the size of the host, can kill juvenile fishes (Overstreet 1978). Some obvious exceptions result from infections in abnormal hosts such as the case of the introduction of the eel nematode *Anguillicola crassus* into the U.S. This is a nematode from East Asia where it is relatively non-pathogenic in native eels. When introduced, first into Europe and then into the United States (Fries et al. 1996), it caused mortalities in the native, naïve eel species. Heavy infections of other nematodes may affect fish condition or behavior. Nematodes (Anisakidae) in the liver of cod results in reduced liver size, weight, fat content, and overall fish condition (Margolis 1970). *Philonema oncorhynchi* affects the orientation of sockeye salmon smolts (Garnick and Margolis 1990). Even without direct physical effects, large numbers of worms, especially in the flesh, can affect the marketability of fish. Red snapper, red drum, and cobia are infected with both juvenile and adult nematodes. Among the most common nematodes in marine fishes from the GOM are juveniles of *Hysterothylacium* (Anisakidae) found in the mesentery. These worms, difficult to identify to species in the larval stages, mature in the intestinal tract of other fishes. Juveniles of *Contracaecum* have been reported as well. At least one larval nematode, a species of *Hysterothylacium*, can cause mucosal hemorrhaging and focal eosinophilia in the digestive tract of rhesus monkeys, and probably humans (Overstreet and Meyer 1981).

Acanthocephala

Acanthocephalans, also known as spiny-headed worms, are a small, unique group of parasites related to rotifers (Dunagan and Miller 1986). Acanthocephalans inhabit either the intestine as adults or the body cavity or tissues as juveniles (cystacanths) and typically have simple life cycles involving two hosts, a vertebrate and an "arthropod." Shell-encased embryos (acanthors) are released from adult worms and passed in the vertebrate definitive host's feces. In species infecting an aquatic vertebrate, a specific crustacean then consumes the acanthor, which develops into a juvenile in the crustacean. Definitive hosts are infected either by consumption of the arthropod intermediate host or, in cases of some species, by a vertebrate or invertebrate paratenic host. Fish may serve as paratenic or definitive hosts (Blaylock and Overstreet 2003). Epizootics of acanthocephalans are known from trout hatcheries (Bullock 1963) and wild populations (Schmidt et al. 1974), but are unusual. Several species are known from a variety of host species in the GOM. *Acanthocephalus* sp. is known from the red drum, and *Serrasentis sagittiferus* (both cystacanths and adults) is known from cobia and red snapper. Heavy infections could cause problems in culture, but the true role of acanthocephalans as primary disease-causing agents in culture in the GOM is unknown.

Crustacea

Crustaceans representing the Copepoda, Isopoda, Amphipoda, and Branchiura typically infest the skin, fins, gill filaments, gill rakers, and mouth and are among the most grossly noticeable of all fish parasites. Life cycles are generally direct and involve various numbers of molts progressing from nauplius to copepodid, chalimus, pre-adult, and adult stages. In copepods, there is great sexual dimorphism, and the majority of observed specimens are female. Copepods associate with the host in a variety of ways ranging from no attachment (as in the caligid *Lepeophtheirus salmonis* which simply grazes along the surface of the host) to grasping onto the host using modified appendages (as in the ergasilids and lernanthropids) to elaborate holdfast organs (as in the pennellids *Lernaeenicus radiatus* and *Phrixocephalus cincinnatus*) which anchor the parasite deep within the tissue of the host. Copepods feed on blood, mucus, and epithelial cells or some combination thereof depending on the species. They can cause extensive physical damage, severe hemorrhage, hyperplasia, and inflammation in the tissue they infest, which can result in the blockage of blood and lymph vessels, loss of surface area for gas exchange (gill parasites), osmotic stress, hyperplasia of epithelium, and infiltration with various immune cells.

Lepeophtheirus salmonis, the sea louse, is well known for the damage it does to netpen-reared salmon (Johnson et al. 2004). Members of *Caligus*, of which there are many representatives in the GOM, also are responsible for disease outbreaks in netpen aquaculture (Johnson et al. 2004). Overstreet (1983) noted that larval seatrout (*Cynoscion nebulosus*) can be infested, and a single *Caligus* individual can kill a small fish. Members of *Ergasilus*, of which there also are many representatives in the GOM, are known to be important parasites of marine-reared salmonid and non-salmonid fishes (Paperna 1975; Johnson et al. 2004). A representative of *Thysanote* (Lernaeopodidae) is found in the nostrils of the red snapper (R. Blaylock, unpublished data). Lernaeopodids, which typically graze on mucus and epithelial cells, are known for their secure attachments to their hosts that can cause substantial physical damage. Representatives of *Cybicola* (Pseudocynidae) are known from the GOM (Blaylock and Overstreet 2003). These copepods can cause major damage from host reaction at the attachment site; however, many individual copepods are probably necessary to cause serious harm to a host unless the host is a juvenile or otherwise compromised. Specifically which copepods are likely to cause problems in netpen aquaculture in the GOM is not known, but some are certain to cause difficulty.

Species of *Argulus*, sometimes known as fish-lice, and related branchiuran genera, comprise this distinct group of parasitic crustaceans. These organisms do not use an intermediate host, but long-lived, well-protected eggs are typically deposited on a hard substratum. A copepodid-like stage emerges from the egg and is immediately infective to the host, usually the same host species from which it came, where it will undergo a series of molts into the adult stage (Lester and Roubal 1995). Argulids feed through a tubular mouth equipped with a stylet that everts and pierces the host releasing hemorrhagic compounds (Overstreet et al. 1992). Thus, a heavy infection with an argulid can decimate hosts, particularly in confined areas (Lester and Roubal 1995). This group of organisms is well represented in the GOM and is likely to present some difficulty for aquaculture.

Isopods belong to a third group of crustaceans with representatives parasitic on fishes. Little is known concerning the complete life histories of parasitic forms. Typically free-swimming juveniles are released from brood pouches to infect either the same or another host. Cymothoids, the most common type of parasitic isopod, typically attach (sometimes in male-female pairs) to the mouth, in the branchial area, or near the base of the fins with their claw-like legs. With these legs and their piercing or sucking mouthparts, some are capable of producing severe lesions, destroying gill filaments, and serving as vectors for other infectious organisms such as viruses (Blaylock and Overstreet 2003). *Lironeca ovalis* obstructs the gill chamber causing the opercula to flare out unnaturally, erodes the gills, and debilitates the host (Overstreet 1978). Further, Pearson (1929) and Overstreet (1983) both suggested that *L. ovalis* might contribute to significant morbidity and mortality among juvenile spotted seatrout and red drum through destruction of gill filaments. Cymothoids (*Ceratothoa oestroides*, *Nerocila orbignyi*, and *Emetha audouini*) kill and retard the growth of seabass in netpen culture in the Mediterranean Sea, and *Ceratothoa gaudichaudii* retards the growth of salmon in netpen culture in Chile (Horton and Okamura 2001). Gnathiid isopods, parasitic on fish only as juveniles, feed on blood and can cause losses in cage-held fishes, particularly in heavy infections (Bunkley-Williams and Williams 1998). Approximately 12 species of cymothoid isopods are known from the GOM, but each of these species may infest more than a single fish species, an important consideration for aquaculturists because wild fish surrounding netpens can transfer their isopods to fish in the netpens. Because juveniles of gnathiid isopods are difficult to identify to species, the number of species infesting fish in the GOM is unknown.

Annelida (Hirudinea)

Leeches are blood-feeding members of the phylum Annelida that live at least part of their lives parasitic on vertebrates. Mating occurs either on or off the vertebrate host. Cocoons are either deposited on hard substrates such as crustacean exoskeletons or brooded on the leech's ventral surface depending on the species and newly hatched leeches seek out the vertebrate host. Leeches serve two roles in fish diseases. First, because leeches are blood feeders that attach to the host, they may act as direct pathogens. *Piscicola salmositica* has caused mortalities in salmon hatcheries, *Myzobdella lugubris* has heavily infested cultured striped bass, and *Johanssonia arctica* has caused severe lesions in cod (Burreson 1995). In addition, there is interesting evidence that leeches alter the energy balance that results in reduced growth or condition in infested fish (Burreson 1995). Second, leeches may serve as vectors for other disease organisms. Their role in the transmission of fish haematozoa is well established, but they are suspected vectors of lethal viral illnesses such as Spring Viraemia of carp and Infectious Haematopoetic Necrosis Virus of salmonids (Burreson 1995). Representatives of at least six genera are known from the GOM (Sawyer et al. 1975), but their potential role as pathogens in netpen culture is unknown.

DISEASE MANAGEMENT

Management of disease problems is accomplished through several avenues. Because netpens will typically be used only for growout, diseases in larviculture can be controlled through biosecurity and quarantine procedures in the hatchery as discussed earlier. Broodstock should be maintained in land-based sites, preferably in more than one biosecure facility to guard against failure at one facility. If fish introduced into netpens are known to be free of pathogens of concern, efforts can focus on managing the netpen to minimize the likelihood of infection. Health information on resident wild fish populations is crucial to managing the cultured fish and decrease the likelihood of disease transference from wild fish to the cultured fish. Further precautions such as single-year-class rearing will reduce the risk of introducing new diseases with new fish as well as maintaining a minimum distance for site separation. Coherent management practices require knowledge of the subtleties of the environment in which you work. For the GOM, because there is no precedent for netpen culture, some of these subtleties will be understood only through trial and error. Some basic information on the physical nature of the environment in the GOM, however, may serve to facilitate the estimation of best management practices.

PHYSICAL ISSUES IN THE GULF OF MEXICO

Water flow is a significant issue in netpen management because sufficient flow can flush out infectious stages of organisms and maintain water quality. The proper choice of site for a netpen, therefore, is critical and can be regulated as part of the licensing process. British Columbia, for example, makes issuance of all new commercial finfish aquaculture licenses contingent on meeting 15 siting criteria that address biological, aesthetic, and legal issues (BC MAFF 2004b). Ordinance 13.001 of the Mississippi Commission on Marine Resources (2000) specifies the parameters for required site assessments and the requirements for placement of the facility in relation to the bottom and surrounding interests. Maximizing tidal flow in the GOM must consider that throughout most of the region, tidal range is usually around only 0.6 m (2 feet). In addition, a substantial portion of the GOM experiences diurnal tides (one high and one low tide per lunar day) or mixed diurnal tides (2 unequal highs and 2 unequal lows per lunar day) that for practical purposes are diurnal. Thus, use of nets that maximize water exchange and keep the net clear of fouling organisms may be critical.

The physical make-up of the environment is important. The GOM is a semi-enclosed, partially land-locked, intercontinental, marginal sea separated from the adjacent Atlantic Ocean and containing a water mass with movements that differ substantially from those in the ocean (Gore 1992). The GOM has a wide shallow continental shelf that slopes to a deep pit, but is interrupted by three relatively deep canyons. In general, however, the 182 m (100 fathom) isocline is well offshore. This physical environment also engenders an additional problem—waves and the associated turbulence. As opposed to deepwater swells typical of oceanic aquaculture sites, the shallow water increases swell height and superimposes shallow water chop on incoming swells in the GOM, creating an extremely high-energy environment. In addition, tropical weather systems regularly traverse the GOM creating severe conditions. Therefore, when one considers that an operation must be approximately 40 km offshore to reach water depths sufficient to achieve an economically feasible scale of operation using present technology, transport to and from the facility under normal conditions is a major endeavor. The additional difficulties superimposed by the weather magnify the problem. From a fish health standpoint, the feasibility of scheduled, regular monitoring and fast response in such an environment becomes questionable. A disease outbreak could be well underway by the time it is detected if weather conditions prohibit contact with the site.

Ocean currents are also an issue to be considered. The current in the GOM is characterized by the Loop Current system. Water driven by the Equatorial and Guiana currents enters the GOM through the Yucatan Channel and moves in a generally north-northwestward direction spinning off series of gyres, particularly in the eastern GOM, along the way before exiting through the Florida Straight as a major component of the Gulf Stream (Gore 1992). The northward extent of the Loop Current varies according to season, extending further north during the summer. Circulation along the shelf is driven by winds, tides, and freshwater discharge sporadically interrupted by the intrusion of the gyres (Johnson et al., in press). The Loop Current, its associated gyres, and the interaction with shelf water are, at least in part, responsible for creating and maintaining the aggregations of nutrients and organisms that result in the high productivity of the region, and fishers are keenly aware of these fertile areas. The northern GOM, in fact, has been referred to as the "fertile fisheries crescent" (Gunther 1963). Indeed, the dispersal of several organisms including the exotic tropical jellyfish *Phyllorhiza punctata* into the northern GOM has been attributed to the gyres that spin off the Loop Current (Graham et al. 2003). Concomitant with these features that facilitate productivity is the abundance of intermediate hosts, vectors, and sources for parasites and diseases as well as animals that can clog nets. Thus, aquaculture operations in the northern GOM must be designed to deal with both the high background productivity and the unpredictability associated with periodic incursions of water potentially containing exotic flora and fauna.

TEMPLATE FOR FISH HEALTH MANAGEMENT IN THE GULF OF MEXICO

Philosophy

The development of an aquaculture industry in the GOM first requires the establishment of an enabling regulatory framework coordinated at the local, state and federal levels (Mitchell and Stoskopf 1999). Chapter 3 in this volume reviews the specific legal and regulatory issues applicable to obtaining the necessary permits to site aquaculture facilities in the GOM. A complete regulatory framework to operate aquaculture facilities must be based on the concept of fish health management whereby all parties, ranging from all levels of government (i.e., local, regional, state, and federal authorities) to the producers and their individual employees, embrace the philosophy of minimizing adverse effects to cultured animals, wild animals, people, communities, and the environment. A proactive, scientifically robust risk assessment process to quantify and manage the relative risks for disease introductions/transfers and environmental impacts (see Arthur and Bondad-Reantaso 2004 and references therein) must be at the foundation of this framework. Based on the scientific risk analysis, the program must develop and enforce a Code of Practice, a Code of Containment, and a Code of Environmental Protection (see the Newfoundland Code of Practice for examples (NAIA 2004)). In addition, the regulatory framework must include mechanisms such as inspections to ensure adherence to the codes (see British Columbia Ministry of Agriculture, Food, and Fisheries—www.agf.gov.bc.ca/fisheries/compl/ce_main.htm). These mechanisms should provide for typical penal repercussions for violations, and facilitate the involvement of producer associations to advocate for the industry and peer review colleagues to implement a good neighbor policy that facilitates adherence to codes of practice such that due diligence is given to the prevention or mitigation of disease or environmental impacts. Finally, some mechanism must be implemented to indemnify producers much like is done in agricultural settings when something beyond the control of a producer, such as a weather event, a disease outbreak, or a cull order, results in the loss of a crop.

Practice

Specific, fundamental questions about operational procedures must be addressed to maximize the likelihood of success in an operation. It is not our intent to speak for those who may eventually face designing an application procedure. Rather, we present these questions from the fish health management perspective espoused throughout this paper. Answers to these questions should be viewed as potentially legitimate information required for consideration of an application to establish an operation. Where possible, we comment on the manner in which those questions have been addressed in other jurisdictions. In other cases, we present only ideas about ways in which they could be addressed. We present these ideas through a series of some basic procedural questions that must be addressed when developing and implementing a regional fish health management plan for the GOM.

What permits are required? Who issues them?

The United States Army Corps of Engineers is responsible for maintaining navigational access to U.S. waters and must approve anything installed in navigable waters for its effect on water, wildlife, recreation, navigation, and pollution. The U.S. Coast Guard requires that installations meet marking and signaling requirements facilitating safe navigation. The Environmental Protection Agency must issue a wastewater discharge permit for any facility discharging wastewater into U.S. waters. The U.S. Fish and Wildlife Service requires review of any permit that impacts aquatic plants and animals and the Minerals Management Service has some jurisdiction over operations near oil, gas, or mineral leases (Fletcher, this volume). Additionally, state agencies may be involved if the operation is within state waters.

What is the approval process?

The order of events must be known (see the Newfoundland Aquaculture Policy and Procedures Manual (NL DFA 2004a) as an example). Public comment and input from a variety of user groups should be encouraged.

What are the conditions of continuance once approved?

The issue of how to insure continued adherence to the conditions of approval should be addressed. Questions such as which inspections are required and at what intervals should be answered. British Columbia, for example, requires at least yearly inspections during which inspectors interview company officials and review the farm's operational procedures, management plans, and maintenance records for completeness and compliance with the regulation with respect to therapeutant use, stock inventory, net and equipment maintenance, mooring systems, containment systems, and predator control systems. The inspectors perform above-water visual examinations of the site, including a perimeter inspection of each containment pen and infrastructure including anchors, walkways and other associated hardware. Spot dive audits are also conducted at randomly selected sites where a dive team is contracted to review the underwater portion of the containment and anchoring system (British Colombia Aquaculture Code of Enforcement—www.agf.gov.bc.ca/fisheries/compl/ce_mainhtm).

Pursuant to the existence of a mechanism for issuing and regulating permits, questions related to the information required in an application must be addressed. We believe that a substantial amount of information should be required. Our view, however, is not that the process should be prohibitive. Rather, we believe that the knowledge gained from this information will increase the likelihood of success.

What constitutes a site? Based on what information?

Hydrography, depth, temperature, oxygen profile, and tidal flow are among the important parameters that must be determined. A formal site assessment process must be developed (DFO 2002; NL DFA 2004b). Some states, including Mississippi, already specify some assessment and placement criteria for aquaculture sites (see Mississippi Commission on Marine Resources 2000); thus, coordination will be required. Certain failure of an aquaculture operation is expected if a decision is made to place a site in a suboptimal environment in relation to the animal's physiology and the seawater/seafloor dynamics.

Land and water ownership must be considered. In Canada, for example, aquaculture sites require the leasing of Crown land/water (see NL DFA 2004a; BC MAFF 2004b). If a lease is required, should there be a rental fee?

How many netpens per site? How much distance between sites is required to mitigate water quality/environmental issues and disease transmission?

One kilometer can be used as a minimum starting point for distance between sites based upon requirements in other jurisdictions (British Columbia and Newfoundland and Labrador, for example), but a mechanism for adjusting that to locally relevant conditions must be considered. Coordination with existing ordinances (Mississippi Commission on Marine Resources, Ordinance 13.001 for example) will be necessary. As well, the site distances should be assessed based on sound epidemiological analysis (Hammell and Dohoo 1999) and marine hydrography. The issue of how many netpens constitute a site will be dependent on logistics, as well as environmental conditions. Because of the emergent nature of the industry in the GOM, the resolution of these issues will require research, the application of sound epidemiological analysis, and adaptive management.

Will sites be single year class sites? Single-species sites?

For optimal health, an "all in-all out" growout cycle is advocated for one stock species. For economic reasons, variances may be issued on a case-by-case basis. The timing and frequency of grading must be in conjunction with the environmental conditions.

In what will the animals be housed? How will food be administered? What is the optimum maintenance and feeding schedule?

Design and specifications of the netpen should be submitted for review to insure adequate engineering. Adequate nutrition based on scientifically derived data must be provided to the stock both for humane reasons and for optimizing performance.

How do you ensure the containment of the animals? How do you safely move and harvest animals?

Mooring systems must be regularly inspected. Adequate protection against rips must be required including net checks, inspection by ROV, and net tensile strength audits. Maximum allowable age for moorings, nets and containment equipment can be set. Plans for moving and harvesting should be disclosed. Specific plans for securing or moving the facility in the event of hurricanes are presently required by ordinance in Mississippi (Mississippi Commission on Marine Resources, Ordinance 13.001).

Who is the Fish Health Professional in charge?

Establishing a relationship with an aquaculture veterinarian is crucial. This will enable access to individualized health management strategies, prescriptions, Investigational New Animal Drugs (INAD), [Experimental Studies Certificates (ESC), Emergency Drug Release (EDR) in Canada], chemotherapeutants, pesticides, and a tailored vaccination regimen. Fish farmers are required by law to seek the advice of a licensed veterinarian when administering prescription-only therapeutants. Veterinarians must develop and maintain a Veterinarian/Client/Patient Relationship (VCPR) in which the veterinarian has assumed the responsibility for making medical judgments regarding the health of the animals and the need for medical treatment, and the client (owner or caretaker) has agreed to follow the instructions of the veterinarian. A review of state legislation is required to determine the details of the Veterinary Medical Act that pertains to maintaining a valid VCPR and offering medical services to the aquaculture producers. There must be sufficient knowledge of the animals and/or appropriate and timely visits to the premises by the veterinarian to initiate at least a preliminary diagnosis of the medical condition of the animals. The veterinarian must be readily available for follow-up in the event of adverse reactions or failure of the regimen of therapy. Federal and state veterinarians are generally available, but someone must be designated as "in charge" and participating parties must understand the relationships. Also, the role of other fish health researchers in the diagnostic and treatment procedures should be established.

Which species will be grown?

This issue is dependent on technical issues to determine which organisms can be feasibly grown. Other critical issues include the consideration of robust economic analyses (Posadas and Bridger, this volume).

How many fish will be stocked? In how many netpens? For how long?

The stocking density in netpens and the biomass in the region must be kept at recognized optimal levels. Research may be required to establish these limits.

Is fallowing considered in the long-term plan? How long will sites need to be fallowed? How many extra sites will be required to insure continuous production?

Standard protocols from other jurisdictions can be used as a starting point. Jurisdictional review must include consideration of the appropriate principles similar to those outlined in Australia that have been considered to manage the aquaculture industry in a sustainable manner to generate wealth for the country's citizens (Aquaplan 2001).

Where will the fry come from? What is the source of the broodstock? Is a selective breeding regime for broodstock desired?

A comprehensive broodstock program to deliver disease tolerant stocks with low feed conversion ratio and optimal performance is required. To diversify risk, the broodstock should be housed in separate locales, buildings and water sources. Nurseries should be implemented to further house the progeny prior to seawater entry. A nursery would enable the stock to be vaccinated, assessed for health, and reach a minimal recognized size prior to seawater transfer. The issue of broodstock and fry genetics should be considered. Presently, the three main candidate species' are considered single unit stocks in the GOM, but a conservative approach requiring stocked fry to come from local broodstock may be desirable. Genetic tagging, such that individual progeny of specific broodstock can be identified, is technically feasible and could be developed as part of a genetics management program.

What health standards must fry meet for transfer to netpens?

Is testing for the organisms specified in the AFS Bluebook, Canada Fish Health Protection Regulations, or the OIE Aquatic Animal Health Code sufficient or necessary?

What biosecurity/disinfection procedures will be in place for people and equipment at both the growout site and broodstock and hatchery facility?

Disinfection is required to minimize the build up and spread of infectious pathogens and parasites. Information is readily available for various disinfection agents, concentrations and appropriate application, neutralization, and disposal methods. The disease of concern must be suppressed by the disinfectant chosen—this requires strict adherence to appropriate application and contact time to allow the disinfectant to be effective. The environmental agency that regulates the use of disinfectants and seawater use must be consulted prior to usage. All organic debris (mucus, blood, tissue and detritus) must be physically brushed or hosed off the area where disinfectant will be applied. Disinfectant contact time on equipment and clothing should be maximized to ensure complete disinfection. For example, when an iodophore disinfectant is applied it should be at a concentration of 100–200 mg/l for a minimum of 10 min (Washburn and Gillis 1998; MLA 2000). Disinfectants containing potassium peroxomonosulphate sulphamic acid and sodium alkyl benzene sulphonate are being used in the aquaculture industry due to high success rates against viral pathogens. Every piece of equipment, including boats, should be either dedicated to a single site or undergo routine disinfection procedures.

The flow of people must be regulated as well. When visiting finfish aquaculture sites, visitors must follow the necessary steps to ensure quality assurance, disease-free sites, and a positive working relationship with the industry.

The following is a recommended protocol to follow when visiting finfish sites. Visits should be appropriately scheduled with the site manager. The purpose is to monitor traffic and prevent unnecessary incursions on to the site. If disease is present or evidence of unknown mortality is detected on site then the visit should be postponed. It is recommended that visitors visit one marine cage site per day. In the spring and summer it is recommended that visitors wear a set of clean, disinfected gear over the life vest when walking on the cage system or housing. Rubber boots are required and must be disinfected prior to entering the boat to bring the visitors to the site. A footbath should be available on the boat with fresh disinfectant. If a footbath is available onsite then all visitors must step into the footbath prior to walking on the site system. The boots and lower pant legs (if rain gear is worn) should be scrubbed while standing in the footbath if it is safe to complete the action. Boots must be immersed in the disinfectant to a depth of 10 cm (4 in) for at least 2 min depending on the disinfectant. If multiple sites are to be visited, clean clothes or different rain gear must be worn to the additional sites. The previous rain gear is to be enclosed in a sealed bag and brought back to shore for disinfection. Routine cleaning of the site apparel must be performed to decrease levels of detritus or organic matter that may impede the activity of the disinfectant and harbor pathogens.

What are the disease monitoring protocols?

How often will samples be taken? Which fish will be sampled? Which tissues will be sampled? How will the samples be handled and processed? Consultation with a biostatistician or an epidemiologist is recommended.

Who will test the samples?

Which laboratories are approved for testing? Which tests do they use? Is your sampling scheme compatible with the test, both in terms of the collection/handling of samples and the sensitivity/specificity of the test. A relationship with those laboratories should be developed to maximize the reliability of the results.

How will pests/predators be controlled? How will chemotherapeutants be administered?

The procedure should not be adversarial. Government agencies (veterinarians, regulators, and other fish health professionals) and producers should cultivate a relationship to ensure the free flow of information. Once required information is reviewed and, at least conditionally, accepted, other pertinent issues critical to success will need to be addressed.

Is the business plan feasible?

See Chapter 7 in this volume for a discussion of business and economic issues.

Vaccination regimen?

Will fry be vaccinated? Against what? Is a SPF broodstock required? If so, which pathogens are to be excluded and why?

What disease issues are characteristic of wild fish at the chosen site? What wild fishes are typically encountered at the site?

Because wild fishes can be a major source of disease in netpen culture, routine monitoring should include observations of wild fishes around and within the site as well as periodic sampling of those fishes for examination for diseases and parasites.

What is the procedure for the collection and disposal of mortalities?

Are divers used? Air lifts? Mortality rings? Some combination thereof? Are there site-specific incineration, composting, offal management or extraction processes? Secondary processing of the residual products can be constituents of tires, ice cream and pharmaceuticals (Goodlad 1999)?

What qualifications or training will be required of staff?

Lack of knowledge and training regarding aquatic species health has been identified to contribute to the failure of some aquaculture operations due to employee turnover or failure to schedule continuing education either in house or through outside agencies. Site workers are crucial to early detection of altered health conditions. Site workers need to be aware that presence of bacteria, viruses or parasites does not necessarily mean disease will occur. The presence of an agent in combination with other risk factors may lead to disease. Risk factors include weakened fish, poor water quality, and poor site selection. Disease is prevented or mitigated by controlling the associated risk factors.

There are a number of characteristics that producers may observe that would indicate a fish health problem initiating at a site. The swimming behavior may be altered and fish may exhibit erratic swimming, flashing/rubbing, jumping, or loner fish circling at the top of the cage. The feeding activity of the fish generally decreases in diseased fish. Skin lesions may become evident such as ulcers, red spots, white spots, or raised scales. Flared gills may be exhibited characterized by open or eroded opercula. Fin erosion may become evident. Floating dead fish may be observed on the top of the water indicating that further mortalities will be found at the net bottom. Changes in water quality conditions may precipitate a health crisis or indicate that one is impending. Water conditions such as increased or decreased temperatures, supersaturation, hypoxia, anoxia, and algal or mussel set may be encountered. If these conditions are observed onsite then management and health personnel must be notified and disease diagnostics initiated.

What size should fry be to maximize survival when introduced into the netpen?

This will require research and may be specific to each species. Survival of released fish is related to size at release (Leber and Arce 1996), but that must be balanced with the economics of raising them to that size in land-based hatcheries/nurseries versus moving fingerlings offshore to cages at a smaller size.

What is the role of public relations in the operation?

An association among the various producers should be formed to facilitate and advocate common interests. An aquaculture liaison committee with local stakeholders should be initiated and dialogue begun with surrounding communities to communicate the farming practice to the public and allow a high degree of transparency. Also, interaction with the federal Joint Subcommittee on Aquaculture (JSA) is advisable because of its role in setting policy. Relationships with academia should be cultivated to facilitate research on challenging health or husbandry issues.

CONCLUSIONS

The history of aquaculture, as in agriculture, has proven that mistakes will be made and sometimes repeated. It is the intention of this chapter to show that when the proper questions are asked, a template for success can be created, implemented, and result in the delivery of a sustainable aquaculture industry from a fish health management perspective. With stakeholder cooperation, enabling regulation, and strong leadership at all levels of government, aquaculture can supply additional benefits from a common resource, such as offshore waters, providing an economic boost to coastal communities.

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CHAPTER 9

INNOVATIVE TOOLS IN PUBLIC EDUCATION & TECHNOLOGY TRANSFER FOR AN EMERGING OFFSHORE AQUACULTURE INDUSTRY[1]

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ABSTRACT

Although principally the same as other aquaculture operations, the details involved in raising fish in cages considerable distance offshore in the Gulf of Mexico can be hard to imagine—for both the general public and aquaculture practitioners. The Offshore Aquaculture Consortium (OAC) turned to technology innovation and to industry and university partnerships as "extension tools" to educate these stakeholder groups. The OAC established Cage Cam to provide real-time Internet feeds of the offshore operations, an aquarium exhibit for conceptualization, and a "How-to…" feature on our web site for logistics transfer.

INTRODUCTION

Many times researchers and extension personnel deal with projects that are difficult "to put your arms around." This poses a unique challenge when you're tasked with disseminating project information to the general public and providing technology transfer to interested industry personnel. The Offshore Aquaculture Consortium (OAC) used new innovative communication tools to take their stakeholders 40 km (26 mi) offshore in the Gulf of Mexico.

The OAC was formed to conduct the necessary research for development of an offshore aquaculture industry in the Gulf of Mexico region (Bridger et al. 2001). Although principally the same as other aquaculture operations, the concept of raising popular recreational and important commercial fish species offshore in the Gulf of Mexico is a substantial departure from the existing visualization of catfish farming in the Mississippi Delta region. Public conceptualization of open ocean aquaculture is further complicated because of its remoteness and distance from shore.

OAC extension efforts, therefore, have focused on bringing the remote, and somewhat abstract, operations of offshore aquaculture to the general public and future investors of this emerging industry. We set the following objectives to meet our extension goal:

1. Provide conceptualization of an offshore aquaculture enterprise to the general public.

[1] This chapter is reprinted with permission from: Reid, T. and C.J. Bridger. 2004. Innovative tools in public education and technology transfer for an emerging offshore aquaculture industry. Journal of Extension [On-line]. 42. http://www.joe.org/joe/2004february/tt2.shtml.

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2. Develop exhibitory that explains the need for national aquaculture production and demonstrates offshore aquaculture operations in the Gulf of Mexico.

3. Transfer the technology of logistics mitigation learned while operating an aquaculture enterprise in the U.S. Exclusive Economic Zone (EEZ).

APPROACH & OUTCOME

Cage Cam

The OAC research site is adjacent to a ChevronTexaco gas platform approximately 40 km (26 mi) offshore in U.S. EEZ federal waters. This site was chosen because it provided sufficient depth that allowed the cage to be sunk in severe sea conditions and its location adjacent to a manned gas production platform provided passive protection from shipping activity in the area and cage surveillance.

ChevronTexaco's strong interest in the project, and the "bird's eye view" of the cage from the platform, led to new collaborative outreach efforts including mounting a camera on the platform and transmitting streaming pictures of the cage via internet to researchers and the general public. OAC researchers used their access to the camera controls to pan, zoom and focus the camera to view the cage's actions in various sea conditions. The education and outreach merit of Cage Cam also provided real-time visualization of an operating cage site to the general public (Fig. 1).

Public Aquarium Exhibit

The University of Southern Mississippi operates the J.L. Scott Marine Education Center and Aquarium (MEC) in Biloxi, MS. More than 80,000 visitors annually tour the MEC including 31,000 students and teachers. OAC researchers approached MEC personnel with the idea of educating the public through an exhibit that explains:

- the expanding role of aquaculture in the United States;

- why offshore aquaculture is needed to

Fig. 1. Cage Cam provides real-time images of the cage 40 km (26 mi) offshore.

meet the country's increasing seafood demand; and,

- how the OAC's research efforts in the Gulf of Mexico can help.

Discussions with the MEC educators resulted in a first-class exhibit that includes a 3,000-gallon aquarium with a scale model of the cage and several individual fish of the candidate offshore aquaculture species—cobia, red snapper, and red drum (Fig. 2). MIT researchers constructed a large-scale model of the cage, including its Robofeeder, shackles, ballast weight, and mooring system. The display also includes two flat-screen monitors. One displays presentations such as the cage's deployment. The second displays real-time images from Cage Cam, illustrating to visitors that the aquarium's scale model replicates OAC's full-size cage in the Gulf of Mexico.

Since its debut in April 2002, thousands have personally visited the exhibit, and an additional 240,000 students and teachers have visited through Mississippi Educational TV.

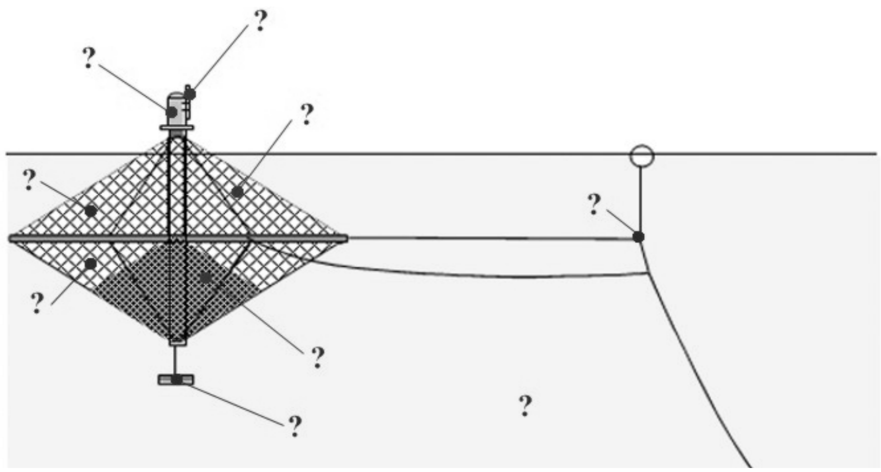
Technology Transfer

Owing to offshore's remoteness of operations and frequent harsh sea conditions, simple transfer of coastal or near shore aquaculture logistic mitigation procedures to offshore aquaculture is unsuitable. Because the OAC project is developmental by nature and is expected to encounter numerous operational issues, a special OAC web site was developed to disseminate lessons learned to other researchers and offshore aquaculture developers (www.masgc.org/oac).

The site's "How-to…" section provides viewers with a cage schematic featuring several hot links to various components of the OAC's cage system (Fig. 3). Each linked page contains explanation and images describing that particular operation so that the viewer could perform the operation on his or her own offshore aquaculture operation.

Fig. 2. OAC exhibit at the JL Scott Marine Education Center and Aquarium.

Fig. 3. "How-To…" web page on the OAC internet site.



CONCLUSIONS

Faced with the challenge of educating the public and industry stakeholders about offshore aquaculture and its research project sited 40 km (26 mi) off Mississippi's coast, the OAC turned to technological innovation and collaboration with industry and public aquaria for help. Through its public education and technology transfer efforts, offshore aquaculture can now be understood and visualized more easily by the public, and researched and developed more efficiently by aquaculture enthusiasts.

ACKNOWLEDGMENTS

The authors wish to thank ChevronTexaco for its support of OAC research and extension efforts; Verizon for supplying the Internet bandwidth giving the public an opportunity to view Cage Cam online; John Grigsby, as designer of the OAC web site; and, the staff of the MEC for their assistance in the development, construction, and maintenance of the OAC exhibit. These OAC extension efforts were funded through the National Sea Grant College Program of the U.S. Department of Commerce's National Oceanic and Atmospheric Administration (NOAA Grant #NA16RG1631), the Mississippi-Alabama Sea Grant Consortium and the University of Southern Mississippi.

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CHAPTER 10

CONCLUDING THOUGHTS: THE FUTURE OF OFFSHORE AQUACULTURE

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ABSTRACT

The Offshore Aquaculture Consortium (OAC) was created as a collaborative, Gulf-wide, interdisciplinary research and development program in response to the U.S. Department of Commerce Aquaculture Policy. OAC research has demonstrated numerous components of offshore aquaculture in the Gulf of Mexico including permitting requirements, mooring systems, cage/mooring survival during several hurricanes and tropical storms, automatic feeding capabilities, and fish survival during hurricane passage. Other components of OAC research will support a future offshore aquaculture industry including use of genetic analysis to identify harvested product originating from aquaculture facilities and creation of both economic and environmental impact models. Numerous impediments still exist that each, in part, retard development of an offshore aquaculture industry in the Gulf of Mexico, and throughout the nation. These impediments include unsteady government support, an unsuitable permitting and regulatory environment, negative public perception and user conflicts, incomplete industry planning, technology suitability, and insufficient and inconsistent fingerling supply.

OFFSHORE AQUACULTURE CONSORTIUM

The Offshore Aquaculture Consortium (OAC) was created as a collaborative, Gulf-wide, interdisciplinary research and development program in response to the U.S. Department of Commerce Aquaculture Policy. The purpose of the OAC was to conduct studies in marine policy, ocean engineering, ocean environmental, and fish grow-out, among numerous other issues, to generate primary scientific data related to offshore aquaculture (http://www.masgc.org/oac/). OAC research has demonstrated numerous components of offshore aquaculture in the Gulf of Mexico including permitting requirements, mooring systems, cage/mooring survival during several hurricanes and tropical storms, automatic feeding capabilities, and fish survival during hurricane passage. Other components of OAC research will support a future offshore aquaculture industry including use of genetic analysis to identify harvested product originating from aquaculture facilities and creation of both economic and environmental impact models. However, economic viability and logistics to manage a commercial-scale operation offshore was not demonstrated. Now, with the termination of federal funds, the OAC has been forced to conclude its research. An offshore aquaculture sector still does not exist in the Gulf of Mexico.

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IMPEDIMENTS TO INDUSTRY DEVELOPMENT

Given the present dependence on foreign supplies to fulfill domestic seafood demand in the United States, one would imagine that developing a responsible aquaculture industry within the U.S. Exclusive Economic Zone (EEZ) would be a high priority. However, an industry has been slow to develop within the U.S., and certainly the Gulf of Mexico region, for a number of reasons. Below is a list of those reasons I feel are most important with discussion from my experiences in the Gulf of Mexico region (additional discussion and more specific research needs are presented, from a consensus of attendees at the most recent OAC regional workshop, in Bridger 2002).

Steady Government Support

The OAC was fortunate to receive funding through the National Marine Aquaculture Initiative (NMAI), administered by the National Sea Grant College Program. The NMAI was established in response to the Department of Commerce Aquaculture Policy signed August 10, 1999. The unfortunate aspect of the NMAI has been the diminishing level of funding provided over the course of the research work plan. Despite increasing seafood trade deficits and fishery pressures on U.S. wild stocks, NMAI Year 2 budgets were reduced by 60% of the original allocation, and subsequently zeroed out for Year 3 funding. The National Sea Grant College Program generously offered funds to the OAC in hopes of completing a grow-out trial, but those funds were insufficient when considering the research would be conducted 40 km offshore. If domestic seafood production is a priority for the nation, then funding for the necessary research to develop a responsible marine aquaculture sector should be established.

In a recent article, Cyr Couturier of the Marine Institute of Memorial University of Newfoundland discussed the “research to commercialization continuum” necessary for aquaculture industry development from a Canadian perspective (Couturier 2003). His commentary provided several important points regarding the continuum: a) duration of each phase (research, development, commercialization) varies but generally decreases along the continuum; b) each phase is interdependent on the others and none are mutually exclusive; c) ongoing research and development is required following commercialization to remain competitive and solve constraints; d) level of risk reduces as commercialization is achieved; and, e) the financial cost increases along the continuum. Couturier provides examples to support these characteristics that show a \$1 million research effort requires \$4–5 million for development followed by another \$5–10 million in commercial financing (likewise the time required for each phase changes with 10–15 years for research and 5–10 years for development in the case of the salmon culture industry). These values may seem extreme but he finishes the argument by stating such levels of effort results in a return on investment potential of \$10 million or more annually to the Canadian economy.

Those dollar values are relative in that they would be dependent on the species or system being developed. New species that utilize existing infrastructure and system management for grow-out would require research efforts to be focused on broodstock handling/spawning and larval/fingerling rearing. In the case of offshore aquaculture, grow-out systems and management plans need to be developed that might depart from existing operations and therefore would require additional funds apart from those designated to species development (both could occur simultaneously if new candidate species were to be raised offshore).

While aquaculture operations are developing in exposed sites throughout the world, most regions utilize adaptive management plans for industry success. In such cases exposed sites represent the natural evolution of the industry requiring additional space for increased production. This would not be the case for most of the U.S., having little coastal cage culture operations (with the exception of the Pacific northwest and Maine), therefore requiring additional research funding to create a new industry that is exceptionally dissimilar to the predominate land-based culture systems (ponds and tanks or raceways) located throughout the nation. A quick back calculation based on the proportions provided from the Canadian experience and a potential regional economic impact of $200 million annually for the Gulf of Mexico yields the requirement for $100–200 million for commercial financing, $100 million for development, and $20 million for research. These values are indeed substantially higher than the level of funding provided to the OAC through federal support for its research.

Despite these challenges, the NMAI program has funded several successful projects throughout the nation and resulted in coastal aquaculture operations off the coasts of Hawaii and Puerto Rico. In both cases, however, NMAI funds have been used mostly to provide the fingerlings for grow-out trials in the sea cages and conduct environmental monitoring of the sites with independent operators responsible for day-to-day management of the farm. The Hawaii case also benefited from approximately three decades of research effort by the Oceanic Institute and the University of Hawaii focused on developing spawning and larval/juvenile grow-out techniques for the candidate species, Pacific threadfin. These successes, however, are difficult to extrapolate to commercial-scale operations offshore given that both are located near shore and operating a very minimal number of cages each—further illustrating the need for government investment to establish regional commercial-scale demonstration farms throughout the nation, comparable to land-based catfish research stations in the southern states.

Permitting and Regulatory Environment

The permitting and regulatory environment for aquaculture in the U.S. has been the subject of much discussion (e.g. Goudey 1996; Bunsick 2003). Commercial ventures in state waters deal primarily with respective state agencies for the necessary permits. Decreased complexity and bureaucracy could be anticipated at this level of governance given the relative ease of access to local regulators and willingness of local agencies to work with industries having positive social and economic impacts for their state. Offshore aquaculture operators—by definition operating in the U.S. EEZ—should expect to experience a more complex regulatory structure, requisite to meet requirements of both state and federal agencies having oversight of aquaculture ventures. Additionally, the pace at which federal regulations change is much slower than at the state level, illustrating this complexity coupled with the political pressures from many stakeholder groups influencing the bureaucratic system of the federal government.

OAC researchers completed a review of the permitting requirements to site an offshore aquaculture operation in U.S. federal waters, and states along the Gulf of Mexico (Appendix A, this volume). This review has assisted several potential commercial operators with the identification of permits necessary and pertinent contact information. Regulatory changes are required, however, for more efficient permitting (not synonymous with easier permitting as some pundits would have you believe). It would be extremely beneficial to empower one lead permitting agency to create a single permit for offshore aquaculture that meets all agency requirements while simultaneously providing a single point-of-contact, one monitoring and reporting scheme, and one expiration/renewal date for that permit, rather than having to deal with all agencies having oversight.

Simply acquiring permits to occupy ocean space is not enough. Comparable to its land agricultural counterpart, the aquaculturist must have access to a long-term lease that encompasses the seabed, water column and surface to conduct its operations. Effective ownership of the entire site will allow the aquaculturist to expand its operations to potentially include multiple species within different trophic levels that might be grown on the seabed (e.g., liverock), in the water column (fish in cages), and within a polyculture or integrated aquaculture scenario (e.g., oyster relaying). A lease existing over a 15–20 yr period will attach monetary value to the farm location. This value could be adjusted based upon site performance associated with stock grow-out, fish health management, survival, and food conversion ratio over an extended period. Finally, and most importantly, a long-term lease will provide collateral that might be used by the aquaculturist to access traditional financial sources to raise the necessary capital funds required to establish commercial scale operations.

Once permitted for offshore aquaculture the operator must contend with operation regulations. In the U.S., aquaculture operators have to meet the demands of a suite of regulations and regulatory agencies. Numerous regulations are expected to exist owing to the nature of aquaculture (especially for cage culture operations) where one has to moor a structure to the seafloor, raise fish species that may also be managed in a wild fishery, meet environmental standards related to feces and excess feed exiting the cage, provide a product that is safe for human consumption, and perhaps dealing with both state and federal agencies that may frequently overlap in scope.

In many instances existing laws were not written specifically for aquaculture operations but attempts are being made to conform laws to meet aquaculture needs. Recently, the National Marine Fisheries Service (NMFS) conducted a legal review of its authority to provide a permit for commercial grow-out of cobia in Gulf of Mexico federal waters. Within its interpretation, NMFS legal council concluded that use of the term “harvest” in the Magnuson-Stevens Act did not allow exemption of aquaculture operations from the same regulations as wild fisheries. This meant that the Fishery Management Plan (FMP) for the species being raised would also regulate the aquaculture industry. In the case of cobia, only two fish per person per day could be “harvested” at the current legal size (84 cm) from the aquaculture cages as outlined by the FMP! One might venture to guess this would certainly remove any chances for economic success. This interpretation could also make it illegal for a fish farmer to hold juveniles under the indicated size in a cage for grow-out. Regardless of how ridiculous, this is just one example of the growing pains for a developing industry trying to fit into established regulations that cannot easily suit its needs.

The Gulf of Mexico Fishery Management Council is presently undertaking the public consultation process regarding a Generic Amendment to allow aquaculture of species federally managed in the Gulf of Mexico, thereby providing the necessary exemption of aquaculture to wild fishery regulations. Although this Amendment is being drafted, the process will require much debate and public review prior to possible adoption. In addition, at the time of writing, the National Oceanic and Atmospheric Administration are developing legislation to govern offshore aquaculture enterprises in the U.S. EEZ. However, criticism of this legislation is that it is in large part based upon near shore aquaculture operations and not commercial aquaculture experiences in the offshore environment. These arguments once again illustrate the need for substantially greater government funding to establish regional commercial-scale offshore aquaculture to determine potential impacts and set regulatory limits for future operators.

Public Perception and User Conflicts

Those groups that best inform create public perception. There seems to be no end recently to the advocacy groups and documents providing manipulated, outdated, and/or misleading information regarding aquaculture and its practices (even with the very limited marine aquaculture industry presently operating in the U.S., the Pew Oceans Commission summary report (2003) listed aquaculture as the fourth "major threat" to U.S. oceans, ahead of coastal development, overfishing, habitat alteration, bycatch, and climate change). In many instances the same individuals play a key role in the authorship applying a new spin to the same outdated and manipulated data. Manipulation may be quite blatant by comparing data that use different units of measure imparting an impression that the situation is much more serious than in reality. Sweeping generalizations of literature findings is also common practice whereby arguments are presented against the entire aquaculture industry as a whole (not separating various aquaculture sectors) based on data collected from a single location in the world and using a methodology that might not be standardized. Such generalizations are dangerous; as one poorly selected or managed farm site becomes representative of an entire industry. Other cases represent research findings that were directly supported by environmental advocacy groups. Regardless, these emotional messages are appealing to much of the general public, resulting in the placement of enormous pressures on government – which is heavily lobbied – and industry – which frequently finds itself occupying the defensive position. Tiersch and Hargreaves (2002) provided a concise discussion for contending with advocacy groups. Their discussion should be studied by individuals in the aquaculture industry prior to publicly commenting on environmental messages.

It is important to note that environmental advocacy is simply an industry to many of the multi-national organizations involved and no different than any other industry worried about its bottom line to survive. For those organizations I pose the questions: If there is no aquaculture industry where would seafood supplies originate in a world of increasing human population growth, increasing per capita seafood consumption, and decreasing wild fisheries resources? If not now, when? (After the majority of the fisheries resources have collapsed and we no longer have time to develop sustainable coexistent operations?)

On the other end of the environmental group spectrum are grassroots organizations composed of the public who are concerned with the integrity and safety of their local environment. Most of the general public can be reasoned with and relied upon to draw their own conclusions after balanced information is presented. With the appropriate dedication of time and consultation, these organizations will understand that aquaculture is indeed the only user group of the world's aquatic resources dependent on a clean and safe water supply for economic success. Even in the case of wild fisheries, wild fish populations will likely avoid polluted regions and wild fishers will follow those fish. Aquaculture, on the other hand, is fixed in space and therefore vulnerable to ambient environmental pollutants that may come either from external sources or originating from the aquaculture industry itself. For this reason alone aquaculturists must operate wearing their "environmental steward hats." While we develop aquaculture in this new frontier, however, we must not lead the public into expecting that offshore operations will have zero environmental impact. This is impossible and will become abundantly clear when numerous commercial scale operations exist in the same general location. A more suitable approach would be to ensure the public that through responsible industry development, impacts to the water column and benthic environment will be well within acceptable limits.

Throughout its existence the OAC has considered public education, outreach, and technology transfer of utmost importance. A considerable portion of the overall budget was allocated towards regional workshops, establishing a public education exhibit (Fig. 1), and maintaining a web site to ensure wide dissemination of research results and lessons learned (Reid and Bridger, this volume). A critical component of this was to inform not only the positive results but also the methods that did not work from our experiences. The integration of education and outreach should become mandatory with all research programs, regardless of the field of study or funding agency. This is becoming more commonplace with some funding agencies. A further step in this direction would be the involvement of an outreach and/or education specialist to ensure the effort is maximized to its greatest extent. Having the appropriately (scientifically) interpreted data enter the public arena for debate will decrease the amount of junk science and advocacy targeted toward aquaculture as the general public will further demand such rigors to be employed by environmental groups. You can't know what's wrong, if you don't know what's right!

User conflicts must be carefully considered to avoid further delays in the permitting process and subsequent vandalism and theft. In the case of the OAC, the cage site was selected merely on two attributes, neither of which was associated with the biological needs of the fish. First was the desire to be in 25 m of water to minimize the impact of northerly or tropical fronts moving through the region. Second was the presence of a manned gas production facility just a few hundred meters away. The latter criterion was very important in the vast expanses of ocean in the Gulf of Mexico and its enormous marine traffic associated with shipping, fisheries, and recreational boaters. Being near a manned gas platform served the OAC through passive protection and surveillance for vandalism and storm damage – to ChevronTexaco the relationship could best be described as altruistic, or being a great neighbor to a research program sharing the same marine environment.

Although passive protection might have been achieved against large ships, one instance was witnessed by workers on the gas platform involving the entanglement of a shrimp trawler into the mooring system. No

Fig. 1. The OAC public aquarium exhibit located at the University of Southern Mississippi's J.L. Scott Marine Education Center and Aquarium, Biloxi, MS (Photo credit: Carole Williams-Keenze, ChevronTexaco).

damage to the cage netting could be attributed with certainty to that incident but a similar event could be devastating to any aquaculture operator in the future. Further, numerous recreational fishers frequently fished in the vicinity of the cage as determined by the large number of hooks and other rigging (including a rod and reel) found on the cage and mooring system (Fig. 2).

The OAC took advantage of the "bird's eye view" of the gas platform by establishing Cage Cam to allow continuous observation of the cage via the internet (Fig. 3). Even with this degree of attention some unexplained holes occurred in the netting that might best be attributed to diver vandalism using a knife to cut entry into the cage (other holes also occurred but were determined to be the result of sea conditions). These experiences reiterate the need for offshore aquaculturists to have some form of control over a leased space and constant surveillance of the cage systems perhaps through a permanent presence offshore.

Appropriate Industry Planning

An important missing component to develop an offshore aquaculture industry has been industry planning. Planning might include a situation analysis to determine existing infrastructure and future needs of the industry; site selection based on existing marine uses and application of GIS technologies; social research to determine the exis-

Fig. 2. Fishing tackle collected off the offshore cage and mooring system (Photo credit: Tim Reid, Mississippi-Alabama Sea Grant Consortium).

tence of an accessible workforce and/or necessary training; and, legal methods to secure tenure of the water column and bottom for aquaculture. The latter has received some attention with regard to establishing Marine Aquaculture Zones (Fletcher and Neyrey 2003) that may be further extended to Marine Aquaculture Parks where numerous operators would co-exist. Most of the remainder of the planning list has received little or no attention to date despite numerous attempts by OAC researchers to acquire funds for these activities. Like most research topics, attention is only given when absolutely necessary and not as a proactive response for planning (i.e., planning and GIS will become a necessity after several farms have been haphazardly sited offshore). These are all critical components of industry development particularly if the research and industry wish to claim some sense of "sustainability" in the future.

Finally, industry planning must incorporate fish health management strategies from the outset to avoid epidemic situations that could devastate this emerging aquaculture sector. Nearly all of the open ocean operations presently operating in the U.S. are sited in sub-tropical environments. These regions will be particularly vulnerable to fish health issues given poor husbandry practices, high stocking densities, unsuitable industry planning, or high ambient water temperatures that favor spread of potential pathogens. Generally accepted fish health management strategies must be adopted including single-year class management, bay management systems, use of tidal excursions or current rates to set site distances, and fallowing.

Technology Suitability

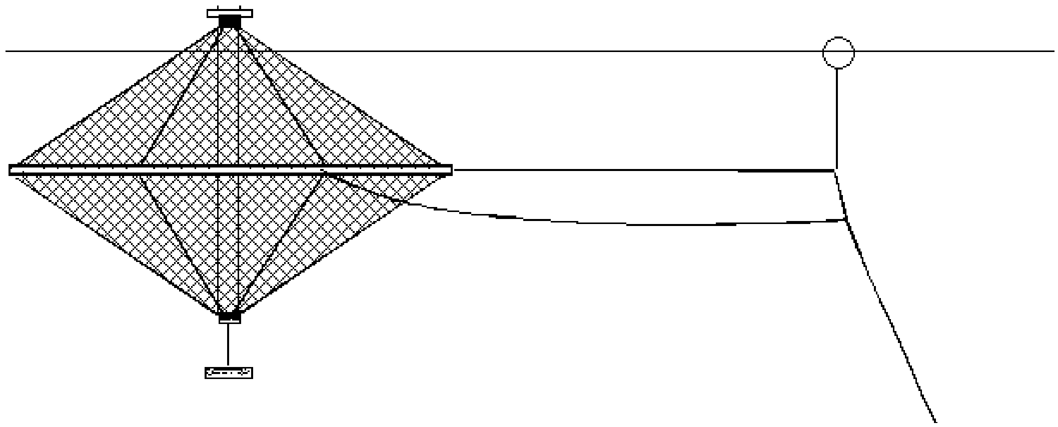
Worker safety and downtime associated with foul weather days should be the two main thrusts driving technology development and automation. Technology suitability requires effective use of individual components and holistic integration into a system for effective farm management. The OAC has made many strides in developing pioneering innovations suitable for offshore aquaculture—including a

Fig. 3. An image of OAC researchers working at the cage site captured from the internet-based Cage Cam (Photo credit: Tim Reid, Mississippi-Alabama Sea Grant Consortium).

suitable single-point mooring system (Fig. 4), an advanced mooring monitor, an autonomous feed system (Fig. 5), and a lift-boat specifically designed for offshore aquaculture (Fig. 6)—all the while keeping a complete offshore aquaculture system in mind for an efficient and safe working environment (Bridger and Goudey, this volume).

All of these innovative components fit together to ensure efficient operations while in the hostile offshore environment. A bottleneck to industry development, however, is integrating and operating these components at a commercial scale followed by production of the components in large quantities to ensure the system can be deployed in an economically feasible manner. Additional innovation is required to make offshore aquaculture a safe enterprise. Present operations in either exposed coastal and offshore environments rely heavily on scuba diving to complete standard farm chores. Dependence on scuba diving represents the "de-evolution" of aquaculture in some sense and certainly counterintuitive when the industry exists in more hostile environments than its near shore counterparts, but requires additional dive time than operations located in coastal bays or fjords. Net cleaning, cage inspection, mortality collection, and harvesting are all chores that presently use extensive diving. Automated

Fig. 4. Illustration of the OAC SPM showing the position of the shorter primary bridles 1.5-m above the longer redundant set of bridles and their respective connection points on the cage rim.



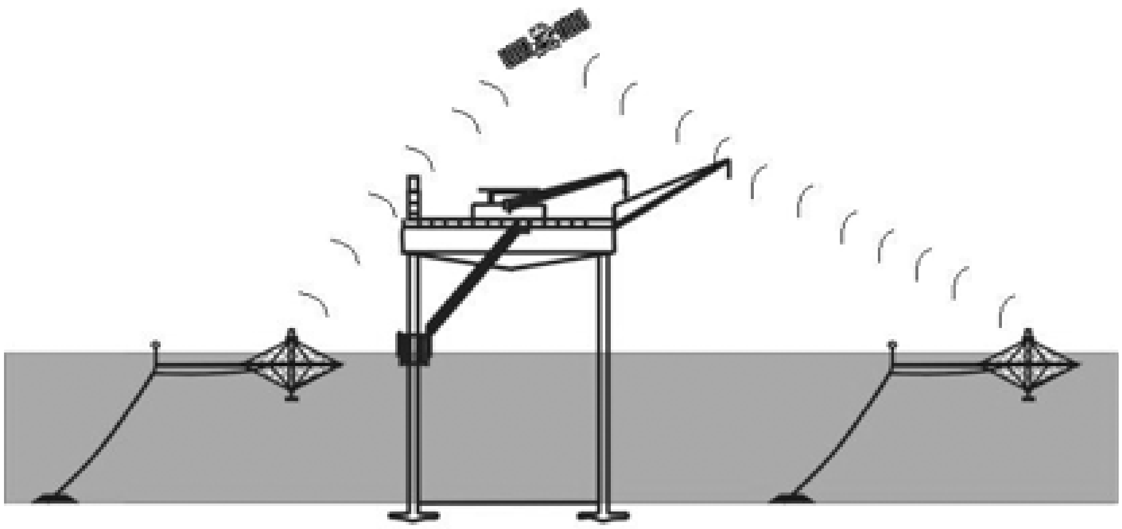
systems must be developed before commercial scale operations are likely to be established.

Fingerling Supply

The offshore aquaculture industry will require a continuous supply of an enormous number of fingerlings. A site consisting of 12–3,000 m^3 cages would require a minimum of 250,000 fingerlings per grow-out cycle for economic success (Posadas and Bridger, this volume; a site of this capacity would be small compared to numerous commercial farm sites throughout the world). With the exception of red drum, sufficient supplies of candidate Gulf of Mexico species are unavailable for

Fig. 5. The MIT Robofeeder (A) is attached to the top of the cage for autonomous fish feeding with feed placed in the silo and falling through two hoses exiting the spar (B).

Fig. 6. A conceptual design of the lift-boat ASV in its operational mode elevated up to 7 m above the water surface. Also note the presence of a helicopter pad, crane for lowering the work boat, satellite communication with each cage system, and a walkway extending to the water surface for easy access not requiring constant crane use to go to the platform.



grow-out and much research is still required to gain the knowledge for consistent fingerling production on demand. The OAC had access to a few hundred fingerlings of several candidate species. However, grow-out of a few hundred, or even a few thousand, individuals would be insignificant for industry development. Such quantities, coupled with inconsistent feeding offshore until automatic feed systems are perfected, would not provide any useful biological or economic data to make informed business decisions given the low stocking densities resulting from so few fish.

CONCLUSIONS

I feel the current situation in the United States is unfortunate. Growing up in Newfoundland and Labrador, I can draw many similarities between those fishing communities and Gulf of Mexico fishery-based communities. In both instances, fishermen refuse to believe that the wild stocks are collapsing, while having to invest increased fishing effort to capture allocated quotas. In addition, captured fish are either generally smaller in size or larger individuals only being caught further offshore. Overfishing, habitat degradation practices, and numerous other interrelated issues resulted in the collapse of the northern groundfish industries and the Gulf of Mexico could perhaps be 10–15 yr behind that situation. The difference is that the United States could learn from the mistakes of others in managing their fisheries and concurrently allocate appropriate levels of research towards aquaculture development. Presence of an aquaculture industry in the Gulf of Mexico during the collapse of commercial fisheries or downsizing an overcapitalized fishing sector could offset many of the economic and social problems expected in affected communities.

I feel confident that the presence of the OAC has raised the awareness for the potential of an offshore aquaculture industry in the Gulf of Mexico and our research efforts have advanced the development of offshore aquaculture throughout the nation.

ACKNOWLEDGMENTS

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The opinions expressed in this chapter are my own based on my experiences in the Gulf of Mexico and do not necessarily reflect the opinions of any of the agencies, individuals, or institutions mentioned and/or involved with the OAC.

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APPENDIX A. PERMITTING REVIEW, ACQUISITION & ISSUES[1]

The following is a comprehensive list of necessary permits and contacts for offshore aquaculture facilities in U.S. federal waters and state waters in the Gulf of Mexico. The following agencies have some regulatory or consultative authority regarding an aspect of offshore aquaculture.

A. Federal Agencies

1) National Marine Fisheries Service

Authority

Under the Magnuson Stevens Fishery Conservation and Management Act, the National Marine Fisheries Service (NMFS) has regulatory responsibilities that will affect aquaculture development in the EEZ. The NMFS is responsible for managing commercial fishing operations, which include aquaculture activities. (50 C.F.R. § 229.2 (2004).

For scientific research, the NMFS requires the applicant to apply for a Letter of Acknowledgment and the NMFS will inform the other agencies (the U.S. Coast Guard and state agencies, if necessary) that this activity is occurring in federal waters in the Gulf of Mexico.

Permit

The necessary item is a Letter of Acknowledgment by NMFS to conduct research in federal waters. This letter should be addressed to the South Regional Administrator, Dr. William Hogarth, explaining the proposal and including a copy. Mr. Pete Eldridge of NMFS recommended that a Principle Scientist contact Dr. Roy Crabtree who can help to construct the letter requesting the Letter of Acknowledgment.

An Exempted Fishing Permit from NMFS is required to hold juvenile fish in federal waters. For commercial facilities in the Gulf of Mexico, the NMFS currently requires a commercial harvesting permit.

Contact

Southeast Regional Office
Sustainable Fisheries Division
9721 Executive Center Drive North
St. Petersburg, FL 33702
Phone: (727) 570-5305
Fax: (727) 570-5583

[1] This appendix represents a portion of a more complete document: Kristen M. Fletcher and Ginger Weston. The Legal & Regulatory Environment: Offshore Aquaculture Permitting Process in the Gulf of Mexico, Report published by Mississippi-Alabama Sea Grant Legal Program, available at http://www.olemiss.edu/orgs/SGLC/Offshore%20Aquaculture.pdf (last visited 9/2/04).

2) U.S. Army Corps of Engineers

Authority

Under Section 10 of the Rivers and Harbors Act of 1899, as extended by the Outer Continental Shelf Lands Act (OCSLA), the Corps requires a permit for the creation of "any obstruction" in federal waters to preserve unhindered navigational access of the nation's waters. (33 U.S.C. § 403 (2004).)

The OCSLA extended the Corps' section 10 authority into the EEZ allowing the agency to regulate "installations and other devices permanently or temporarily attached to the seabed, which may be erected thereon for the purpose of exploring for, developing or producing resources from [the outer continental shelf]." (43 U.S.C. § 1333(a), (e) (2004).)

Permit

The necessary permit is the Section 10 Permit; a Nationwide or General permit may be available in which case the Corps issues a letter of permission that serves as the permit. The Corps considers a broad range of potential environmental and other impacts before issuing or denying a Section 10 permit for an open ocean aquaculture facility. These include effects and cumulative impacts upon the water quality; effects of the facility or structure on recreation, fish, and other wildlife; pollution; economic factors; safety; aesthetics; protection of navigational integrity; and accurate charting of any structures (if facility is present beyond the specified time, it is added to permanent chart).

There are several scenarios for receiving permission from the Corps:

a. Letter of Permission

If the structure to which the cage is attached does not interfere with navigation, the Corps will not require a permit, and will issue a Letter of Permission that states the Corps has reviewed the applicant's proposal and will allow the proposed activities to be conducted as proposed. The letter serves as a permit from the Corps.

b. Existing Scientific Permits

There are also several existing General and Nationwide permits for scientific research in the Gulf. When the Corps receives the information regarding the structure and plans, it will determine if the project fits within one of those programs.

c. Anchoring/Mooring Structure Permit

Any permit issued by the Corps will be conditioned on compliance with the Coast Guard regulations regarding required marking (by lights, etc) of all structures. Moreover, the pilings or anchoring devices used to moor the cage, both in the Sound and out in the Offshore waters, will constitute "Permanent Anchorage" and, therefore, be subject to permitting by the Corps and Coast Guard regulations for marking.

Contacts

Mobile District (E of Pearl River)
U.S. Army Corps of Engineers
Mobile District
P.O. Box 2288
Mobile, AL 36628-0001
Phone: (334) 690-2658

Vicksburg District (W of Pearl River)
U.S. Army Corps of Engineers
Vicksburg District
4155 Clay Street
Vicksburg, MS 39180
Phone: (601) 631-7071

Galveston District (coastal Texas)
U.S. Army Corps of Engineers
P.O. Box 1229
Galveston, TX 77553-1229
Phone: (409) 766-3004

Jacksonville District
U.S. Army Corps of Engineers
P.O. Box 4790
Jacksonville, FL 32232-0019
Phone: (904) 232-1650
Fax: (904) 232-2237

New Orleans District
U.S. Army Corps of Engineers
P.O. Box 60267
New Orleans, LA 70160-0267
Phone: (504) 862-2201
Fax: (504) 862-1724

3) U.S. Environmental Protection Agency

Authority

Under Section 318 of the Clean Water Act, the EPA has asserted jurisdiction to require point source pollution discharge permits for aquaculture projects in the open ocean. (Regulations are located at 40 C.F.R. § 122.24 (NPDES)). The EPA delegates its authority for state water issues in Mississippi to the Mississippi Department of Environmental Quality.

In addition, the Ocean Dumping Act (33 U.S.C. § 1412 (2004)) grants authority to the EPA to permit the dumping of material into U.S. waters when such dumping will not unreasonably degrade or endanger human health or the marine environment, ecological systems, or economic potentialities. The criteria for reviewing such permits include the need for the proposed dumping; the effect of such dumping on human health and welfare, including economic, aesthetic, and recreational values; the effect of such dumping on fisheries resources, plankton, fish, shellfish, wildlife, shorelines and beaches; and the effect of such dumping on marine ecosystems.

Permit

The necessary permit is the National Pollution Discharge Elimination System (NPDES) permit which can be acquired through MDEQ. Also, an Ocean Discharge Permit may be necessary, depending on the amount of waste from the facility. The EPA is more concerned with the amount of feed put into the water than with the amount of waste actually existing in an offshore cage.

Contact

For Alabama, Mississippi and Florida
USEPA, Region 4
Atlanta Federal Center
61 Forsyth Street, SW
Atlanta, GA 303033104
Phone: (404) 562-9387

For Louisiana and Texas
USEPA, Region 6
1445 Ross Ave.
Dallas, TX 75203
Phone: (214) 665-6444

4) Gulf of Mexico Fisheries Management Council

Authority

The Gulf of Mexico Fishery Management Council (Council) is one of eight regional Fishery Management Councils, which were established by the Fishery Conservation and Management Act in 1976 (now called the Magnuson-Stevens Fishery Conservation and Magnuson Act). The Council is responsible for managing fishery resources in federal waters in the Gulf of Mexico (generally, from state waters seaward to 200 miles). According to the NOAA Office of General Counsel, aquaculture farms are subject to the Magnuson-Stevens Act because harvesting fish from the EEZ by U.S. vessels constitutes "fishing" under the Act. This gives the Council the authority to manage aquaculture in the EEZ and requires it to amend appropriate fishery management plans to accommodate proposed farms.

On the regulatory front, the Fisheries Management Councils are becoming involved in the decisionmaking process for offshore permitting for aquaculture. Because permitgranting may involve the granting of exclusive use in a designated area to an aquaculture business, the traditional users of the resource must be incorporated into the regulatory process.

Permit

There is no necessary permit but the Council has issued a Mariculture Policy and, under new Essential Fish Habitat regulations, an applicant may be required to provide information about potential impacts to fishing habitat and information to amend fishery management plans. The Council is responsible for commenting on the proposed facility.

At the time of the project, the Council Executive Director recommended writing a letter to the Council explaining the facility and future plans, possibly making a presentation to the Council at its monthly. The Corps usually consults with the Council and/or the director during the application process.

Contact

Executive Director
Gulf of Mexico Fishery Management Council
The Commons at Rivergate
3018 U.S. Highway 301 North, Suite 1000
Tampa, Florida 336192266
Phone: (813) 228-2815, (888-833-1844 (toll-free))
Fax: (813) 225-7015

5) Department of Agriculture

Authority

The National Aquaculture Act Development Act of 1980 established a coordinating group, the Joint Subcommittee on Aquaculture (JSA), chaired by the U.S. Department of Agriculture. The JSA has been responsible for developing the National Aquaculture Development Plan, which identifies the relative roles of the U.S. Departments of Agriculture, Interior, and Commerce, and establishes a strategy for the development of an aquaculture industry in the United States.

Permit

None. The Department of Agriculture provides research and a variety of services (see http://ag.ansc.purdue.edu/aquanic/jsa/federal_guide/usda.htm) but has not maintained a regulatory role in mariculture.

Contact

Southern Regional Aquaculture Center
Delta Research and Extension Center
Mississippi State University
127 Experiment Station Road
P.O. Box 197
Stoneville, Mississippi 38776
Phone: (662) 6863285
Fax: (662) 6863569

6) U.S. Coast Guard

Authority

The U.S. Coast Guard is responsible for the regulation and enforcement of various activities in the navigable waters of the U.S. and requires that such aquaculture-related structures are marked with lights and signals in order to ensure safe passage of vessels. Installation and maintenance of the markers must be done by the aquaculturist as long as the structures are located in navigable waters. The Coast Guard provides detailed requirements for markings.

Permit

The requirements for marking structures are often included as stipulations for permit approval with the Corps of Engineers or EPA. The aquaculturist must ensure markings are done properly but does not need to file an individual application directly with the Coast Guard.

Contact

For offshore Texas, Louisiana, Mississippi, Alabama and Florida (W of Appalachicola)
Chief of Private Aid to Navigation
Eighth Coast Guard District
Hale Boggs Federal Bldg.
501 Magazine St.
New Orleans, LA 70130-3396
Phone: (504) 5896235
Fax: (504) 589-6654

For offshore Florida (E of Appalachicola)
U.S. Coast Guard Seventh District
Aids to Navigation
Federal Building
51 SW 1st Avenue
Miami, FL 33130
Phone: (305) 350-5654

7) U.S. Fish and Wildlife Service

Authority

When there is federal involvement (a permit, license, funding, etc.) in a permit under review by the Corps, the FWS comments on the proposed action under authority of:

Fish and Wildlife Coordination Act (general to all species, including plants)
Endangered Species Act
Marine Mammal Protection Act (very limited authority)

The FWS has not exercised its authority under the MMPA in the southeast but is more often used in other parts of the country depending upon the presence of certain marine mammals.

The FWS contact during the project advised that the agency would probably have no involvement in a “cage culture” environment unless the agency discovered that a “take” of some covered species was involved. If a private entity were undertaking a commercial venture, the FWS would not comment unless asked to do so, and the responsibility to avoid any take rests on the private entity.

Permit

Comment/Review only.

Contact

Assistant Field Supervisor
Baldwin County, Alabama Field Office
P. O. Box 1190
Daphne, AL 36526
Phone: (334) 441-5181
Fax: (334) 441-6222

8) Minerals Management Service

Authority

The Outer Continental Shelf Lands Act established jurisdiction over submerged lands on the outer continental shelf and the Minerals Management Service has authority over lease sites on the shelf. Consult the MMS if the project will be near or attached to an oil or gas platform or if ownership will be transferred.

Permit

For platform removal approval or transfer of ownership.

Contact

Gulf of Mexico OCS Region
1202 Elmwood Park Blvd.
New Orleans, LA 70123-2394
Phone: (504) 736-2894

B. Alabama

1) Alabama Department of Conservation and Natural Resources

Authority

This agency has no written policies with regard to offshore mariculture but the Department of Conservation may consider on or offshore mariculture proposals on a casebycase basis.

Lands Division—Permit

A standard lease from the state is required, called a Bottom Lease.

Marine Resources Division – Permit

Comments on proposals in the interest of the State Wildlife & Fisheries for the state.

Contact
Director of Marine Resources
P. O. Drawer 458
Gulf Shores, AL 36547
Phone: (334) 9687577 or 9687576
Fax: (334) 9687307

2) Alabama Department of Environmental Management

Authority

The ADEM regulates discharge into public waters of the state and has authority over the state's Coastal Area Management Program. (Alabama Code 9-7-20.) The responsibilities of the Alabama Coastal Program are divided between the Alabama Department of Economic and Community Affairs (ADECA) and the Alabama Department of Environmental Management and advised by the Coastal Resources Advisory Committee (CRAC). ADECA is responsible for overall management of the program including planning, fiscal management, and public information and education. ADEM is responsible for coastal area permitting, regulatory and enforcement functions, and for water quality regulation (Alabama Code § 22-22-9). The program goal is to protect and, where possible, to enhance or restore coastal resources.

Permit

Discharge permit, and Consistency Review.

Contact

ADEM, Chief, Permits & Services Division
P.O. Box 301463
Montgomery, AL 361301463
Phone: (334) 2717714
Fax: (334) 2717950

ADECA, Coastal Programs Office
1208 Main Street
Daphne, AL 36526
Phone: (334) 6260042
Fax: (334) 6263503

C. Florida

Florida enacted its Aquaculture Policy Act in the late 1980s and established the Department of Agriculture and Consumer Services (FDACS) as the lead agency. The Florida Aquaculture Plan was recently updated and proposed rules are soon to be adopted making FDACS a "one-stop shop" for aquaculture in Florida. The Bureau of Aquaculture Development provides extension and education services, assistance with business and production plan development, and guides applicants through the application processes to obtain permits from other agencies, all at no charge. This agency does conduct scheduled annual inspections of all certified aquaculture facilities.

1) Florida Department of Agriculture and Consumer Services

Authority

The Florida Department of Agriculture and Consumer Services is the state's lead aquaculture agency. FDACS administers the Aquaculture Certification program under Florida Code § 597 and the Sovereign Submerged Lands Leasing Program under Florida Code § 253. Details on the Certification and Leasing programs can be found on Florida's official aquaculture website (see www.floridaaquaculture.com).

Permit

Aquaculture Certification

To obtain the Aquaculture Certification, an aquaculturist must provide to FDACS' Bureau of Aquaculture Development a plan for compliance with Florida's Best Management Practices for Aquaculture or obtain an exemption from the Bureau of Aquaculture Development. The Best Management Practices are set out in Florida Administrative Code proposed rule 5L-3. The various exemptions are also listed in proposed rule 5L-3, and they include systems not making discharges into waters of the state, those engaged in certain marine bi-valve culture systems which circulate natural sea water without adding anything to the water, fee-fishing sites with less than 1,000 pounds of fish per acre, and individual production units producing less than 10,000 pounds per year of product.

An application may be obtained from the Bureau of Aquaculture Development, and requires the names, address and phone number of the applicant, information on the facility location, a description of the production facilities and a list of the products cultured together with estimates of annual production. The fee for application is $50.00, and the Certification expires on June 30 of each year.

Sovereign Submerged Lands Lease

Submerged lands owned by the State of Florida may be leased for aquaculture activities, upon the recommendation of FDACS to the Board of Trustees of the Internal Improvement Trust Fund (the "Board"). The Board is composed of the Florida Legislature, the Governor and his Cabinet.

The Bureau of Aquaculture Development (the "Bureau") provides applicants with the AquaPak, which includes an application form, guidelines for completion and a list of steps involved in the application review and approval process. First, the lease site must be identified and submitted with a description of the proposed activity, a business plan, and a $200.00 application processing fee. The Bureau then conducts a comprehensive four to six week review of the proposal and makes a site inspection to determine the suitability of the site for the proposed use. Once a satisfactory review has been performed, there is a public notice period, and the Bureau makes its recommendation to the Board. The Board makes all final leasing determinations, and the entire application process can be completed in six months to one year. Current lease rates are $15.95 per acre per year, with a $5.00 per acre surcharge.

Contact

Florida Department of Agriculture and Consumer Services
Bureau of Aquaculture Development
Bureau Chief
1203 Governor's Square Boulevard
Tallahassee, Florida 32301
Phone: (850) 4885471
Fax: (850) 410-0893

2) Florida Department of Environmental Protection

Authority

The Department of Environmental Protection (FDEP) administers Florida's NPDES permitting authority. Because of recent streamlining in the aquaculture regulatory process in Florida, an NPDES permit may or may not be required for an aquaculture facility.

Permit

NPDES permits are not required of aquaculture facilities in compliance with the FDACS' Best Management Practices for storm and wastewater. If, however, a facility is large enough to require an individual NPDES permit under the federal guidelines, FDEP will require NPDES permitting. Most larger farms are required to obtain an NPDES permit from FDEP. Any dredge or fill activities will also require a permit from FDEP.

Contact

Florida Department of Environmental Protection
Industrial Wastewater Section
2600 Blair Stone Rd.
Tallahassee, FL 32399-2400
Phone: (850) 9215330
Fax: (850) 488-6579

3) Florida Fish & Wildlife Conservation Commission

Authority

Since the streamlining of Florida's regulatory program for aquaculture, the Fish & Wildlife Conservation Commission (FWCC) has very limited authority over the marine species in the state. The remaining authority is derived from Florida Statutes section 372.072 (4)(a).

Permit

FWCC's permitting authority has been relegated to FDACS, but aquaculturists who plan to cultivate game/sport fish, such as redfish, snook or sea trout, are required to work with FWCC to ensure compliance with FWCC guidelines and procedures designed to control poaching of wild stock.

Contact

Bureau Chief
Florida Fish and Wildlife Conservation Commission
620 South Meridian Street
Tallahassee, FL 323991600
Phone: (850) 4870554
Fax: (850) 487-4847

4) Florida Water Management Districts

Each of the five districts permits consumptive uses of Florida's water resources within their district, but a permit is not required for aquaculture facilities using tidal body salt water exclusively. Local ordinances are likely to require a permit for fresh or brackish waters consumed from an aquifer or well, but only when an annual average of more than 100,000 gallons/day will be consumed or the intake pipe has a diameter of four (4) inches or more.

D. Louisiana

Louisiana is developing its marine aquaculture program. Limited permitting for mariculture is allowed (Title 56, section 579) on private property in the coastal zone. The users must show separation of domestic stock from wild stock and sets reporting requirements. The regulations currently apply to oyster cultivation only, which is done in brackish waters. Louisiana has no permitting provisions for public waters.

1) Louisiana Department of Wildlife and Fisheries

Authority

Louisiana currently has no permit system for offshore aquaculture facilities in public waters. The agency with authority is the Louisiana Department of Wildlife and Fisheries.

Permit

A Mariculture Permit may b required after the coastal use permit issued by Department of Natural Resources and a lease from State Land Office have been obtained.

Contact

Habitat Programs Manager
Marine Fisheries Division, Louisiana Department of Wildlife & Fisheries
P. O. Box 98000
Baton Rouge, LA 70898
Phone: (225) 765-2956

2) Louisiana Department of Natural Resources

Authority

Louisiana Department of Natural Resources relies heavily on the assessment made by Wildlife and Fisheries in the regulation of coastal uses. Past mariculture issues involved cultivation of redfish inshore in old abandoned oil and gas canals. If activities complied with Health and Wildlife and Fisheries regulations and the users held a Wildlife and Fisheries permit, DNR waived involvement. In the past, DNR has gotten involved in the past when a significant structure was erected that affected wetlands.

Permit

Coastal Use Permit, if required after the Wildlife and Fisheries assessment.

Contact

Coastal Management Division Administrator
Office of Coastal Restoration & Management
P. O. Box 44487
Baton Rouge, LA 70804
Phone: (225) 342-7591
Fax: (225) 342-9439

3) Louisiana State Land Office

Authority

The State Land Office has authority over the use of the water bottoms and air space above the water in the state. (Louisiana Revised Statutes Ann. section 30:172.)

Permit

For commercial ventures, Louisiana's SLO charges $0.02/sq. ft. to lease a water bottom. The Lands Office advised that when projects have a scientific or otherwise public purpose, the SLO looks for exceptions to the fee requirement, usually successfully. The state does, however, want to be held harmless and would require an indemnification agreement to cover any damages suffered, such as vessel collisions with the structure.

Contact

Contract/Grants Reviewer (Oversees water bottom leases and permits)
Lands Manager (Makes recommendations to Director of SLO)
Louisiana State Land Office
P. O. Box 44124
Baton Rouge, LA 70804
Phone: (225) 342-0120
Fax: (225) 342-5458

4) Louisiana Department of Environmental Quality

Authority

The Department of Environmental Quality has authority over the water quality for the waters of Louisiana. (Louisiana Revised Statutes Ann. section 30:2074).

Permit

Cheryl Lejeun, Industrial Permits Coordinator, advised that NPDES water permits would be required by Louisiana DEQ for an some aquaculture activities, but not usually for those conducted for scientific or research purposes.

Contact

Industrial Permits Coordinator
Office of Environmental Services
P. O. Box 82135
Baton Rouge, LA 70884-2135
Phone: (225) 765-0199
Fax: (225) 765-0222

E. Mississippi

1) Mississippi Department of Agriculture

Authority

Under the Mississippi Aquaculture Act of 1988, the Department of Agriculture and Commerce is the responsible agency for permitting aquaculture activities in both fresh and marine waters. The law states:

"The Department shall issue a cultivation permit for any aquaculture facility located, in whole or in part, in the Mississippi Sound, the Gulf of Mexico, or bays or estuaries thereof at such time that such facility complies with all state and federal requirements to protect marine resources." Miss. Code Ann. § 79-22-17 (1999).

The Department must approve the proposed aquaculture facility design and may conduct periodic inspections. The Department may prohibit the culturing of any species at any location if it determines that it would be detrimental to the public interest and presents its determination in writing with supporting justification.

When you apply with the Department of Agriculture, the agency will distribute the permit application to other federal and state agencies. These agencies are:

U.S. Army Corps of Engineers
Environmental Protection Agency
Mississippi Department of Marine Resources
Mississippi Department of Environmental Quality
Mississippi Secretary of State's Office

Permit

Aquaculture Permit.

Contact

P.O. Box 1609
Jackson, MS 392151609
Phone: (601) 3591100
Fax: (601) 3546290

2) Mississippi Department of Marine Resources

Authority

The Mississippi Department of Marine Resources has responsibility for regulating activities under the Mississippi Coastal Wetlands Protection Act that affect any coastal wetland. (Miss. Code Ann. § 49-27-5 (1999)). Generally, any aquaculture operation that is to be sited in an area below the high tide line, in coastal wetlands, or in areas suitable for water-dependent industries must obtain a permit from the DMR.

One obstacle facing aquaculture in Mississippi waters is the completion by DMR of the Marine Aquaculture Environment Monitoring Program Guidelines, which were drafted for an earlier aquaculture project but never completed.

Permit

The necessary permit is the wetlands permit but the DMR will also be responsible for granting consistency under the Mississippi Coastal Program and the Coastal Zone Management Act.

For information purposes, DEQ's concerns during the last project were hundred of lbs of feed/day, the length of time cage in place and how long various species will actually be captured and held.

Contact

Mississippi Department of Marine Resources
Coastal Ecology
1141 Bayview Ave, Ste 101
Biloxi, MS 39530
Phone: (228) 3745000
Fax: (228) 3745008

3) Mississippi Secretary of State

Authority

The Secretary of State is responsible for permitting uses and conserving the state lands, including public trust tidelands, of Mississippi. Aquaculture activities that propose to use the water column or sea bottom require an aquaculture lease from the Secretary. The amount of annual rent is negotiated and the parcel is required to be identified and well-marked.

Permit

The necessary permit is an Aquaculture Lease of Public Trust Tidelands.

Contact

Office of the Secretary of State
P.O. Box 97
Gulfport, MS 39502-0097
Phone: (228) 864-0254
Fax: (228) 864-0325

4) Mississippi Department of Environmental Quality

Authority

The Mississippi Department of Environmental Quality is responsible for regulating discharges into the waters of Mississippi. (Miss. Code Ann. § 49-17-1, et. al. (1999).) In addition, the EPA has delegated its authority for state water issues in Mississippi to the Mississippi Department of Environmental Quality, making the MDEQ responsible for granting NPDES permits.

Permit

The MDEQ will determine the need for an NPDES permit for marine net-pen aquaculture on a case-by-case basis. The MDEQ contact, Mr. Steve Spengler advised that a permit may not be necessary for temporary research sites. MDEQ requires scientific information during the application process, and suggests contacting this agency before filling out a DEQ application.

The possible necessary permits are:

NPDES Discharge Permit
Water Quality Certification
Possible Health Department (if living quarters are constructed on the site)

Contact
Mississippi Department of Environmental Quality
P.O. Box 20305
Jackson, MS 392891305
Phone: (601) 9615171
Fax: (601) 9615349

F. Texas

1) Texas Department of Agriculture

Authority

The Texas Department of Agriculture (TDA) is the lead agency charged with regulation of aquaculture in Texas. Specifically, TDA is statutorily required to encourage the raising of cultured species, development of the aquaculture industry and the marketing of aquaculture products. Texas Agriculture Code § 12 et seq.

The Agriculture Code authorizes both TDA and the Texas Parks and Wildlife Department to adopt rules to carry out their respective duties. It also authorizes TDA to establish record-keeping requirements for commercial aquaculture facilities. Texas Agriculture Code § 134 et seq. As of July 1, 2000, TDA is still working to promulgate these requirements.

Permit

An Aquaculture License must be obtained from TDA prior to beginning operations. Texas Agriculture Code § 134.011(b)(2). A standardized form is to be submitted together with $100.00 to TDA. The same form is used for Fish Farm Vehicle Licenses required by § 134.012, below. Before an Aquaculture License will be granted by TDA, an applicant must obtain either a permit for wastewater disposal or a Certificate of Exemption from Texas Natural Resource Conservation Commission (TNRCC). Copies of all applications are sent to TPWD and TNRCC for review within 10 days of receipt by TDA.

In addition to the Aquaculture License, an aquaculturist in Texas must obtain Fish Farm Vehicle Licenses from TDA for all vehicles used to transport cultured species from a private facility for sale. Texas Agriculture Code §134.012. Licenses must be purchased for each truck in operation, including vehicles from which fish are sold by a non-aquaculturist. The only exemption is for the vehicle owned and operated by the holder of an aquaculture license, and a copy of the aquaculture license must be kept in the vehicle. The cost is $100.00 per vehicle, and the form is attached as Exhibit F1.

Penalties

The penalty for unlawfully fishing or taking fish from an aquaculture facility is the penalty imposed for a third degree felony, and all other statutory violations are Class C, B and A misdemeanors. Texas Agriculture Code § 134.023

The Texas Water Code provides for institution of suit by state agencies for injunctive relief and civil penalties. Texas Water Code § 7.

Contact

Texas Department of Agriculture
Regulatory Division
P.O. Box 12847
Austin, Texas 78711
Phone: (512) 463-7604
Fax: (512) 463-8225

2) Texas Natural Resource Conservation Commission (TNRCC) Water Quantity

Authority

TNRCC is charged with approving water appropriation permits for mariculture operations using brackish or marine waters. Permits are generally required to appropriate water belonging to the State of Texas. Texas Water Code § 11 et seq.

Permit

No permit is required to appropriate waters for mariculture activities, but notice must be given to TNRCC of intent to appropriate water for mariculture activities. Texas Water Code § 11.1421. Notice must be given prior to appropriating, and each appropriation must be reported. No permit is required to appropriate water from the Gulf, it's adjacent bays and arms for mariculture operations. The amount appropriated is that "appropriate" to the mariculture activities as determined by TNRCC.

TNRCC may, after notice and hearing, issue an order requiring interruption or reduction of the appropriation if it determines there is an interference with the "natural productivity" of bays and estuaries because of low freshwater inflows.

Contact

Texas Natural Resource Conservation Commission
Division of Water Permits and Resource Management
P.O. Box 13087
Austin, TX 787113087
Phone: (512) 239-6373
Fax: (512) 239-2214 or 239-4770

Water Quality

Permit

Commercial shrimp-culture facilities in the coastal zone must obtain a site-specific wastewater discharge permit from TNRCC. Texas Agriculture Code § 134.013. Prior to issuance of the permit, an applicant must provide an environmental report on the conditions at the proposed site. The report must assess potential impacts on sensitive aquatic habitats, significant impacts related to the construction or operation of the facility and any mitigation actions proposed by the applicant. The report must be provided to TNRCC and TDA. TNRCC must consider this report before making a determination on the wastewater discharge permit, and TDA will only require the report if the proposed activity will occur within the coastal zone, which is defined by the TPWD. TNRCC is required to establish guidelines for this report and its requirements. Licenses are valid for two years.

All other aquaculture operations must obtain either an individual permit, permission from TNRCC to operate under a General Permit, or a Certificate of Exemption. Individual permits are obtained in much the same way as the shrimp-culture permits described above, and the cost is approximately $350.00. As of July 10, 2000, the General Permit is still in the promulgation stages, having just been submitted for public notice and comment. The anticipated cost for application review under the General Permit is $100.00. Applicants for Certificates of Exemption are required to complete the application under Texas Administrative Code §30.321, Subchapter O. Only those facilities that recycle all water, rely only upon evaporation or otherwise conduct no activities recognized as discharge by TNRCC can be certified as exempt.

An aquaculture-specific facility fee limit is imposed by Texas Water Code § 26.0292, which limits total fees to $5,000 annually. Fees are assessed according to the pollutant load of the facility.

Contact

Texas Natural Resource Conservation Commission
Wastewater Permitting
Phone: (512) 239-4618

3) Texas Parks and Wildlife Department

Authority

The Texas Parks and Wildlife Commission (TPWD) is required by the Agriculture Code to adopt rules regulating exotics and enforce them. Texas Agriculture Code § 134.020. TPWD regulates exotic fish, shellfish, and aquatic plant species in order to protect indigenous Texas species and aquatic habitats. TPWD is required to make a list of exotics for which a permit will be required, define the zone inside which exotics will be excluded, approve shellfish disease specialists for the disease free certification of exotics, adopt rules to regulate exotics, and issue Exotic Species Permits for the possession, propagation, sale and transportation of exotics under TPWD Code § 66.007. Additionally, TPWD is authorized to inspect aquatic products at the dealer/handler's place of business during normal business hours, and no person may refuse the inspection. P&WD Code § 47.037.

TPWD also has the water quality control enforcement authority for violations affecting aquatic life and wildlife. Water Code § 26.129. Section 66 of the TPWD Code prohibits any person from catching or taking aquatic life from any private waters without consent, TPWD Code § 66.002, and defines the penalties for violations of that prohibition in TPWD Code § 66.012.

Statistical information on the harvest of aquatic products in Texas must be gathered and compiled by TPWD under TPWD Code § 66.019.

Permit

The TPWD Code, like the Agriculture Code, requires aquaculturists and those transporting aquatic products to obtain and keep the standard fish farm vehicle/aquaculture licenses. TPWD Code § 66.014. A special license issued by TPWD is required to collect, hold or propogate indigenous fish or aquatic life, when Texas law regulates those activities. TPWD Code § 43.021.

A dealer's license must be obtained by any person transporting aquatic products or bringing them into the state under TPWD Code § 47.018, and aquatic products transportation invoices must be prepared by the shipper and kept with the products under TPWD Code § 47.0181. Wholesale fish dealers not licensed under §134.011 of the Agriculture Code must be licensed by TPWD. TPWD Code § 47.009. The same license requirements are imposed upon retail fish dealers under TPWD Code § 47.011 and upon bait fish dealers under TPWD Code § 47.014.

A permit must be obtained from TPWD for introduction of any aquatic products into public waters, and the Department is charged with establishing the rules and regulations governing those permits. TPWD Code § 66.015. This section exempts native "non-game" fish, as defined by the Commission, except where threatened or endangered fish are present.

TPWD Rules § 57.111 et seq. outline TPWD's regulation of exotics. Prior to importing live exotic shellfish, documentation of the inspection and certification of the exotics as disease-free must be provided to TPWD, and the importer must receive acknowledgment that such documentation has been received. Monthly certification is required for certain species, and additional examinations and certifications are required before the first discharge of waste in any calendar year.

To obtain an Exotic Species Permit, an applicant must possess either a valid Fish Farmer's License, a TNRCC permit for operation of a wastewater treatment facility, a TPWD approved research proposal or operate a public aquarium. The application fee is $250.00, and the applicant must complete TPWD's application form and submit an accurate-to-scale plat of the facility. TPWD Rules § 57.117. Applicants must also meet all the disease free certification requirements in TPWD Rules § 57.114, and facilities located within the exclusion zone must submit and obtain approval of an Emergency Plan to prevent the release or escape of exotics during a natural catastrophe, such as a hurricane or flood. Permits expire every year on December 31.

Contact

Texas Parks and Wildlife Department
Inland Fisheries
4200 Smith School Road
Austin, Texas 7744
Phone: (512) 389-8037
Fax: (512) 389-4388

4) Texas Agency Cooperation

Generally

TNRCC must provide copies of applications for aquaculture wastewater discharge permits to TDA and TPWD. All three agencies shall each appoint one representative to review aquaculture wastewater discharge permits. Texas Agriculture Code § 134.031. TPWD has the authority in consultation with TNRCC to establish guidelines that identify sensitive aquatic habitats in the coastal zone, those guidelines to be used by TNRCC in reviewing applications for new aquaculture facilities or expansions of existing facilities in the coastal zone. As of July 1, 2000, the timing of the application-sharing described above is subject to a Memorandum of Understanding, which has not yet been completed. The representative group charged with reviewing the permits has not yet convened, and the Memorandum of Understanding will define the make-up of this review group.

Collective Permit

A 1999 amendment to the Water Code requires TNRCC, DOA and the P&WD to collectively permit discharges of suspended solids from aquaculture (specifically shrimp) facilities in the coastal zone. Texas Water Code § 26.0345.

General Permit

Water Code § 26.040 Issuance of General Permits
A copy of the Draft General Permit to Dispose of Wastes is attached and is current through December 20, 1999. The permit is aquaculture-specific, and it allows discharge subject to Texas Surface Water Quality Standards, the regulations imposed by TNRCC and the State of Texas.

5) Texas Department of Health

Authority

The Texas Department of Health (TDH) is authorized to regulate molluscan shellfish, including oysters, clams, mussels and scallops under the Texas Aquatic Life Act, Texas Health and Safety Code § 436.001 et seq. TDH's regulatory authority extends to ensure the shellfish are harvested from approved waters. TDH is responsible for licensing and inspecting seafood processors and distributors, and has adopted the federal regulations governing seafood processors, Title 21 of the Code of Federal Regulations, part 123. The Manufactured Foods Division may become involved when unauthorized antibiotics or other adulterants are used on cultured products.

Permit

Anyone taking, selling, offering for sale, or holding for sale molluscan shellfish from a restricted or conditionally restricted area, as defined by TDH, must obtain a permit from TPWD and have those activities supervised by TPWD. TDH's regulatory role is primarily that of an inspector charged with determining the suitability of an area for the taking or holding of molluscan shellfish. Areas are to be classified according to the categories in the National Shellfish Santiation Program Manual of Operations as an approved, conditionally approved, restricted, conditionally restricted or prohibited area. TDH Code § 436.101. The director must also designate growing areas as closed or open areas.

Sanitary surveys of the areas from which oysters are harvested are to be conducted by TDH, and the meat of the oysters must also be sampled at the earliest time following the designation as a closed area. The oyster program must also be consistent with the National Shellfish Sanitation Program. TDH Code § 436.104. TDH issues shellfish certificates and licenses for the processing of crabmeat. TDH Code § 436.111. Applications are first filed with TDH, then the director or an authorized agent inspects the property for conformity with TDH rules. TDH Code § 436.113. Certificates expire on August 31 of each year, and licenses on the last day of February each year. TDH Code § 436.113.

Contact

Texas Department of Health
Seafood Safety Division
Phone: (512) 719-0215
Fax: (512) 719-0220

6) Texas Bureau of Land Management

Authority

Texas Natural Resources Code § 51 authorizes surface leasing by the Texas General Land Office (TGLO). All lands and waters are held in trust to the Permanent School Fund, and all revenues generated by mineral, land or seabed leases belong to that fund. Texas, unlike most states, claims territorial waters out to ten (10) miles from shore.

Leasing

Applicants interested in leasing Texas land or waters for aquaculture are encouraged to contact the TGLO very early in the planning process. The application consists of two main parts. The first requires the name, address and financial status of the applicant, a description of the proposed location and a statement of the parameters of the project. The second portion involves a due-diligence examination of the first portion by TGLO to determine the nature of the lessee, creditworthiness of the lessee, and the soundness and feasibility of the overall aquaculture proposal. TGLO then uses the results of that examination to determine the rental fee, which consists of a base fee and a royalty-style rent based on the revenue or income of the project.

Contact

Texas General Land Office
Asset Inspections
1700 North Congress Avenue
Austin, Texas 78701-1495
Phone: (512) 463-5139
Fax: (512) 463-5304