Advances in Hatchery and Growout Technology of Marine Finfish Candidate Species for Offshore Aquaculture in the Caribbean

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ABSTRACT

This paper describes advances in hatchery and growout technology of selected candidate species of marine finfish for offshore aquaculture in the Caribbean, Gulf of Mexico and the Southeastern US. Emphasis is given on relevant progress achieved with mutton snapper (*Lutjanus analis*), greater amberjack (*Seriola dumerili*) and cobia (*Rachycentrum canadum*), focusing on our own research and development program. The following topics are reviewed: broodstock management, including capture, transport, handling, sampling, prophylaxis, acclimation and quarantine; biological control of parasites; biosecurity; broodstock nutrition; and environmentally conditioned and hormone-induced spawning techniques; intensive and semi-intensive larval rearing using mesocosm systems with artificial substrates; proactive health management, specifically the use of probiotics to improve health and aquaculture performance of marine fish during early developmental stages; nursery techniques; and, studies conducted on growth, survival and feed conversion rates of mutton snapper raised in floating cages.

Site assessment criteria and environmental issues related to offshore fish aquaculture in net cages are addressed, as well as the legal framework and relevant regulatory issues. A project being developed by Snapperfarm and the University of Miami to demonstrate the technological, environmental, social and economic viability of offshore aquaculture in Puerto Rico is described. The project is scheduled to begin in 2002 with the deployment of two 3,000 m^3 SeaStation submersible cages and their subsequent stocking with mutton snapper and cobia fingerlings. The offshore growout demonstration project is the first and most important component of the "*Sustainable Offshore Aquafarm*", a conceptual idea that Snapperfarm and the University of Miami set out to establish in the region within the next few years. The Sustainable Offshore Aquafarm concept is also described in this paper.

Most countries throughout the Caribbean have appropriate offshore areas with great potential for sustainable aquaculture development. Adequate utilization of available areas and infrastructure can lead to the development of unexploited resources with the potential of generating a large number of jobs and enormous social and economic benefits to the region. The main hurdle is the required establishment of an effective and integrated collaborative effort among private industry, local governments, academic and research institutions, non-government organizations, and stakeholders from influential social and professional sectors.

KEY WORDS: Offshore aquaculture, marine fish culture, sustainable aquaculture

INTRODUCTION

Aquaculture currently contributes approximately 30% of total world fisheries production and is increasing at an impressive annual growth rate of approximately 12%. Since 1984, marine aquaculture production around the world has increased by an average of nearly 12% per year. In contrast, world marine capture fishery production has remained stagnant since the late 1980s with landings in recent years increasing by only 0.6% per year (FAO 2001). Future projections of marine capture landings do not indicate significant increases in the near and mid term. As exemplified by the tuna ranching in Mediterranean countries, aquaculture development is entirely reshaping the fishery industry as well as fishery management strategies in many regions throughout the world. By 2030, aquaculture will be the dominant source for supplying fish to world markets, and less than half of the fish consumed worldwide are likely to originate in traditional capture fisheries (FAO 2001). The same report estimates that the role of capture fisheries in the economies of the wealthier countries will be further reduced as developing countries increase their share of production. Aquaculture will have expanded geographically, in terms of species cultured and technologies used. It is very unlikely that Asia will continue to dominate production to the extent that it did during the 1990s. Mariculture will account for a larger share of total production, particularly when offshore culture technology becomes viable (FAO 2001). High-value marine finfish landings are and will remain inadequate to meet worldwide demand. Imports into developed nations have risen dramatically within the past decade, and the prospects of replacing imported wild-caught fish with a farm-raised product are excellent.

Due to greater depths, stronger currents, and distance from shore, environmental impacts are considerably lower in the open ocean, suggesting that offshore cage systems are among the most environmentally sustainable methods for commercial marine fish culture (McVey 1997). Inevitably, commercial operations for raising high-value marine fish will be established within the next few years in the offshore areas of the Caribbean, southeastern United States, Gulf of Mexico, and Latin American countries (Benetti et al. 1999, McVey and Treece 1999). Most of these regions have suitable offshore areas with great potential for the development of this emerging industry. Adequate utilization of available areas and infrastructure can lead to the development of unexploited resources with the potential of generating a large number of jobs and enormous social and economic benefits for those countries taking the aquaculture initiative.

Beginning in 2002, Snapperfarm, Inc. will implement an important project for the demonstration of the technological, environmental, social and economic viability of offshore aquaculture. The project will include the deployment of two 3,000 m^3 SeaStation submersible cages in Caribbean waters off of Puerto Rico followed by stocking of the cages with mutton snapper and cobia fingerlings that will be produced by the Aquaculture Center of the Florida Keys (ACFK). The Aquaculture Program of the University of Miami's Rosenstiel School of Marine and Atmospheric Science has been conducting the research and development in collaboration with both the ACFK and Snapperfarm, Inc. The projects are funded by the private sector with the assistance of NOAA's National Marine Aquaculture Initiative, Sea Grant, and PRIDCO (Puerto Rican Industrial and Development Corp.). The University of Puerto Rico is collaborating with the University of Miami for conducting environmental assessment and social and economic studies related to the project.

This paper reviews recent technological progress in marine finfish aquaculture at the hatchery and growout levels within the context of relevance to the Caribbean region. The levels of feasibility of native candidate species are also addressed, with emphasis on the use of environmentally friendly technology such as offshore cages. We emphasize the use of applied technology for the development of a commercially feasible and environmentally sustainable marine fish aquaculture industry in the Caribbean.

SPECIES

Emerging technologies for the artificial propagation of marine finfish species endemic to Caribbean and American countries have brought the establishment of marine fish aquaculture industry a step closer to reality. Considering recent technological advances and market demand, species with potential for commercial aquaculture development in offshore areas of Caribbean countries are the snappers (Lutjanidae, *Lutjanus spp*), dolphin fish or mahi mahi (Coryphaenidae, *Coryphaena hippurus*), jacks and pompanos (Carangidae, *Seriola spp, Caranx spp* and *Trachinotus spp*), tunas (Scombridae, Thunnus *spp*), cobia (*Rachycentrum canadum*), and groupers (Serranidae, *Epinephelus spp*). Red drum (*Sciaenops ocellatus*) has potential for offshore cage aquaculture and is indigenous to the Gulf of Mexico. However, it is not recommended to introduce this species anywhere outside of its distribution range, which does not include most Caribbean Islands. Only indigenous species should be considered for aquaculture development in these regions. Several projects dealing with the hatchery and growout stages of these species are in the early stages of development. It is foreseen that two to three of the listed species will be raised commercially within the next few years in the Gulf and Caribbean regions. Technological progress has been fast with a few species (e.g. mutton snapper, cobia, amberjacks), but slow with important species such as groupers (Serranidae). Results of research and development conducted thus far indicate that mutton snapper, yellowtail amberjacks, cobia, and red drum exhibit the best potential for aquaculture development in the Caribbean and Gulf of Mexico within the next five years. Red drum is a traditional species whose aquaculture technology is available, but progress towards development of its commercial aquaculture in the Gulf has been slow due to questions regarding its market.

BREEDING PROGRAM

The development of a successful breeding program is the first and most important stage for the formation of a sustainable aquaculture industry in the Caribbean. The basis of every hatchery operation is the maintenance of a healthy group of sexually mature broodfish conditioned to spawn year-around using environmental cues such as photoperiod and water temperature. The consistent supply of a large number of high quality fertilized eggs can only be achieved through the implementation of a rigorous protocol aimed at reducing stress levels in the broodstock fish from the time of initial capture and acclimation to containment to final maturation. The techniques for the capture, transport, handling, sexing, sampling and acclimation of marine finfish have recently been described by Benetti and Alarcón (2000). Prophylaxis using chemotherapeutants, antibiotics, and quarantine are necessary before introducing fish into maturation facilities. Recent advances have led to improved transportation, handling, sampling and biological control of parasites through symbiosis. The effectiveness of clove bud oil as an anesthetic has been demonstrated for a number of species and can be an effective alternative to synthetic anesthetics. Some marine fish species have reacted negatively to other anesthetics such as MS-222 and 2-phenoxy-ethanol. Clove bud oil at dosages of 20 ppm has been used for anesthetizing *Lutjanus griseus*, *L. analis*, and *S. dumerili* and *Rachycentron canadum* with remarkable results. The use of cultured and wild-caught neon gobies, *Gobiosoma oceanops*, and wild-caught juvenile porkfish, *Anisotremus virginicus*, has proven to be an effective long-term means to control ectoparasites on mutton snapper, *Lutjanus analis*, greater amberjack, *Seriola dumerili*, and cobia, *Rachycentron canadum*, broodstock in recirculating systems.

Following quarantine and acclimation, broodstock fish are stocked in maturation tanks, where they are conditioned to spawn naturally through the manipulation of environmental parameters such as photoperiod and temperature cycle. Chillers and/or heat pumps and banks of fluorescent lighting are used for supplying required temperature and light cycles. Hormone-induced ovulation followed by voluntary spawning or manual stripping has also been widely used for several species that do not complete vitellogenesis and ovulation in captivity in response to environmental stimuli alone. In addition to traditional methods of inducing spawning with injections of HCG (Human Chorionic Gonadotropin) at 500 – 1000 IU/kg body weight, LHRH-a (Luteinizing Hormone Releasing Hormone analogue) at 50 - 100μg/kg and/or other natural and synthetic hormones, techniques involving the implantation of synthetic copolymers and cholesterol pellets – which serve as inert matrices for LHRH-a and GnRH (gonadotropin releasing hormone) - in the muscle tissues of the target broodstock fish – have been widely used with various degrees of success, depending on the species. Specifically, either natural or induced spawning of males and mature females have been achieved in all species listed by intramuscular injections of HCG (500 -1,000 IU/kg body weight), and LHRH-a (50 - 100μg/kg) or GnRH-a intramuscular implants.

Captive mutton snapper broodstock have recently been conditioned to spawn voluntarily in maturation tanks at the Aquaculture Center of the Florida Keys on the sole basis of manipulating environmental cues such as varying the water temperature between 20 and 28 °C. This has been an unprecedented achievement. Mahimahi, amberjack, and red fish have also been consistently spawned without hormonal inducement in several hatcheries in the United States. In Japan, Australia and Ecuador, spawning of *S. quinqueradiata*, *S. lalandi* and *S. mazatlana* have been consistently achieved in captivity, and research is underway in the U.S. to spawn *S. dumerili*. Research with yellowfin tuna (*Thunnus albacares*) conducted at the Inter-American Tropical Tuna Commission Achotines Laboratory in Panama has resulted in daily voluntary spawns of high quality fertilized eggs with additional plans for establishing protocols for the larval rearing phase (Scholey et al. 2001). Induced and voluntary spawning of cobia have been achieved in Taiwan and the U.S. through research taking place at University of Texas in Texas, Southland Fisheries in South Carolina, and Virginia Institute of Marine Sciences in Virginia. Currently, the Aquaculture Center of the Florida Keys and the University of Miami are conducting intensive R&D work with cobia, aiming to develop a breeding program for controlled reproduction to make fingerling production available for stocking offshore cages beginning in 2002.

LARVAL HUSBANDRY

Intensive and semi-intensive (mesocosm) larval rearing techniques have been used to demonstrate the feasibility of fingerling production of several high-value marine finfish species. Spawns are collected by a surface skimmer installed in each maturation tank and are passed into an egg collector. Eggs are rinsed with sterilized salt water and stocked into incubator tanks where volume and fertility counts are obtained. A rinse with formaldehyde solution (10 ppm) is also used on newly hatched eggs to reduce bacterial levels. At 26 °C, eggs of tropical species generally hatch within 24 hours and the larvae begin feeding two days post hatching (DPH). Yolk-sac larvae are stocked at densities of up to 100 per liter in intensive systems, while semi-intensive larval rearing uses stocking densities of up to 20 larvae per liter. Larval feeds consist primarily of microalgae-fed rotifers, *Brachionus plicatilis and B. rotundiformis* (ss-strain), wild plankton (particularly copepods), *Artemia* nauplii and enriched metanauplii and subadults. Feed types are overlapped and the growth rate of a particular species determines the timing at which feed items are introduced at progressively larger sizes. Traditional live feeds can be supplemented with wild zooplankton, including copepods of the genus *Acartia* and others, which are part of the larvae's natural diet in the wild and therefore ideal first food items. Live food production research is now focusing on the mass production of copepods in outdoor systems.

Probiotics and artificial substrates have been used in mesocosm systems bloomed with phytoplankton and zooplankton to improve larval rates of growth and development. Preliminary results of trials conducted with mutton snapper indicate that, while survival rates remain low, rates of growth and development of *L. analis* are faster in outdoor semi-intensive mesocosm systems than in intensive indoor systems. High mortalities are still observed during early developmental stages, especially at first feeding and metamorphosis and can sometimes be linked to poor broodstock nutrition. Weaning from live feeds onto artificial diets in species like snappers, amberjacks, grouper, and drums may take up to 40 days post hatching (DPH). Cannibalism during early stages does not constitute a problem in the case of mutton snapper, but it can be a constraint during larval rearing of pelagic species, especially after metamorphosis. Lower stocking densities, stronger water flow and aeration, and increased feeding frequency are some of the strategies used to alleviate this problem. Larval fish are highly susceptible to stress and will not tolerate handling prior to 30 DPH. Intensive larval culture methods have been successfully used to produce significant numbers of juvenile mutton snapper, although commercial feasibility of the operation has not yet been achieved.

Commercial-scale hatcheries exist for groupers and snappers in southeast Asia and in Japan, for red drum in the U.S., Taiwan and Israel, and for several temperate species in Taiwan, Japan, Australia and Japan. The aquaculture of *Seriola dumerili* and *S. mazatlana* are still in the research and development stage (Benetti 1997), but a survival rate of 9% from eggs to fingerlings of *S. quinqueradiata* has been reported in Nagasaki. In Australia, yellowtail kingfish (*S. lalandi*) offshore cage aquaculture is currently expanding to commercial scale with fingerlings produced in hatcheries. Tuna larval rearing is a new field emerging after the recent success with spawning of captive adult brood fish (Scholey et al. 2001). Cobia is considered to be a prime candidate for aquaculture in the southeastern United States, Gulf of Mexico, and Caribbean based on the combination of successful commercial development of this species in southeast Asia (Su et al. 2000) and recent research conducted in the US, in which larvae and fingerlings exhibited high survival rates and remarkable growth.

GROWOUT

Of the species considered in this review, only cobia in Taiwan, *Seriola spp* in Japan and Australia, yellowfin tuna in Mexico, red rum in several Asian countries and grouper in southeast Asia are being commercially grown in cages. The industry is quickly moving away from relying on wild caught juveniles to hatchery-produced fingerlings to stock growout cages. A remarkable cage culture industry based on hatchery-produced fingerlings has been developed in European countries, particularly in Greece, with sea bream (*Sparus aurata*) and sea bass (*Dicentrarchus labrax*) (Kissil et al. 2000a, 2000b). Currently, there is a major effort towards the development of offshore aquaculture in the southeast U.S., the Gulf of Mexico and the Caribbean (McVey and Treece 1999).

Preliminary data regarding the aquaculture performance of hatchery-reared high-value marine fish cultured in cages are only recently becoming available in this part of the world. In a growout trial recently conducted in the Florida Keys, growth, survival and feed conversion rates of mutton snapper raised in floating net cages have been assessed (Benetti et al. 2002). Results are summarized as follows: out of approximately 18,000 fingerlings produced at ACFK in 1999/2000, 10,500 juveniles were stocked in two circular high density extruded polyurethane (HDEP) floating net cages moored in a 7-acre saltwater lake in the Florida Keys. The dimensions of the cages used were 10m diameter x 7 m deep (600 m^3) and 7 m diameter x 7 m deep (300 m^3), and both were fitted with 1/2" mesh (stretched). Fish grew from an average weight of 12.25 g to over 300 g in nine months, indicating that the commercial size of 0. 5 kg (over 1 lb) can be achieved within a 1-year growout period (Figure 1). Estimated survival rate was over 70%. Stocking densities were 25 fish/m^3 (3.2 kg or 6.0 lb/m^3) and 5 fish/m^3 (0.72 kg or 1.4 lb/m^3). Fingerlings were fed a 2.5 - 5.0 mm marine grower (Moore-Clark) pellet containing 50% crude protein and 14% crude fat and a 1/4" pellet (AquaXcel, Burris) containing 53% crude protein and 10% crude fat. Estimated feed conversion ratio (FCR) was 1.4, ranging from 0.79 - 3.4. Results, described in detail by Benetti et al. (2002), confirm that *L. analis* has excellent potential for commercial aquaculture development in net cages in the U.S. and the Caribbean. These results corroborated an earlier work by Watanabe et al (1998), who raised this species in tanks with similar results.

When compared to other species, growth rates of pelagic species such as dolphin fish, cobia, tuna, and amberjack are significantly higher (Benetti 1997). Captive dolphin fish, *Coryphaena hippurus*, grew to almost 5 kg in weight and 76 cm in length from hatching in 9.5 months in Hawaii (Benetti et al. 1995). Cobia cage-culture production in Taiwan produced an estimated 1,500 tons in 1999, with reported growth rates of up to 6 kg after a one year growout period (Su et al. 2000). Red drum can tolerate a wide range of salinities as adults as well as during their early life history stages, therefore its commercial growout can be done in both ponds and cage systems, where favorable environmental conditions (water temperature 24 - 30 °C) allow for the production of 1 kg fish after a growout period of 8 - 12 months (Sandifer 1993).

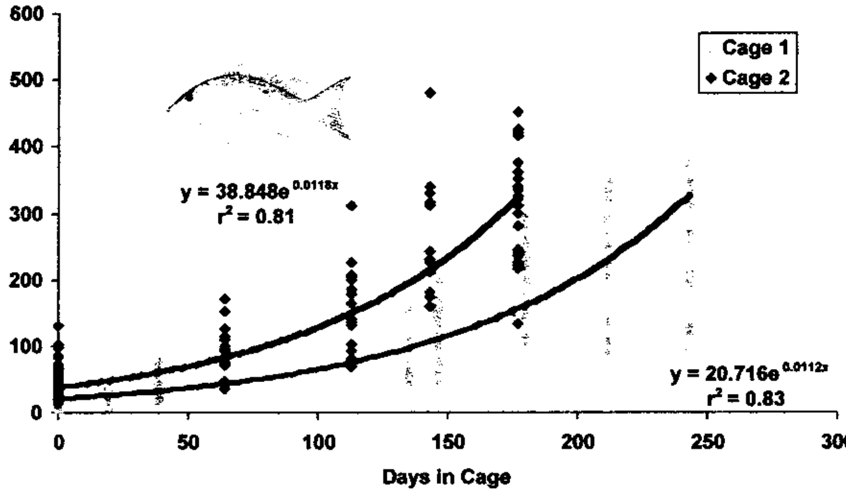

Figure 1. Growth rates of hatchery-reared mutton snapper, *Lutjanus analis*, reared in floating net cages. (Data from Benetti et al. 2002).

OVERVIEW OF OFFSHORE PROJECT DEVELOPMENT AND REGULATIONS

Beginning in June 1999, Snapperfarm, Inc. and RSMAS University of Miami joined efforts to develop a project to perfect and apply aquaculture technology of mutton snapper (*Lutjanus analis*) and other high value marine fish species using offshore cage systems. During the first stage of this project, an interdisciplinary site assessment and feasibility study were conducted to evaluate potential sites for project development in the Caribbean. Combining all relevant criteria, several potential sites were selected with many unsuitable sites eliminated on the basis of conflicting uses. The selected site covers 250,000 square meters in the Vieques sound, two nautical miles southwest of Culebra Island, Puerto Rico. The site is ideal for the deployment of two SeaStation 3000 submersible cage systems, and the water quality parameters are optimal for the growout of mutton snapper, among other species. Social, economical and educational issues were evaluated in great detail during site assessment. Snapperfarm and RSMAS have formed a partnership with the Culebra Fisherman Association, a cooperative of about 40 fishermen on the island of Culebra. Eighty percent of Snapperfarm's workforce will be comprised of local fisherman and regular educational seminars will be held on the island so that the community may learn more about the emerging offshore cage culture industry.

Once the appropriate site was selected and a productive relationship was established with the local community, the Federal and Commonwealth Joint Permit Application (JPA) for Puerto Rico was submitted in September 2000. In December of the same year, a National Pollution Discharge Elimination System (NPDES) permit application was submitted to the U.S. Environmental Protection Agency. Due to the overwhelming support that the project received from governmental, academic, and public sectors in Puerto Rico, Snapperfarm and RSMAS anticipated a short permitting process. However, a number of extrinsic factors led to delays. The new government is currently supporting the project, the federal permit has been issued and Snapperfarm and RSMAS anticipate a short wait for the approval of the final permits. The following is a short summary and interpretation of existing policy, zoning and regulations in Puerto Rico, where the Snapperfarm offshore aquaculture operation is being established:

Policy

The Commonwealth of Puerto Rico has declared, in Title 5, Chapter 52 of the 1999 Laws of Puerto Rico, that "fishing and aquaculture shall be promoted as important activities for the economic development and nutrition of the Puerto Rican people." As such, systems are in place to assist with expansion of aquaculture into offshore waters (i.e., a coordinated single application procedure). The laws and regulations are conducive to aquaculture development, but companies that apply for a permit must endure a lengthy and complex procedure to ensure that all environmental aspects related to project development are in full compliance with the laws and regulations of the 13 agencies directly involved in the permitting process. The permit application must be reviewed and approved by all 13 agencies before a final permit can be granted. An underwater archeological survey is but one example of the large number of studies required. The Army Corps of Engineers (ACE), the United States Coast Guard (USCG) and the National Oceanographic and Atmospheric Administration (NOAA) are three of the main agencies involved in the process, along with the Department of Natural and Environmental Resources (DNER).

Zones

Puerto Rico has jurisdiction, subject to all applicable federal laws, for all coastal waters (including bays and inland waters) from the established low water mark out to 12 NM.

Regulations

All Puerto Rico commonwealth laws are subject to applicable U.S. federal laws (i.e., Puerto Rico can enforce stricter laws but can not ease or try to limit federal laws). The Department of Agriculture and the DNER each oversee different regulatory aspects of the aquaculture industry in Puerto Rico. However, the Fishing and Aquaculture Industry Council (with a separate representative for mariculture) works as an interagency group to ensure that these industries thrive with the least amount of governmental interference. Leases are available for submerged lands and associated water columns. Regulations are strictly enforced, and the DNER treats every permit application with diligence.

The two SeaStation 3000 submersible cage systems will be deployed in 2002, when the Snapperfarm offshore aquaculture demonstration project is scheduled to officially begin. The two cages will be stocked with mutton snapper and cobia fingerlings produced at the Aquaculture Center of the Florida Keys. This project is the first and most important component of the Sustainable Aquafarm concept, which is briefly summarized in the following section.

THE "SUSTAINABLE OFFSHORE AQUAFARM"

The offshore growout demonstration project previously described is the first and most important component of the "*Sustainable Offshore Aquafarm*", a conceptual idea that Snapperfarm and the University of Miami set out to establish in Puerto Rico within the next few years. The main overall objective is to develop and implement technology for a new, environmentally responsible and commercially feasible industry that will generate scientific, technological, social, economic, and educational benefits.

The development of offshore sustainable aquaculture technology will require combined expertise in science and technology as well as in management, socioeconomic, environmental, and legal issues. In addition to the establishment of the cages and infrastructure, we propose to develop models for the prospective environmental impacts of EEZ-based aquaculture. Like any human activity, aquaculture in the EEZ waters of the US will have impacts on the ecology of ambient waters. Establishing benchmark conditions, modeling potential impacts on planktonic and benthic processes, and providing mechanisms to adapt aquaculture technology with the least environmental impact, will be the major objectives of this component. For example, environmental models based on energy budgets, mass balance, current velocity and direction, depth (bathymetry) and water quality parameters must be constructed to determine the amount of solids and nutrients being generated by the offshore growout systems (cages), to estimate the biomass of filter-feeder mollusks (e.g. oysters, mussels) and nutrient-stripper macroalgae (e.g. *Gracilaria*, *Ulva*) required to "clean up" the water downstream. These parameters can be determined using mass balance and differential equations. The carrying capacity of the area must be precisely determined to avoid the risks of eutrophication. The conceptual Sustainable Offshore Aquafarm can be summarized as follows:

The Offshore Aquafarm demonstration project will be completely submerged, as illustrated in Figure 2. This preserves the aesthetic aspects of the area. In compliance with USCG regulations, systems comprised of cages, rafts, lanterns, longlines and moorings will clear at least 25 ft (8 m) from the surface in order to avoid impediments with navigation. The depth of the site (90 ft/30m) and steady current (0.5-1.5 knots) maintain water movement in a downstream direction, dispersing organic and inorganic pollution that could potentially be associated with aquaculture operations. No coral reefs are present in the area surrounding the Offshore Aquafarm. Rather, sparse patches of *Halimeda* - a macroalgae characteristic of oligotrophic environment- are found at the predominantly sandy bottom. The cages, to be stocked with hatchery-reared snapper, cobia or amberjack for growout, will inevitably generate a certain amount of nutrients and suspended solids, which will not dramatically affect the nutrient deprived, offshore environment due to its carrying (i.e., environmental) capacity. Downstream from the cages' site, the concept includes the deployment of rafts and longlines of filter feeder mollusks and banks of macroalgae that will utilize the inorganic nutrients being released by the system.

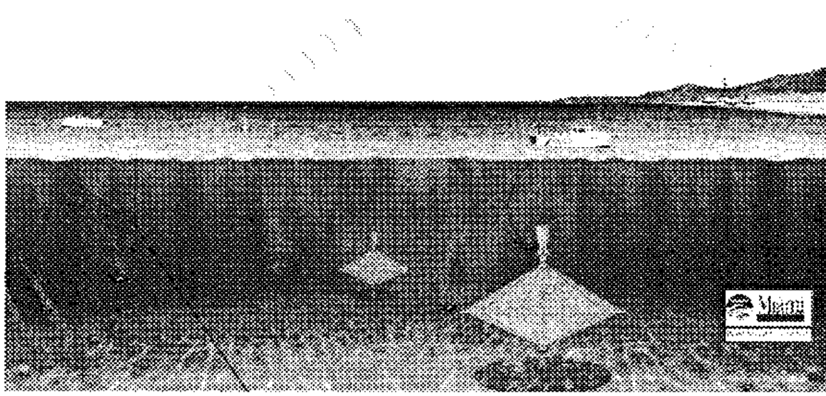

Figure 2. The Conceptual Offshore Aquafarm, currently being developed in Puerto Rico.

The submergible cages will also function as FADs (Fish Aggregating Devices). Since an estimated 50% of the hatchery-reared fish will be suitable for stock enhancement purposes, FADs will provide the ideal habitat for releasing fish. Additionally, the combination of FADs and hatchery-reared released fish will promote the enhancement of fish stocks in the area. The concept of Acoustic Ranching in Aquaculture (ARIA) will also be tested. To ensure long run autonomy of the Offshore Aquafarm, a state of the art marine hatchery and school will be established in the Island of Vieques and/or Culebra. The marine hatchery and school are seen in the background of Figure 2. An educational program and curricula will be established for training of personnel at all levels, from high-school to technical and graduate level. Simultaneously, the marine hatchery will be producing larvae, post-larvae and juveniles of high-value marine fish and invertebrate species for aquaculture and stock enhancement.

The submersible cages being used, SeaStation, are state of the art, manufactured in the U.S. by Ocean Spar Technologies, NET Systems. To ensure long-term sustainability and to develop this concept properly, scientific research is required. For example, environmental models based on energy budgets, mass balance, current velocity and direction, depth (bathymetry), and water quality parameters must be constructed to determine the amount of solids and nutrients being generated by the fish cages to estimate the biomass of filter-feeder mollusks (oysters, mussels) and nutrient-stripper macroalgae (*Gracilaria, Ulva*) required to "clean up" the water downstream. These parameters can be determined using mass balance and differential equations. The environmental carrying capacity of the area must be precisely determined to avoid the risks of eutrophication. Since the cages deployed and their mooring systems will act as artificial reefs or FADs (Fish Aggregating Devices), the model should also incorporate data on fish and invertebrate assemblges surrounding the cages.

The Offshore Aquafarm will be autonomous and self-sustained. Automated feed hoppers loaded with environmentally friendly feeds will dispense automatically pre-calculated rations to ensure the highest assimilation and feed conversion rates with minimal organic and inorganic wastes. A key determinant in the success of major aquaculture operations is the ability to monitor water quality parameters such as temperature, salinity, oxygen, pH, suspended solids, as well as nutrients, in order to determine whether fish feeds are being dispensed at the optimum rate. We propose to accomplish this by installing autonomous monitoring devices with several sensors in the cage system. The Seakeepers monitoring device will allow for gathering and transmission of real time data via satellite to computerized systems in the control room at the hatchery. This will be a fundamental tool in assisting the development of improved management strategies for minimizing solid organic and inorganic wastes (feeds, feces and nutrients) as well as promoting optimal food conversion and growth rates. The International SeaKeepers Society, which owns a patent on this monitoring device, is a technological partner in the proposed offshore project.

Properly developed, this concept may enable the simultaneous development of aquaculture of high-value organisms that feed low in the food chain such as filter feeders and nutrient strippers in areas of the Caribbean which could otherwise not be utilized for any purpose because of the extremely low productivity. Mollusks and algae, for instance, can only be cultured in nutrient rich areas. Therefore, nutrients and solids being released by the fish cages will create a favorable environment for raising species of mollusks and algae that could, in turn, provide additional crops while removing the organic and inorganic nutrients from the area. The University of Miami's Center for Sustainable Fisheries is supporting this initiative.

CONCLUSIONS

Advances in technology, suitable environmental characteristics, excellent candidate species, the need for diversification, and a growing market demand have brought the prospect of developing an environmentally sustainable and commercially viable marine fish aquaculture industry in the Caribbean and the Gulf of Mexico a step closer to reality. However, the development of reliable techniques for mass production of fingerlings of several marine finfish species through artificial propagation in hatcheries is necessary for the establishment of a sustainable offshore cage industry in the region. Research is currently focused on improving technology in the areas of broodstock nutrition, egg quality, live feeds, first feeding, larval nutrition, and bacterial contamination of live feeds, which are the main constraints for the development of the industry at the hatchery level. Progress has been fast with a few species (e.g. mutton snapper, cobia), but slow with important species such as groupers (Serranidae).

Growout technology is readily available. At the growout level, the main hurdle to overcome is the required establishment of an effective and integrated collaborative effort among the private industry, government agencies, non-government organizations, academic and research institutions, as well as stakeholders from different social and professional sectors. Both private and governmental sectors recognize that now is the perfect time for the development of high-value marine finfish aquaculture industry in this part of the world. Indeed, most countries throughout the Caribbean have appropriate offshore areas with great potential for the development of this emerging industry.

Adequate utilization of available areas and infrastructure can lead to the development of unexploited resources with the potential of generating a large number of jobs and enormous social and economic benefits to the region. However, extreme caution must be undertaken to ensure that the operations are properly planned and developed, primarily taking into account the environmental sustainability of the projects. Environmental assessment is an obvious requirement for all projects, and access to all data and information should be made readily available to environmental managers, decision-makers, and scientists. Based on real data collected prior to and during the operation, mass balance and carrying capacity modeling should allow for a high degree of environmental monitoring and control of offshore aquaculture operations in oligotrophic areas. Since the private sector is primarily profit driven, much of the regulatory and monitoring responsibility will rely on the government and academic sectors.

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LITERATURE CITED

Benetti, D.D., E.S. Iversen and A.C. Ostrowski. 1995. Growth rates of captive dolphin, *Coryphaena hippurus*, in Hawaii. *Fishery Bulletin* **93**:152-157

Benetti, D.D. 1997. Spawning and larval husbandry of flounder (*Paralichthys woolmani*) and yellowtail (*Seriola mazatlana*), new candidate species for aquaculture. *Aquaculture* **155**:307-318

Benetti, D.D., A. Clark and M.W. Feeley. 1999. Feasibility of selected candidate species of marine finfish for cage aquaculture development in the Gulf of Mexico with novel remote sensing techniques for improved offshore systems monitoring. Pages 103-119 in: R. Stickney (ed.) Joining Forces with Industry. Proceedings Third International Conference on Open Ocean Aquaculture, 10-15 May 1998. Corpus Christi, Texas, USA.

Benetti, D.D., and J.F. Alarcón. 2000. General prophylaxis and quarantine of marine brood fish. *Global Aquaculture Advocate*. **3**(6):60-61.

Benetti, D.D., J. Matera, O. Stevens, J.F. Alarcón, M.W. Feeley, F. Rotman, Y. Minemoto, G. Banner-Stevens, J. Fanke, S. Zimmerman, and L. Eldridge. 2002. Growth, survival and feed conversion rates of hatchery-reared mutton snapper, *Lutjanus analis*, cultured in floating net cages. *Journal of the World Aquaculture Society* **33**(3):349-357

Food and Agriculture Organization, FAO. (2001). The State of World Fisheries and Aquaculture 2000. FAO Fisheries Department, Rome. 160 pp.

Kissil, G.W., A. Tandler, A. Elizur, A. Colorni, and Y. Zohar. 2000. Gilthead sea bream culture. Pages 408-416 in: R. Stickney (ed.) *Encyclopedia of Aquaculture*. John Wyley & Sons, Inc. New York, New York USA. 1063 pp.

Kissil, G.W., A. Tandler, A. Colorni and A. Elizur. 2000. Sea bass culture. Pages 778-784 in R. Stickney (ed.) Encyclopedia of Aquaculture. John Wyley & Sons, Inc. New York, New York USA. 1063 pp.

McVey, J. 1997. Overview of offshore aquaculture. Pages 12-24 in: Charles E. Helsley (ed.) *Open Ocean Aquaculture '97, Charting the Future of Ocean Farming*. Proceedings of an International Conference, April 23-25, 1997, Maui, Hawaii. University of Hawaii Sea Grant College Program #CP-98-08. Honolulu, Hawaii, U.S.A.

McVey, J. and G.D. Treece. 1999. Joining forces with industry. In: Robert Strickney. (ed.) *Third International Open Ocean Aquaculture Conference.*

Corpus Christi, Texas, May 10-15, 1998. Texas Sea Grant College Program Publication. Corpus Christi, Texas USA.

Sandifer, P.A., J.S. Hopkins, A.D. Stokes, and R.D. Smiley. 1993. Experimental pond growout of red drum *Sciaenops ocellatus* in South Carolina. *Aquaculture* **118**:217-228.

Scholey, V., D. Margulies, R. Olson, G. Wexler, G. Suter, and S. Hunt. 2001. Lab culture and reproduction of yellowfin tuna in Panama. *Global Aquaculture Advocate* **4**(2):17-18.

Su, M.-S., Y.-H. Chien, and IC. Liao. 2000. Potential of marine cage aquaculture in Taiwan: Cobia culture. Pages 97-106 in: IC. Liao and C.K. Lin (eds.) *Cage Aquaculture in Asia: Proceedings of the First International Symposium on Cage Aquaculture in Asia.* Asian Fisheries Society. Manila, Phillippines.

Watanabe, W., E. Ellis, S. Ellis, J. Chaves, C. Manfredi, R. Hagood, M. Sparsis, and S. Arneson. 1998. Artificial propagation of mutton snapper *Lutjanus analis*, a new candidate marine fish species for aquaculture. *Journal World Aquaculture Society* **29**:176-187.