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Model management plan to optimize production of marine tropical systems

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Abstract NOAA, the University of Puerto Rico Sea Grant College Program, and other federal, state, and private partners are proposing to develop model management plans suitable for tropical marine ecosystems. In this paper we offer a new ecosystem-based management scenario using aquaculture to optimize value and function of tropical island ecosystems. Experience in Puerto Rico offers an excellent opportunity to combine several management plans while maintaining the flexibility to work with user groups to manage and optimize sustainable production from marine tropical systems. Puerto Rico has several tropical ecosystems available for study ranging from the high energy coastlines found on the north coast to low energy, mangrove shorelines on the southwest coast. Coral reefs are prevalent in the east, south, and west. All Puerto Rico coastal communities have seen a decline in fishery resources and habitats with subsequent decline in monetary value. A new approach for coastal resource management is needed.

The key element in coral reef management is that large scale commercial removal of reef resources has proven basically unachievable on island coral reef systems and larger coral reef systems. There are many species but not a lot of any one species. Commercial operators travel farther to find commercial levels of catch until the reef is exhausted and out of balance. Our premise is that the reef should be maintained with minimum impact to foster tourism and some subsistence fisheries to keep populations intact to maintain ecological balance of the reef and possibly provide broodstock for offshore aquaculture. Proper placement of offshore aquaculture in water over 30 m and 2-5 km offshore, away from coral reef structures has minimal environmental impact. With guidance from coral reef experts and aquaculturists, island communities can decide to combine marine protected areas, habitat protection, tourist scenic reefs, rigorous fisheries management and enforcement, and innovative marketing to optimize the value of coral reef systems. Technology exists to implement these management tools. Culebra Island, Puerto Rico, offers an excellent location to demonstrate this assumption.

Culebra has attracted international attention by petitioning the government to establish a "no-take" marine reserve. The subsequent increase of reef fish is a clear demonstration of a grassroots effort to manage local fisheries resources. By combining the knowledge of recognized coral reef experts with innovative offshore aquaculture techniques, Culebra community leaders have the opportunity to optimize the value from their coral reef systems and to protect their marine resources. Recent advances in the development of offshore, submerged, marine aquaculture technology for island locations provides a new tool to optimize production of marine tropical systems. A panel of reef specialists, enforcement agents, aquaculturists, and environmentalists would advise the community and develop a management plan to optimize scenic reefs, promote rigorous fisheries management and enforcement, and propose innovative marketing strategies.

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Introduction

Management of tropical marine systems has had varying degrees of success. These systems have been impacted heavily, resulting in detrimental impacts in many areas. Many approaches are suggested: closed fisheries, seasonal closing, or maintenance of the status quo. In most coastal communities, environmentalists, non-government agencies, fishermen, and recreational users are concerned about their marine resources. Community-based decisions, guided by professional advice, provide a grass-roots approach to optimize production from marine systems. In this paper, we suggest offshore aquaculture as an additional tool for optimizing marine production.

During the Thirtieth Joint Meeting of the United States-Japan Cooperative Program in Natural Resources (UJNR) Aquaculture Panel Meeting in Sarasota, Florida, discussions entailed joint efforts to change the perception of aquaculture by developing environmentally sound aquaculture practices using broad-based ecosystem management that includes aquaculture and fisheries. Three priority areas should include on-shore recirculating systems, offshore aquaculture, and marine stock enhancement.

Increasingly complex aquaculture management strategies require a multifaceted approach involving many subject disciplines, human resources, and public and private institutions. This approach will include industry partners and community involvement, combined with strong research and collaboration related to coastal ecosystem modeling. The addition of aquaculture to these strategies could help alleviate the impact on the fisheries habitat while still providing healthy seafood products for the public. In this respect, US and Japanese aquaculture and fisheries in both the public and private sectors can work together to combine fisheries and aquaculture to improve marketing, exports, and value of fishery products in both countries.

One caveat of this paper is that we use the popular term "offshore" aquaculture to indicate open ocean conditions. Thus the term "offshore" in this paper does not have a legal context involving economic zones or legal boundaries. The popular term "mariculture" is a specialized word for "marine aquaculture"; we generally prefer to use the phrase "marine aquaculture".

Since 2001, Puerto Rico (PR) has maintained an offshore, submerged-cage aquaculture project (Fig. 1) similar to Hawaii's recent efforts. Based on cutting-edge technology developed in the US, a New York based company, Snapperfarm, Inc., has successfully grown two fish species in cages located 3 km southwest of Culebra, Puerto Rico. Snapperfarm worked for four years to write a business plan, obtain experimental permits from the PR Department of Natural and Environmental

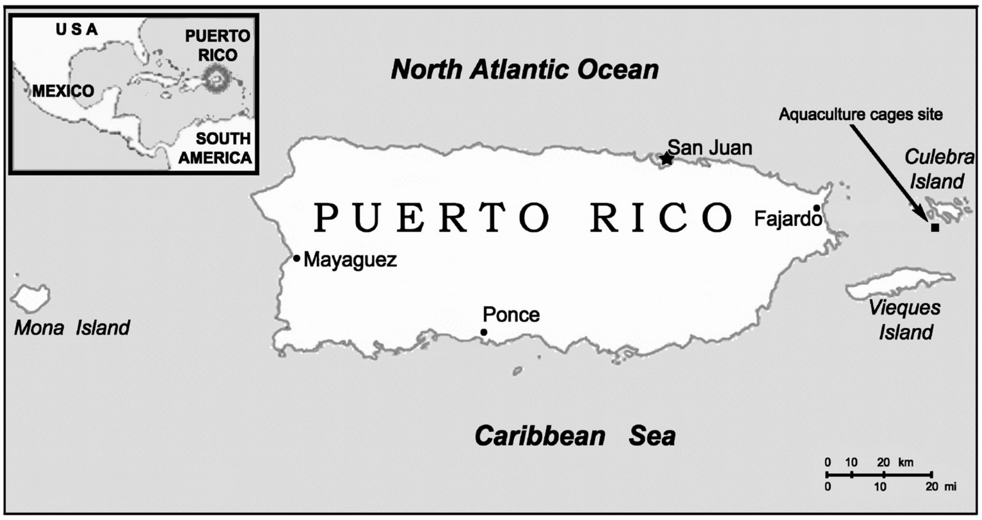

Fig. 1. Location of Snapperfarm offshore aquaculture cage site, Culebra, Puerto Rico.

Resources, assemble two submerged Ocean Spar Sea Station cages, and deploy them in 90-feet of water at the Culebra site. Snapperfarm's success has sparked the initiation of two other farms planning to install 16 more cages in Puerto Rico within two years. Growth of R. canadum (cobia) to 6 kg in one year has been the primary success factor driving this new industry with little environmental impact.

In addition to the marine aquaculture project, the island of Culebra has attracted international attention by petitioning the government to establish a "no-take" marine reserve (Causey 2002). The subsequent increase of reef fish is a clear demonstration of a grassroots effort to manage local fisheries resources. By combining the knowledge of recognized coral reef experts with innovative offshore aquaculture techniques, we expect to persuade Culebra community leaders to continue to optimize the value from their coral reef systems by developing other marine protected areas (MPAs) to ensure habitat protection. For instance, the plan should include scenic reefs, rigorous fisheries management and enforcement, and innovative marketing.

The resulting increase of reef fish is a clear demonstration of a grassroots effort to manage local fisheries resources. By combining the knowledge of recognized coral reef experts with innovative offshore aquaculture techniques, Culebra community leaders will have the opportunity to optimize the value of their coral reef systems to protect their marine resources. Simultaneously, marine aquaculture provides a new tool for managing island coastal resources to optimize production of marine tropical systems. A panel to advise the community would include reef specialists, enforcement agents, aquaculturists, economists, sociologists, and environmentalists to develop a management plan to optimize scenic reefs, promote rigorous fisheries management and enforcement, and propose innovative marketing strategies.

Deterioration of coral reefs

On a world-wide basis, coral reefs are at a 'fork in the road' (Wilkinson 2002). Either reefs will continue to decline due to increasing direct human stresses and indirect pressures of global climate change; or there could be major improvements in coral reef health in specific areas as a result of the conservation and management projects; or more likely coral reefs will travel down "both roads," with some reefs showing major improvements with increased coral cover, fish populations, and better

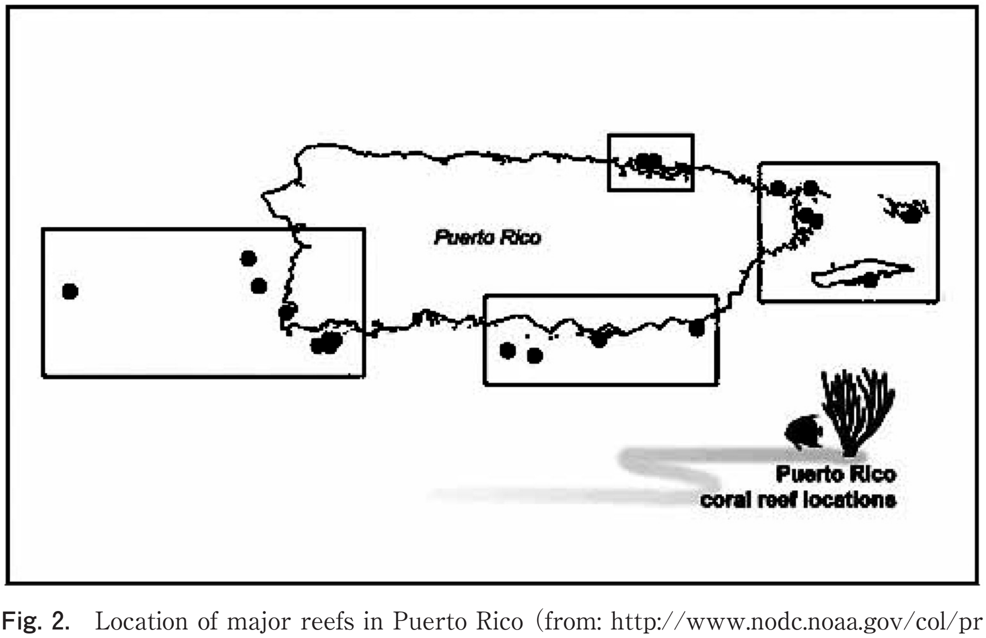

Fig. 2. Location of major reefs in Puerto Rico (from: http://www.nodc.noaa.gov/col/projects/coral/coralreef/CoralPR.html).

water quality, while many others will continue to lose corals and result in smaller fish populations and poor water quality.

Caribbean corals have been impacted. On Curacao, Netherlands Antilles, settlement of corals onto experimental plates has dropped from 22.8/m^2 in 1981 to 3.0/m^2 in 2001 (Wilkinson 2002). Many of the causes of coral reef decline have been identified and management techniques can be used to reduce pressures degrading coral reefs. It is imperative to apply this knowledge and demonstrate to coral reef user communities and their governments that coral reef conservation pays off in the long run.

In addition to the main island of Puerto Rico, there are 2 inhabited small islands off the east coast (Culebra and Vieques) and 3 uninhabited islands (Mona, Monito, Desecheo) off the west coast. Most coral reefs are located on the east, south, and west coasts (Fig. 2), with fringing reefs being the most common type. The western two-thirds of the north coast consists of mainly hard ground and reef rock with low to very low coral cover and some small, sparse, low coral colonies. The main islands of Puerto Rico, including Culebra and Vieques, are almost completely encircled by reefs, although coral reef abundance is highly variable, depending on local conditions (http://www.aims.gov.au/pages/ research/coral-bleaching).

Puerto Rico and related management plans

The Magnuson-Stevens (M-S) Act Fishery Conservation and Management Act set the standards for managing fisheries, so any plans must follow these guidelines. For instance, a fishery is defined as one or more stocks of fish which can be treated as a unit for purposes of conservation and management and which are identified on the basis of geographical, scientific, technical, recreational, and economic characteristics. Any plan must include the best scientific information available and be responsive to the needs of citizens. The term "conservation and management" refers to measures to rebuild, restore, or maintain any fishery resource and the marine environment to assure that the food or products taken is continuous, and that irreversible or long-term adverse effects on fishery resources and the marine environment are avoided. The terms 'over fishing' and 'overfished' mean a rate or level of fishing mortality jeopardizing the capacity of a fishery to produce the maximum sustainable yield on a continuing basis. The term 'fishing community' means a community which is substantially dependent on or substantially engaged in the harvest or processing of fishery resources to meet social and economic needs. The term 'optimum', with respect to the yield from a fishery, means the amount of fish which will provide the greatest overall benefit, taking into account the protection of marine ecosystems and prescribing for maximum sustainable yield from the fishery, as reduced by any relevant economic, social, or ecological factor. In the case of an overfished fishery, the plan should provide for rebuilding to a level consistent with producing the maximum sustainable yield in such fishery.

These definitions allow considerable leeway to develop management plans to provide sustainable products with little environmental impact. However, many environmentalists want to close the resource to any human activity. While this may be suitable in some instances, most laws are designed to promote the best use of a resource.

The Department of Natural and Environmental Resources of PR (DNER) is responsible for the management of marine components (http://mpa.gov/mpa_programs/states/puerto_rico.html). The Natural and Marine Reserves are managed by the Natural Reserves and Commonwealth Forests Divisions of the Bureau of Reserves, Refuges, and Coastal Resources. Additional sites are administered and managed by the PR Conservation Trust. All of the sites included in the Marine Managed Areas Inventory have been designated by the Puerto Rico Planning Board, except Isla Desecheo Marine Reserve and Seven Seas Natural Reserve which was designated by the PR Legislature. Most sites have year-round protection, excluding three red hind (Epinephelus guttatus) spawning aggregation sites, which have a temporary fishing ban (December to February), designated by a joint effort between DNER and the Caribbean Fisheries Management Council. Many sites include critical habitat and essential fish habitat for endangered and threatened species including coral reefs, seagrass meadows, lagoons, mangroves, estuaries, wetlands, offshore keys, sandy beaches, and rocky shores. The sites protect a great diversity of endemic, endangered, and keystone species, both terrestrial and marine.

Fishermen are notoriously vociferous as a group. Because PR has a tradition of fishing, albeit at an artisanal level, they are generally supported by the government. Our suggestion is to include the major players in the decision-making process, including fishermen, environmentalists, non-government organizations, and representatives from the general community. Communities should have the choice of deciding the fate of fishery activities in their area. This grass-roots approach should make it easier for fishermen to accept new strategies. Efforts should be made to include the fishermen in proposed aquaculture activities. After all, they are familiar with marine operations and should continue to contribute their skills within their respective communities. A major problem is enforcement. By having the communities join in the decision-making process, we would hope the locals would provide self-enforcement, especially if MPAs would benefit the community as a whole.

We also suggest avoiding managing specific species; instead focus would be on maintaining the reef in optimum condition. This should greatly minimize expensive studies for each target species; instead effort could be re-directed toward optimizing the health of reefs.

Culebra Island as an example of community involvement

The Island of Culebra is 27 km east of Puerto Rico and is 11 by 5 km. The surrounding waters sustain an extensive and varied coral reef that is healthier than most others in Puerto Rico. The Culebra Fishermen's Association recognized that over fishing was a problem in their area with serious consequences for their artisanal fishing livelihood. Through their own initiative and with the assistance of a volunteer fisheries scientist, the association catalyzed the conservation effort by petitioning the Department of Natural and Environmental Resources of the Puerto Rico Government to designate a "no-take" zone on the west side of the island in 1999. The Biology Department of the University of Puerto Rico-Rio Piedras conducted scientific monitoring, both before and after the establishment of the reserve, and their results show that fish abundance increased dramatically and species numbers increased by 38%. Dramatic increases in the abundance (2,539%) and in the biomass (26,618%) of the yellowtail snapper (Ocyurus chrysurus) were noted, as well as significant increases in the abundance (414%) and biomass (868%) of the schoolmaster (Lutjanus apodus). Thus, the designation of the Luis Peña Channel No-Take Marine Reserve in Culebra, Puerto Rico is a clear demonstration of a grass-roots effort to manage local fisheries resources. Please refer to Hernández-Delgado and Sabat (2000) or Hernández *et al.* (2000) for additional details referring to the no-take marine reserve.

Dr. Sarah Keene Meltzoff, University of Miami, and Dr. Janet Bonilla, UPRM contributed to a socio-economic study of Culebra in relation to the new offshore aquaculture project by Snapperfarm. Most comments concerning the new cage culture industry were positive or neutral with a "let's wait and see" attitude. Several respondents indicated they would like to know more about the industry. Questions arose concerning the competition of the cages with the local subsistence fishing industry. Snapperfarm has repeatedly stated its goal to work closely with the Culebra Fishermen's Association and has voluntarily agreed to hire locals first to fill vacant positions; however, realities in education and work experience (professional diving, aquaculture experience) severely limit employment opportunities. This is an area that could be the focus for future projects, especially to train locals in offshore aquaculture techniques.

Community involvement and education

Any management process should include community involvement. All too often "top to bottom" plans impose new strategies and management policies for the natural resource without incorporating community ideas. Phillips (1998) used the term "social sustainability" which incorporates systematic community participation which will only be socially sustainable if it conforms to social norms or does not stretch them beyond a community's tolerance for change. If the community is not involved from the initiation of the project, imprecise or erroneous perceptions emerge. These perceptions become reality. Therefore the community must participate in the initial decision-making phase. Education becomes an essential component in these interactions and should be continued throughout each phase of the project.

Fong (1999) reported enhanced environmental responsibility and participatory self-governance by fishermen. The previous model utilized centralized governmental control and input that was distant in time, space, and purpose in relation to the local fisheries industry, which resulted in low productivity by the fisheries. Although centralized controls were set in place to cover a variety of environmental conditions, they were not appropriate for all local conditions. Such distant governmental control promoted neglect or outright damage to the environmental conditions, to the detriment the fishery in question. Taiwan tried a different approach to involve the communities by dividing their "counties" into individual units to develop policies unique to their area. This has the advantage of being site specific so plans can be adapted to varying hydrological and terrestrial habitats. When the local government worked with local fisheries associations and communities, productivity increased with increasing participation of fishermen and officials. Thus, Taiwanese fisheries cooperative practices were developed to involve the interaction of the community and the fishermen with technical input from the government (Fong, 1999).

Many legislators traditionally consider the ocean as a common property resource to be managed for all the people, assuring free and equal access (Corbin and Young 1997). Others have feared that leasing could lead to widespread subdivision of ocean space by large, financially well endowed companies, thus taking away the use and enjoyment of ocean resources by the general public. Legislators are now considering the "best use" of the oceanic environment; however, care should be continued to provide for sustainable development. Ecosystem based management schemes could be the basis for these plans.

Whatever the management strategy developed, education needs to be included in the plan. The public will be more apt to accept new strategies when they understand the consequences of the "status quo" situation that benefits no one and will learn to appreciate the accrued benefits by incorporating suitable management plans to optimize the productivity of their marine resource. In addition, they will be able to make valuable suggestions to adapt the plans to their respective community. By playing a role in the decision-making process, community participants will be much more disposed to accept management plans that benefit the environment and the community. It is important to include the major players in the discussions, including fishermen, environmentalists, non-government organizations, and representatives from the general community. The discussion group should be advised by experts.

Offshore aquaculture as an additional management tool

The key element in coral reef management is that managed removal of reef resources has shown to be basically unachievable on island coral reef systems and even larger coral reef systems. Wilkinson (2002) reported the following:

All regions of the world report that human factors are behind the declining health of coral reefs. The major stresses are increased sediments and pollution by nutrients and toxic compounds, and reef damage from exploitation of fishes, invertebrates, algae, rock and sand, and constructions. The most extreme example from the 2002 Reefs at Risk analysis is that 88% of all reefs in Southeast and East Asia are under moderate to very high human pressures.

For Southeast and East Asia, Wilkinson (2002) reported that "most reefs continue to decline under increasing human impacts, except where there has been strong community involvement in MPA design and management. Unstressed and protected reefs are recovering from losses in 1998, but there was further bleaching in Japan in 2001, with 50% mortality on some reefs. By far the most serious threats are destructive and over-fishing, followed by coastal development, increased sedimentation, and pollution. Monitoring and management capacity is relatively strong, but not sufficient for adequate reef assessment and conservation."

Caribbean activities have been boosted with some new funding, but many the problems remain (Wilkinson 2002). The corals in Florida, US Virgin Islands and Puerto Rico are either declining or have not recovered after decades of losses. No-take reserves in Florida have larger fish populations than in fished areas, and public support for management is increasing.

Healthy coral reefs have many species, but not many of a particular species. Commercial operators travel more to find commercial levels of catch until the reef is exhausted and out of balance. Our premise is that it is better to maintain the reef with minimum impact to be used as a source of enjoyment for tourists and some subsistence activities, but to keep populations intact to maintain the reef in balance and possibly provide broodstock for offshore aquaculture. Proper placement of offshore aquaculture in water over 30 m and 2-5 km offshore, away from coral reef structures has minimal environmental impact. With guidance from coral reef experts and aquaculturists, island communities can decide to combine protected areas, habitat protection, tourist scenic reefs, rigorous fisheries management and enforcement, and innovative marketing to optimize the value from coral reef systems. Technology exists to implements these management tools.

FAO (1997) identifies environmental deterioration and land availability as important constraints for marine aquaculture. Over 70% of the total world population lives in Asian coastal areas (Phillips 1998); about 60% of the world's population currently lives within 60 km of the sea (Phillips 1998). Puerto Rico, with 3.9 million inhabitants occupying 9100 km^2, has a central mountainous region, thus forcing the majority of the population to live near the coast. Puerto Rico's coastal pollution is typical of many industrialized regions (eutrophication, sediments, and other contaminants), but deterioration is also exacerbated by intense recreational and artisanal fishery activities. Reef decline is widespread in Puerto Rico and the fishery is heavily impacted. Each of these factors will continue to impact coastal aquaculture; even land based operations utilize coastal waters to culture species such as marine shrimp and tropical aquarium fish.

The term "sustainability" is controversial and has several related factors that should also be considered with its usage. The concept of sustainability should include not only the ongoing operation and its long-term impacts on the environment and society, but also the infrastructure, materials, and regenerative capacity of the natural system which generates these latter items (Phillips 1998). Thus "sustainability" entails prolonged socially acceptable, economically viable, and technologically appropriate production without degrading the environment. Simultaneously, additional resources supporting the industry (i.e., feeds, wild juveniles) should be renewable, or if not renewable (i.e., hatchery reared juveniles), these resources should be replaced with suitable substitutes on a timely basis.

Environmentalists are justifiably disturbed that offshore aquaculture depends on feeds containing a high percentage of fishmeal. However, only a portion of fishmeal and fishmeal derived oils are used in fish culture operations. The rest is used in feed for food animals such as poultry, cattle, or swine and a portion is incorporated into pet foods. Feed suppliers are willing to incorporate other ingredients into high quality, high protein feeds, but farmers report inferior growth. Perhaps environmental costs are too high to continue using fishmeal in animal feeds. An international ban on fishmeal use will be complicated, however, because incorporating bycatch from fisheries operations or offal from processing procedures (like tuna, catfish, etc.) is considered a legitimate use of an otherwise wasted resource. Nevertheless, a fishmeal ban should not discriminate among various aquaculture sectors or by country. This complicated topic should be subject to multi-lateral deliberation with input from scientists, governments, and the fisheries industry. In the meantime, the marine aquaculturists should purchase feeds which minimize the incorporation of fishmeal. Recent studies indicate excellent growth from feeds containing a minimum of fishmeal.

Offshore aquaculture has been hindered because of the energetic oceanic environment, lack of suitable equipment, fingerling fish, and unclear policies and regulations concerning this nascent industry. Reviews of monitoring strategies and methods revealed the need for standardized approaches flexible enough to cover the wide range of environments in which fish farms are located (Cochrane *et al.* 1994; Codling *et al.* 1995; and Alston *et al.* 2004). Future challenges to offshore aquaculture include clarification of policies and regulations, strengthening marketing and distribution channels, coping with rapid growth of biofouling organisms, improving harvesting techniques, and establishing a source of marine fish juveniles to achieve a viable, sustainable industry. A dynamic, flexible strategic plan is essential for incorporating the needs of the private industry, optimizing support from the government, and providing for adequate research support from Puerto Rico universities. Evaluation of the industry should utilize assessment methodologies, including socio-economic considerations and comparisons with domestic and foreign offshore industries.

Marine aquaculture operations may have positive or negative effects on the environment (Phillips 1998). The environment may have positive or negative effects on aquaculture, especially if external factors continue to degrade the environment. Eutrophication may provide nutrients beneficial for aquaculture production, especially for oysters, clams, and mussels. However, toxic pollutants can damage aquaculture investments (Phillips 1998). Aquaculture operations may affect each other, especially where the carrying capacity is exceeded by rapid expansion of many farms within a limited area. Each of the suppositions mentioned generally refer to land-based or inshore mariculture operations. Offshore aquaculture avoids many of these factors. Thus far, studies by the University of Puerto Rico and the University of Miami of the Snapperfarm submerged cage operation have indicated negligible negative environmental effects. As expected, the "footprint" of the effects was limited to directly beneath the cage and attributed to a combination of nutrient release (uneaten feed, fish feces) and shading by the cage itself.

Fisheries production for Puerto Rico and the US Virgin Islands (USVI) averaged 3,360 MT (FAO, 2004) for the years 1993-2002 (Fig. 3). In 1996, there were 1758 fishermen with a total of 1501 vessels. Using conservative estimates (survival of 85%, mean weight of 6 kg) of Snapperfarm's actual stocking and fish mean weight after 12 mo, each cage should produce about 61 MT/per year (4 fish stocked/m^3 * 3,000 m^3/cage * 0.85 survival * 6 kg/fish * 0.001 to convert kg to MT = 61 MT). Rachycentron canadum are stocked at 4-6 fish/m^3 and harvested at 6-10 kg/fish in Taiwan (Su *et al.* 2000), so Snapperfarm's stocking rates are similar to those used in Taiwan. Even though all the fish were not harvested at 10 months, we are assuming a survival of 85% after 12 months. Using these conservative numbers, only 55 cages of fish would produce tonnage equaling the entire Puerto Rico and USVI fishery production (3360 MT divided by 61 MT = 55 cages). Taiwan reported that 1,500 cages were in operation in 1999 with volumes ranging from 216 to 1,884 m3. Thus if Puerto Rico and the USVI operated 55 cages, they could alleviate fishing pressure on reefs and still maintain present fishery production levels.

Alternatively, the Snapperfarm cages served as fish aggregation devices (FADs). Most subsistence fishermen in Puerto Rico focus their efforts in inshore areas, so are dependent on reef species. This causes a high pressure on coral reef species (Weiler and Suarez-Caabro 1980). Hence, FADs to attract pelagic fishes are integrated into management strategies to enhance local fisheries. FADs serve as additional substrate, shade, and refuge from predators (De Silva 1982); as an additional food source; and offer a break in the monotonous offshore environment. Friedlander (1986) compared small-scale fishing-gear techniques at six FADs deployed off northeast Puerto Rico and found differences in species diversity between FADs and control areas, indicating FADs may enhance recreational fishing catch rates. Beets (1989) found that FADs not only aggregate fishes but also have the potential to enhance the recruitment of benthic artificial reefs. Offshore cages offer protection and substrate similar to other FADs and also supplement the nutrient supply in the area through feeding the cages which could serve as direct or indirect sources of food for opportunistic feeders (Koslow *et al.* 1988;

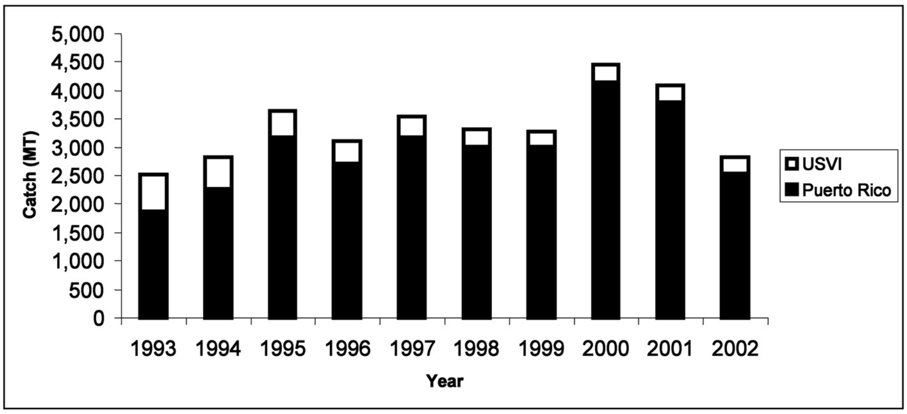

Fig. 3. Fishery landings for Puerto Rico and the US Virgin Islands, 1993-2002. Source FAO, 2004 (http://www.fao.org)

Humann 1994).

Because of the cage structures themselves and the constant food supply, we hypothesize that the offshore aquaculture industry could enhance the local fishery by facilitating new pelagic resources or serving as a source of recruitment to replenish impacted reefs. This could occur by two mechanisms. The fishermen could have access the aquaculture site to catch fish attracted to the cages. The cage site could serve as a "mini-reserve" where the cage site is restricted to fishermen. In the first case, fishermen could fish for pelagic species not normally accessible, therefore offering an additional income and economic options. However, fishermen would have to be careful to avoid damaging the cages. Pelagic fish species are not frequently captured by artisanal fishermen because of the difficulty and effort needed to find and capture these fishes. Fishing for pelagic species is more expensive.

However, fishery activities understandably makes cage aquaculturist nervous; so initially, Puerto Rican aquaculturists have decided to close their site to fishing. The second mechanism to allow the site to serve as a "mini-reserve" provides an opportunity for reef and pelagic species to use the cages as an artificial reef and spawning ground. Recruitment from the aquaculture site to area reefs could indirectly improve the fish catch on the reefs themselves. Thus, the first step was to determine the qualitative and quantitative composition, and the relative abundance of wild fish associated with the offshore cage site.

The Snapperfarm cages attracted 40 fish species from 23 families and 6 orders and mean fish abundance recorded near the cage site was approximately 40 times higher than at the control site (Bejarano *et al.* final preparation). Although the cage site was located in offshore conditions approximately 1 km from the nearest reef, 23 reef species, and 17 pelagic species were observed aggregating near the cages. Twelve reef species included juvenile individuals in most of the observations. Thirty-one of the species found near the cages are commercially important in Puerto Rico, representing 43% of the total numbers of individual recorded. Of the commercially important fish, 94% are used for human consumption (10 pelagic species and 8 reef species) and 6% are used by the aquarium industry. The majority of the fish used for human consumption were pelagic fish swimming in schools with numerous individuals. Some species exhibited a solitary behavior such as Sphyraena barracuda, Scomberomorus cavalla, Scomberomorus regalis, Ginglymostoma cirratum, Dasyatis americana, Aetobatis narinari, and Lutjanus jocu. Many were seen several times by the divers, usually moving away if closely approached.

Our data indicate submerged aquaculture cages are suitable for juvenile fish, acting as artificial habitats with additional substrate, refuge, and food. Artificial habitats in tropical waters attract reef fishes and contribute to artisanal fishing activities (Johannes 1997). With appropriate management strategies, fishermen could work with cage-culture operations, possibly kindling a proprietary and protective interest in fishing grounds. Fish collectors often become active stewards, guarding the resources against destructive uses and often creating conservation areas (Galvez 1991).

The rate of accumulation and coverage of biofouling organisms attached to the surface of the cage netting were assessed because they obstruct water flow through the cages, add additional weight to the cage, and increase the net drag. Even though biofouling was apparently not a problem in Hawaii's submerged cages (Helsley 2002), Snapperfarm reportedly cleaned their cages biweekly, thus, significantly increasing their operational costs. Because growth conditions apparently are optimum for biofouling growth, this provides an interdisciplinary opportunity to look for suitable organisms which could be grown quickly and harvested within a short time.

Although Puerto Rico historically has not cultured seaweed, the climate is suitable for tropical seaweed culture. By contrast, the Philippines produces 895 mt of aquatic plants (mostly marine algae) (http://www.fao.org/fi/statist/statist.asp), including Eucheuma alvarezii and E. denticulatum (Trono 1981). A separate species of Eucheuma isiforme is reported from Puerto Rico (Ballantine and Aponte 2002). Each has a tropical marine environment, so Puerto Rico should be suitable for seaweed culture. Ballantine and Aponte (1997) reported 473 benthic marine algae, some of which could be useful for culture.

Areas for collaborative efforts

Possible US and Japanese collaborative efforts related to optimizing production in the marine environment:

- "Culture" useful algae outside of cages instead of letting "wild" biofouling organisms dominate; in tropical conditions biofouling growth is rapid and results in economic loss for the aquaculturists due to frequent cleaning procedures.
- "Culture" filter-feeding pearl oysters on or near the cages to minimize wastes.
- Place urchins on cages to consume biofouling and explore markets for sale of urchin roe.
- Enhance BMPs (best management practices).
- Develop standardized monitoring techniques for cages.
- Automation of harvest system.
- Automation of feeding systems.
- Automation of cleaning biofouling from cages.
- Improve cage technology (shape, resistance to hurricanes/typhoons, maximize volume per dollar spent).
- Share information concerning disease and parasite infestations.
- Develop feeds with little environmental costs (i.e., without using fishmeal) that support rapid fish growth.
- Develop methodologies to measure genetic dilution from fish escapes.
- Compare carrying capacity per unit area (i.e., kg/km^2) of tropical versus temperate systems.
- Model nutrient flow (i.e., nitrogen into fish flesh, uptake by biofouling or sediment, dissolved nitrogen in water column).
- Compare discharge permit regulations.
- Compare social perception of cage culture operations.
- Study evidence of benign or beneficial interactions with the environment rather than solely concentrating on the devastation of accidental releases, eutrophication due to over feeding, or overproduction in a confined body of water (Helsley 2001).

Conclusions

Offshore aquaculture needs to confront problems inherent to the industry, especially those that seem "unavoidable" at the moment. These include the acknowledgment that unforeseen disasters could:

- ■ Cause the escape of thousands of culture animals with little genetic diversity thereby possibly diluting the gene pool of native fish.
- ■ Result in large-scale havoc by escapees on local reef ecology (predation, competition, etc.)
- ■ Spread of parasites and diseases to wild populations. The inherent crowding of cultured fish provides ideal conditions for parasites and diseases.

The public has acknowledged and accepted that land agriculture perturbs the environment; the same will be true of offshore aquaculture.

However, by integrating aquaculture as an additional tool to manage marine tropical systems, reefs can be protected while the community can benefit from aquaculture fish yields. In the meantime, we need to continue to determine the environmental effects of marine aquaculture. Except for unforeseen natural disasters, the potential benefits of marine aquaculture seem to outweigh the negative aspects.

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