

Sustainable development of marine aquaculture off-the-coast and offshore – a review of environmental and ecosystem issues and future needs in tropical zones

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ABSTRACT

The ecological impacts of intensive tropical coastal mariculture have reduced its potential for expansion. The increasing opposition to projects such as shrimp farms and the eutrophication of coral reef habitats in the tropics is among the chief incentives driving offshore operations. Tropical off-the-coast and offshore mariculture is a growing industry with considerable economic and ecological potential. However, its growth in the tropics will require a major allocation of capital, knowledge and planning resources to tropical nations, most of which are poor, underdeveloped, lack infrastructure and are distant from target markets. Hence, the benefits and costs of off-the-coast and offshore farms in tropical regions are not directly comparable, since extensive pond aquaculture and other low-tech production systems benefit the rural poor, whereas offshore mariculture is currently restricted to corporate initiatives which have the capacity for large capital investment, import of technology and assumption of significant risks. Individual offshore farmer ownership and operation in the tropics is therefore still a substantial socioeconomic challenge due to the large initial investment required. While the warm climate regime between the tropics of Cancer and Capricorn offers numerous advantages and potential for the cultivation of various marketable species, these are different to the species reared in temperate offshore farms. Whereas this may appear to be a trivial point, it is essential to note that the high cost and capital investment involved in offshore mariculture dictates the production of high-value species intended for export to the rich developed world. Most offshore projects have thus, focused on high-value predator species such as cobia, snapper, amberjack, seabream, red drum, pacific threadfin, seabass and tuna.

Unlike coastal aquaculture, tropical off-the-coast and offshore are not limited by site availability but rather by availability of capital, technology and expertise. Two regions, namely the Far East and the Caribbean/USA-Hawaii, have recently emerged as geographic epicentres of tropical and offshore aquaculture development. Off-the-coast and offshore aquaculture in the Far East is dominated by China (and is mirrored by Viet Nam and Taiwan Province of China) which has achieved commercial production levels. Operations in these nations are driven by substantial national subsidies, lucrative fish prices from regional markets, limited coastal space, and are estimated at 500 000 tonnes. Over 60 species have been tested for tropical off-the-coast and offshore culture in both sea-worthy and submersible farming systems in China. Most systems are either imported from Norway or adapted (from existing designs) and developed locally; focusing mainly on cobia and amberjack as the most abundantly cultured species, alongside flatfishes, seabreams and a host of other species, most of which are native to the tropics. On the wake of the boom in off-the-coast and offshore production in China neighbouring tropical countries, such as Viet Nam and India are actively joining this industry as well.

The second epicentre for off-the-coast and offshore farms is largely U.S.-sponsored and lies in Hawaii (USA) and the Caribbean, with additional projects planned for tropical South and Central America. It differs from the Asian experience mostly in the small-scale (most operations are still in experimental phases, with low total production), source of funding (predominately private sector), and the low number of cultured species, although here too emphasis is being placed mainly on cobia. Furthermore, these operations often focus on development of technology, rather than on commercial production.

Isolated, small-scale attempts at off-the-coast and offshore aquaculture production have been reported in Oman, the United Arab Emirates and elsewhere, where Mediterranean-like operations of seabream culture were conducted. Other tropical regions such as Africa have coastal aquaculture operations, but no offshore activity, with the exception of European sponsored efforts in the islands of La Reunion, Mayotte and Mauritius.

While offshore mariculture is more costly, risky and logistically difficult, properly planned offshore facilities can avoid many of the environmental problems of sheltered (coastal) systems while maintaining high production levels. Indeed, a number of tropical projects, mainly in China today, explore the feasibility of polyculture and integrated aquaculture systems in highly-exposed sites. Moreover, several operations have started to experiment with offshore systems for growing pollution-mitigating complimentary species, such as shrimp, scallop, sponge and mussels. This departs from the majority of aquaculture in developing tropical nations, which is dominated by production of shellfish, shrimp and seaweed for export, as well as freshwater carp, milkfish and tilapia intended for local consumption.

The main challenges identified for development of off-the-coast and offshore mariculture in the tropics include:

1. The need to lobby for development, which should address permitting, financing and government subsidy issues.
2. The need to select species on the basis of trophic level, with preference for herbivorous fish, shellfish and algae.
3. The need for site selection criteria, favoring sites with good flushing rates to maximize fish health, and highlighting the need for: proximity to hatcheries, processing plants, markets and distance from ecologically sensitive areas or other farms.
4. The need to balance distance from shore with ecological impact, carbon footprint/tourism/NIMBY/distance traveled by farm workers.
5. The need to develop protocols for environmental monitoring and farm management.

INTRODUCTION

The ever growing demand for food from the sea has led to heavy exploitation of wild marine stocks. Dwindling oceanic stocks and marine fishery yields have prompted

mankind to rely today more than ever on aquaculture. As a result, there has been a notable surge in aquaculture, with an annual increase of almost nine percent per year since 1970 (WHOI, 2007). Aquaculture has also shown considerable growth in the tropics in recent years (Troell, 2009) and especially in China (Halwart, Soto and Arthur, 2007).

Despite the abundance of rains, ample sunshine and warm temperatures that characterize the tropics (i.e. potentially rich food webs and high production rates) they are home to some of the poorest countries in the world (de Silva, 1998). The industry that many associate with tropical aquaculture is that of shrimp farming in earthen ponds, since this practice showed an exponential growth in the 1980s, but that is changing radically in recent years. Although basic physical conditions may be similar throughout the region, most tropical aquaculture takes place in Southeast Asia and South America, whereas very little exists along the coasts of Africa. This disparity is probably related to the physical features of the coastline and lack of expertise and capital (needed for investment), but is probably also related to cultural and social differences.

Whereas mariculture can provide a solution for the huge demand for aquatic food and products, it relies and impacts on many marine resources. There are numerous issues that cause concern among stakeholders in the coastal zone with regard to aquaculture, including:

- visual pollution;
- pollution of the water column with farm effluents;
- modification of coastal and benthic habitats (e.g. mangroves, coral reefs);
- creation of benthic anoxic zones due to deposition of waste feed and faeces;
- feed and seed from wild stocks;
- 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;
- introduction of exotic species; and
- interactions with threatened or endangered species.

In addition, there are global-scale or ecosystem-wide issues such as the need for fishmeal/fish oil to feed fish, destruction of essential wetlands such as mangrove forests, etc.

In general, there is a huge demand for space in the coastal zone and competition among stakeholders is fierce. The list of coastal stakeholders (defined as individuals or organizations who have a direct and/or indirect interest in the area) is long and as a newcomer to the coast (coastal aquaculture is one of the newer industries in coastal areas), aquaculture is at a clear disadvantage relative to the more veteran stakeholders. In addition, the public, and the media, often have an unfavorable opinion regarding the environmental effects of aquaculture in general, and net-cage finfish farming in particular (Mazur and Curtis, 2008).

Another factor that must be considered is the quality of coastal water. As human population continues its exponential increase, with a disproportional percentage living in the already crowded coastal regions, water quality in coastal waters is often poor. Activities that affect coastal water quality are not limited to those that occur at or near the water line, but actually all activities within watersheds (FAO, 1998). In protected bays and lagoons that are not strongly flushed these water quality problems are often exacerbated as nutrient and organic matter loadings exceed the ability of the ecosystem to dissipate these. In some cases, intensive mariculture may contribute to nutrient

loading, water quality deterioration and benthic habitat destruction (Barraclough and Finger-Stich, 1996) and these may add to the negative image of the industry. In contrast, aquaculture of bivalves and seaweeds, also known as “extractive aquaculture” (Rawson *et al.*, 2002) generally removes nutrients from the marine system thereby improving water quality and potentially improving the public image of aquaculture. Since most marine organisms require good water quality to grow properly, it would be counter-productive to situate aquaculture facilities in waters with poor or variable water quality. Moreover, in many countries there are fairly stringent food-safety standards and these would preclude aquaculture in regions that are subject to water pollution.

In view of the considerations listed above, entrepreneurs in the mariculture sector began to look into the possibility of moving aquaculture systems away from the coast (e.g. National Research Council, 1992; Bridger, 2004). There are various advantages and disadvantages involved in moving aquaculture away from shore and this paper reviews some of them in the following sections. It is suitable to quote Neville Thompson’s (1996) assessment of the four major factors that impact offshore aquaculture: “the market, costs of production, technology/expertise and funding availability”. Although all of these are also applicable to coastal or sheltered aquaculture, the higher costs (and risks) associated with offshore ventures accentuate the importance of these aspects.

This review focuses on ecological/environmental aspects of “off-the-coast” and offshore tropical mariculture. Although there is an ongoing discussion revolving around the actual definition of, and distinction between, off-the-coast and offshore, this review will not dwell on these, but rather accept the formal definitions, as described in Table 1, where off-the-coast is the region of “coastal” waters that are near to shore but in semi-exposed conditions whereas offshore is further from shore in what we consider exposed and “open-ocean” conditions. The tropical region is defined as the area between the tropics of Cancer (23.5 N) and Capricorn (23.5 S). Although there are numerous examples of aquaculture in nearby subtropical regions that are warm and similar in many ways to the tropics, these will not be included in this review.

Definitions proposed by FAO for off-the-coast and offshore aquaculture from an environmental perspective and proposition of new boundaries

It is necessary from a policy/governance aspect to provide fish farmers, coastal managers, stakeholders and entrepreneurs with a clear idea of the distinction between coastal and non-coastal sites for aquaculture. However, with the criteria used for the three categories: coastal, off-the-coast and offshore, these are not satisfactory for defining what types of aquaculture can be practiced at a given site. The categories preferred are “sheltered” and “exposed” or “open-sea” sites (see also Bridger, 2004) because despite the distance from shore, bottom depth or other physical features, the prevailing conditions at these sites (irrespective of their actual distance from shore) will determine whether aquaculture activities are practical/feasible. Where aquaculture is practiced in bays (e.g. Sungo Bay in China), the waters may remain calm even as far out as 5 km or more from shore due to the prevailing winds and the orientation of the bay with respect to the “open sea”. The definitions in this table state that coastal aquaculture is always accessible (and landing is always possible) when it is situated within 500 m from shore, but local conditions which vary considerably from place to place will determine whether or not this is true. The same argument applies to the proposal that off-the-coast aquaculture facilities situated 0.5–3 km from shore will be accessible >90 percent of the time; this will depend entirely on local conditions, since at some sites that are suitable for aquaculture, conditions are “exposed” within less than 0.5 km from shore, and as such, the sites will not always be accessible. The description of conditions and accessibility at offshore sites is more acceptable since these sites are basically oceanic in nature and fully “exposed”. In terms of operation of aquaculture facilities, this is an important factor that needs to be included in the criteria, and the

TABLE 1

Proposed definitions (FAO) for coastal, off the coast and offshore aquaculture based on some environment and hydrographic characteristics. Present study will not involve directly “coastal aquaculture”

	Coastal	Off-the-coast	Offshore
Location/ hydrography	<500 m from the coast ≤10 m depth at low tide; within sight usually sheltered	500 m–3 km, 10 m <depth at low tide <50 m; often within sight somewhat sheltered	2+ km, generally within continental shelf zones, possibly open-ocean >50 m depth
Environment	Hs usually <1 m, short period winds, localized coastal currents, possibly strong tidal streams	Hs ≤ 3–4 m localized coastal currents, some tidal streams	Hs 5 m or more, regularly 2–3 m, oceanic swells, variable wind periods, possibly less localized current effect
Access	100 % accessible landing possible at all times	>90 % accessible on at least once daily basis, landing usually possible	usually >80 % accessible, landing may be possible, periodic, e.g. every 3–10 days
Operation	Regular, manual involvement, feeding, monitoring, etc.	Some automated operations, e.g. feeding, monitoring	Remote operations, automated feeding, distance monitoring, system function

Terminology: Hs = significant wave height – approximately equal to the average of the highest one-third of the waves.

Source: Modified from Muir (2004).

authors would recommend placing the “distance from shore” in this rubric because it provides information on the difficulty/cost/energy involved in getting to the site from a practical aspect, and will play a major role in determining the economic feasibility of the activity. It is possible that one might want to consider a “fuzzy” approach (e.g. Cheng, Molenaar and Stein, 2009), incorporating both physical features at a given site and operational aspects, rather than use the clear distinctions (<500 m is coastal, whereas >500 m is off-the-coast) proposed in this table.

ADVANTAGES AND DISADVANTAGES OF MOVING AWAY FROM THE COAST

There are few differences among tropical and temperate aquaculture insofar as the rationales for moving away from shore. Offshore sites offer less competition with other stakeholders, more space, greater (seafloor) depths, a greater supply of dissolved oxygen and more rapid dilution of waste products released from the cages, with less of a perceived impact on the surrounding water and underlying sediments and healthier fish, i.e. a “greater” environmental holding capacity. In addition, because of their greater depth, offshore sites are less likely to affect ecologically-sensitive areas such as coral reefs, seagrass beds and mangrove forests. The disadvantage of offshore sites is their distance from hatcheries, maintenance and processing facilities and markets. The physical distance from shore to farm can be a major obstacle (logistically, financially and regarding their carbon or ecological footprint) on a daily basis since it is not feasible to house large teams of workers at sea for lengthy durations. The increased exposure (in comparison to coastal farms) of off-the-coast and offshore farms to severe storms considerably raises the investment costs required to protect the farm structures (e.g. moorings and nets) against the elements. Thus, economies of scale dictate that offshore farms must be larger-scale to cover these investment costs. These and other issues highlighting the pros and cons of moving offshore will be discussed in the following sections.

Advantages of offshore mariculture

The carrying capacity for dissolved nutrients and particulate organic matter depends on depth, current speed and acceptable environmental impact standards (Marine Aquaculture Task Force, 2007). Offshore cultivation of finfish provides several advantages over near-shore production.

Due to their size (assuming offshore cages will be larger than coastal cages) and location, offshore cages allow for more active swimming and provide cleaner water due to lower concentrations of shore-based pollutants and better clearance of wastes (Feng *et al.*, 2005; McVey, 2006). This results in healthier stocks with lower mortality. As a result, intensive application of antibiotics is rendered unnecessary. While coastal mariculture systems generally use antibiotics, most operational offshore systems studied did not apply antibiotics in their open-water facilities. This reduces the environmental impacts of antibiotic pollution and antibiotic-resistant pathogen development.

Depending on site placement and cage orientation, it is anticipated that offshore mariculture sites will experience higher flushing rates which will greatly reduce localized nitrification, related oxygen depression and algal blooms (Atkinson, Birk and Rosenthal, 2001; Cao *et al.*, 2007). Effects on bottom sediments are dependent on the depth of the site and benthic flow regimes, but since offshore sites are likely to be deep, there is reduced concern about damaging sensitive, highly productive benthic ecosystems such as coral reefs and seagrass beds (Wu, 1995; Feng *et al.*, 2005; Beltran-Rodriguez, 2007).

The development of management schemes for offshore farms within ecosystem based management should incorporate studies of the ecological roles of biological assemblages, both wild and cultured. This information must be coupled with knowledge of nitrogen and phosphate fluxes from other anthropogenic sources such as land based agriculture, urban wastes and treatment plants and atmospheric deposition (Livingstone, Smith and Laughlin, 2000; Atkinson, Birk and Rosenthal, 2001; McVey, 2006). The removal rates of nitrogen as a result of biological activity have to be inferred to ensure prevention of local eutrophication.

Logistical advantages of offshore mariculture include reduced theft and vandalism, though this advantage is conferred by the relative disadvantage of reduced accessibility.

Growth of tropical offshore mariculture

In recent years there has been a gradual growth in offshore mariculture farms within tropical regions. Cage culture in general is undergoing a rapid growth and a shift from simple, semi-intensive cultivation towards more intensive systems (Halwart, Soto and Arthur, 2007), however this development often halts just short of the open ocean. The growth of offshore aquaculture appears to follow large-scale regional development trends, implying that industry growth is not primarily limited by site availability, but rather by availability of capital, technology and expertise.

The most successful aquaculture region to date has been Southeast Asia, mainly China (Feng *et al.*, 2005; Lovatelli *et al.*, 2008; Halwart, Soto and Arthur, 2007; Cao *et al.*, 2007). This trend is surprising in light of the low availability of capital and the challenging hydrography of the surrounding seas (mainly storms), which do not allow for the technology available elsewhere to be easily transferred and implemented there (Halwart, Soto and Arthur, 2007). Offshore farms have also been established in Hawaii (Marine Aquaculture Task Force, 2007), in the Caribbean (Bennetti *et al.*, 2006, 2008) and in Oman (Al-Yahyai, 2008), and additional projects are planned for tropical South and Central America (Bennetti *et al.*, 2008; Stemler, 2009) and Australia (Duckworth and Wolff, 2007). Other tropical regions such as African coasts, in which cage aquaculture is still in its infancy (Halwart and Moehl, 2004) have no offshore activity at all, except for European sponsored efforts in La Reunion, Mayotte and Mauritius (Dabbadie, 2009).

Table 2 summarizes current information on specific offshore mariculture projects by region. The majority of growth has been in systems which are distant from shore, but remain in relatively calm waters due to placement in broad, shallow zones of the coastal shelf that often benefit from sheltering bays or in/near peninsulas. This highlights the inconsistencies between the descriptive and functional definitions of offshore

mariculture, since low-exposure offshore systems often combine the advantages, difficulties and requirements of both coastal and open-ocean systems in varying proportions. For example, locating a farm three kilometres from shore in a sheltered bay would result in high transportation costs and promote maximum automation even while obviating the need for heavy duty, storm-worthy submersible netcages.

Overall, the high cost and capital investment required for offshore mariculture incentivizes the cultivation of high-value species intended for consumption in the rich markets. Since carnivorous finfish fetch the highest prices within the current global market, most projects have focused on predator species such as cobia, snapper, amberjack, seabream, red drum, pacific threadfin and seabass. This departs from the majority of aquaculture in developing tropical nations, which is dominated by cultures of shellfish, shrimp and seaweed (for export) as well as milkfish and tilapia intended for regional/local consumption (Troell *et al.*, 2003).

New (previously uncultured) species are, or were recently, being developed for rearing in offshore facilities. These species include tuna (Benetti and Watchinson, 2000; Kent, 2003; Ottolenghi, 2008), amberjack (Chen *et al.*, 2008; Halwart, Soto and Arthur, 2007), Pacific threadfin (Kam, Leung and Ostrowski, 2003) and cobia (Liao *et al.*, 2004; Benetti *et al.*, 2006; Benetti *et al.*, 2008; Nguyen *et al.*, 2009). Cobia culture has been successful from the onset due to the extremely rapid growth rates (up to 6 kg/individual/year) and high market price of this species (Benetti, 2006; Liao *et al.*, 2004). Tuna, though highly profitable, is cultivated as a value-added species only, since the life cycle of this species had not been closed and juvenile tuna stocks must be caught in the wild (Ottolenghi, 2008). A number of projects in Spain, Japan, Croatia and other nations are currently developing broodstock and hatching facilities for tuna (Kent, 2003). Until this technology is advanced, large-scale aquaculture of tuna remains unfeasible, and one of the alternatives – harvesting of wild tuna juveniles – would quickly deplete wild stocks.

Another group of fishes considered for offshore aquaculture is the flatfish. Summer flounder, *Paralichthys dentatus* is in great demand in the United States of America, and elsewhere. *P. dentatus* were the target of intense research as the coastal and fishery managers attempted to restock wild populations in Long Island Sound and to provide farm-reared fish to replace the wild caught fish when the flounder fishery plummeted (Bengton, 1999 and others). Summer flounder were also reared in offshore cages at GreatBay Aquafarms in Portsmouth, New Hampshire (USA).

Flatfish such as flounder, sole, turbot and halibut are also very lucrative in China, but their production was limited because these flatfish were cultivated only in indoor ponds or tanks. The introduction of the Chinese submersible cages now enables farmers to rear these flatfish in offshore farms (Chen *et al.*, 2008) with excellent water quality and other advantageous growth conditions.

In addition, a number of projects have begun experimenting with offshore-compatible systems (bottom cages, bottom lines, etc.) for growing shrimp, scallop and mussels. These species may be especially useful as pollution-mitigating complimentary species for finfish in offshore polyculture. Conchs grown near-shore in Turks and Caicos as well as *Trochus* in several Pacific island nations could be expanded offshore. Bottom sponge culture is another branch of offshore mariculture which is being assessed for productive and economic viability (Duckworth and Wolff, 2007). Several finfish species have been suggested for future development, including the yellowfin amberjack (*Seriola quinqueradiata*) and mahi-mahi (*Coryphaena hippurus*) (Abellán and Basurco, 1999).

Corals on netcages and on netcage infrastructure

One of the recent findings that have come to light in warm-water net-cage aquaculture over the past decade is the recruitment of corals to farm structures. On the one hand, this is not surprising since corals release planktonic larvae into the water column and

these settle onto available surfaces like many other “fouling” invertebrates. What is surprising is the fact that beyond their initial recruitment, Bongiorno *et al.* (2003) and others (e.g. Bosc, 2004) have found that corals growing adjacent to active fish farms are wildly successful in comparison to corals growing at nearby reference sites. In addition to the corals, there are numerous sponges and a myriad of invertebrates that develop on farm infrastructure in warm waters, as well as reef fishes that associate with the invertebrate community (D. Angel, personal observation). Although it would involve some research and development, these findings indicate that tropical offshore fish farms could serve as a basis for cultivation of corals and reef organisms for the marine aquarium industry and for coral reef restoration efforts.

Highest potential for growth

Due to the fact that offshore aquaculture involves large capital investment, considerable technological know-how and a strong export (or local profit) potential, this industry is most suitable to the tropical regions in Southeast Asia, Brazil, India and developed Central American countries (Belize, Mexico, Costa Rica, etc.). In Africa, the Caribbean and the Pacific Islands (Oceania) the industry faces challenges related to inexistent infrastructure and unavailable capital. In an attempt to make aquaculture more profitable, high-end fish may be chosen but the industry will fail if the nearest markets are too far away to be economically competitive (high transport costs). In many countries, the local economy does not have the necessary capital to get started, and in such cases, foreign companies establish the industry (see examples below), bringing with them various questions related to equity and environmental integrity.

The highest potential culture species in the tropics appears to be cobia, and indeed, the countries mentioned above have shown interest in or taken first steps toward its rearing and culture. India is in the process of investigating the option of cobia offshore farming (20–30 m depth) using Norwegian (polar circle) cages near Tharuvikulam in Tuticorin (Kerala). This is expected to give some of the much-needed boost to the country’s rising seafood demand and export market. Central and South America are currently taking first steps toward cobia farming. In Ecuador, the United States of America based “Ocean Farm”, company that developed the “Aquapod” technology, plans to start raising cobia using HDPE cages. The Aqualider and TWB companies in Brazil already rear cobia, and in Panama Pristine Ocean, Farallon and Ocean Blue Sea Farms are all planning offshore cultivation of cobia, snapper and other species.

Mariculture of cobia and other marine species has been evaluated and reviewed for Namibia (Iitembu, 2005) in a first mainland African endeavor in this direction, but the industry has not yet developed there.

Although it lags behind cobia, another lucrative warm water fish with great potential for offshore growout is the tuna. Mexican farms (mainly in Baja California), driven by considerable U.S. investment currently fatten more than 5 000 tonnes annually of bigeye, bluefin and yellowfin tuna (Morales and Morales, 2005; Halwart, Soto and Arthur, 2007). In Costa Rica a tuna farm was planned on the mouth of the Golfo Dulce, two kilometres off the coast (Rojas and Wadsworth, 2007), however, these plans faced strong opposition from local surfers and environmental groups and the future of this venture is unclear.

In Martinique, the endemic (Gulf of Mexico) red drum is reared in net cages in a local bay and although conditions there are considered “sheltered”, this farm successfully withstood a hurricane that devastated large parts of the Caribbean, suggesting the technology can probably be taken offshore, as is. Similar cage-culture activities are under way in the Indian Ocean islands, La Reunion and Mayotte.

Challenges facing offshore mariculture

One of the challenges facing offshore mariculture is the uncertainty we have regarding environmental and ecosystem effects of the industry, mainly because currently there

are few offshore, commercial-scale operations and very little information on their interactions with the surrounding system. The distance from shore and greater water-column depths of offshore facilities should reduce ecological impacts, as well as impacts related to escapes and disease, based on our understanding and experience with coastal aquaculture. However, the distance from shore also means increased exposure to storms and to large predators, hence, potential damage to the farm structures and the farmed stock. The use of offshore waters also raises many legal questions such as the rights of individuals or nations to “lease the ocean” (Middleton, 2004; Rimmer and Ponia, 2007).

Environmental effects of offshore systems

Considerable aquaculture impact research has been carried out at warm water subtropical sites that are similar in many ways to tropical sites (e.g. Angel *et al.*, 1995; Pitta *et al.*, 1999; Karakassis *et al.*, 1999; Machias *et al.*, 2006; Apostolaki *et al.*, 2007; and others). These studies suggest that intensive aquaculture activity will most likely affect the benthos, though the degree of the impact will be a function of the prevailing site-specific conditions (e.g. Atkinson, Birk and Rosenthal, 2001; Kalantzi and Karakassis, 2006; Mantzavarakos *et al.*, 2007), farm husbandry and management.

Whereas “offshore” or “open-water” sites are thought to reduce the benthic impact of net-cage fish farms by virtue of the greater seafloor depth and exposed conditions, this is a contentious topic at some tropical aquaculture sites. It has been reported, for example, that sediments under offshore Pacific threadfin farms in Hawaii showed negligible benthic impacts (Helsley, 2006). Recent findings at the same sites suggest this is not necessarily the case. Infaunal communities sampled near the fish farm have shown a clear temporal shift in species richness and composition in comparison to a reference site (Lee, Bailey-Brock and McGurr, 2006), and have only undergone partial recovery during a 6-month following period (Lin and Bailey-Brock, 2008).

At the Snapperfarm facility near Puerto Rico, the effects of cobia (*Rachycentron canadum*) and snapper (*Lutjanus analis*) reared in offshore net cages on the environment were monitored. The monitoring included measurements of dissolved nitrogen and phosphorus, phytoplankton biomass, epiphyte growth potential, particulate organic matter flux, organic content of the sediments, and benthic microalgal biomass. During the demonstration phase of the project (50 tonnes produced/year) Alston *et al.* (2005) examined the environmental effects and concluded that these were trivial. This led Bennetti *et al.* (2006) to report that “in no case were significant differences found as a function of distance from the cages or relative to upstream-downstream direction”. Beltrán-Rodríguez (2007) examined changes in sediment biogeochemistry one year after cages were more heavily stocked. Her results showed a significant nutrient and organic matter enrichment in the sediments under the farm, as compared to reference sites. Morales-Nuñez (2005) carried out a parallel study of the sediment fauna and reported an increase in Tanaidaceae (Crustacea) abundances and a decrease in macrofauna diversity at the end of the year-long study. These results suggest that the farms that were studied are not what we would consider truly “offshore” farms, or that the farm husbandry may not have been very good. Hincapié-Cárdenas (2007) examined the dynamics of biofouling communities on the Snapperfarm cages in an attempt to assess whether offshore farms which are potentially more isolated from large concentration of planktonic larvae, for example may be less susceptible to fouling than near-shore farms. Results showed that there were no significant differences between the fouling communities on cobia versus snapper cages. Unfortunately, the study did not include a comparison between the fouling on these offshore cages versus onshore or coastal farms. It is noteworthy that despite their small-scale, several environmental studies were carried out and published with regard to Caribbean and Hawaiian offshore farms. Unfortunately, there are very few publications on environmental assessments of the much larger Chinese off-the-coast and offshore operations.

The organic enrichment of the seafloor under aquaculture systems is generally viewed in a negative light due to considerable experience in shallow coastal waters, where hypoxic/anoxic sediments have generated virtual “dead zones” below net pens. It is possible, however that in deeper waters in tropical, oligotrophic regions the detritus from aquaculture operations may serve as an attractant to benthic detritivores, thereby altering the composition of local communities and benthic food webs, which could have wider, possibly “positive” implications on the ecosystem, as described by Machias *et al.* (2006).

Most studies of the water column around coastal aquaculture in subtropical regions have found either no effects or only slight increase in such water quality indicators as nutrients, turbidity and chlorophyll-a (Wu *et al.*, 1994; Wu, 1995; Helsley, 2006; Pitta *et al.*, 2006 and 2009). There have also been a few observations of substantially reduced water quality conditions around farms that were improperly sited (e.g. Aure and Stigebrandt, 1990; Wu *et al.*, 1994) since these suffered from inadequate flushing of metabolic wastes. It is anticipated that tropical offshore aquaculture will have similar interactions with the surrounding waters and one of the main criteria that should be considered when selecting farm sites, configurations (layout of cages and infrastructure) and orientations (with respect to currents) is the ambient hydrodynamic regime. Although it is assumed that the physical environment becomes more energetic with distance from shore, this is not necessarily so and the hydrodynamic regime should be assessed during the site selection process. It has been suggested that tropical offshore areas are more oligotrophic and as such, can receive greater loadings of nutrients (in comparison to mesotrophic areas, for example) before developing water quality problems. The premise here is that the dogma “the solution to pollution is dilution” actually works, yet it is not clear that it actually does.

Although we tend to think of macrophyte aquaculture as extractive and therefore ecologically “beneficial” or benign, there is evidence of a variety of impacts of tropical open-water seaweed farms on the surrounding environment. Seaweed aquaculture may impact seagrass systems (Eklöf, Henriksson and Kautsky, 2006), macrofauna (Eklöf *et al.*, 2005), meiofauna (Ólaffson, Johnstone and Ndaro, 1995) and even fish communities (Eklöf *et al.*, 2006). These impacts include the dispersal of the cultivated seaweeds to seagrass meadows where they may act as a source of shading (as epiphytes on the seagrasses or seaweed detritus) and organic loading which may lead to habitat alteration, hypoxia and in some cases destruction. The macrophytes may also serve as an added source of nutrients to herbivorous fish (e.g. siganiids) which normally inhabit seagrass beds, thereby enhancing fish populations and as such, the impact may even be positive from the perspective of fishers.

Unlike fed aquaculture which involves addition of feed to net cages, extractive aquaculture relies on natural plankton for bivalve growth, i.e. it is “extractive” (cite). In eutrophic waters, the removal of phytoplankton from the environment is generally considered a positive outcome of the industry, however, it is really a question of scale. If the size of bivalve farms is very large, they will have a significant impact on local phytoplankton communities (Tenore, Corral and Gonzales, 1985) and the benthic organic loading due to deposition of faeces and pseudofaeces may be considerable (Stenton-Dozey, Jackson and Busby, 1999; Chamberlain *et al.*, 2001). If bivalve aquaculture is situated in tropical offshore waters, these waters will need to be assessed with respect to what large scale grazing of phytoplankton may do to the local populations of planktonic and benthic herbivores.

Environmental impacts due to disease and escapes

Disease is one of the major concerns of all farmers, including marine farmers, as it may lead to rapid loss of the cultivated stock. In many cases, pathogens originate from wild fish or invertebrate populations (e.g. Diamant and Paperna, 1995) but may reach epidemic

proportions in intensively cultivated net pens, as in the case of sea-lice and salmon (Goldburg and Naylor, 2004; Naylor and Burke, 2005). This threat is also a source of concern to environmentalists since disease may rapidly spread from farmed organisms to wild stocks (e.g. McVicar, 1997) with widespread community-wide impacts. Pathogens abound in all environments, but due to the greater natural biodiversity in the tropics, there is also a larger diversity of disease agents (Avisé, Hubbell and Ayala, 2008). In addition, the rate of infection is magnified due to the naturally high ambient temperatures which affect metabolic rates of hosts and pathogens alike, and their activity levels. One of the most important water-quality factors that affect most of the cultivated marine animals is dissolved oxygen. As temperature and salinity levels increase (higher temperatures often lead to higher salinities), the concentration of dissolved oxygen in seawater decreases so that in perpetually or generally warm water regions (tropics), animals are constantly dealing with oxidic stress and are therefore, more susceptible to disease. In addition to oxidic stress, a problem that has emerged in the cultivation of (the tropical) cobia in Taiwan Province of China is sensitivity to seawater temperature. It appears that this fish becomes stressed and more susceptible to disease when temperatures drop below its optimal growth temperature (Liao *et al.*, 2004), as observed when comparing the survival and growth rates of cobia reared in Penghu Islet (northern part of China) as compared to Shiao-Liu-Chio, Pingtung (southern part of China).

If it is assumed that the frequency of diseased fish is higher in captive (farm) populations (Costello, 2006), then one mechanism for broadcasting disease is a massive release of (escaped) fish, e.g. following net cage damage. There are, as yet, no documented cases of disease outbreaks as a direct result of these escapes.

Many escapes have been documented in the marine environment. Net pens in the Dominican Republic and Mexico sustained considerable damage following hurricanes and many of the stocked fish (estimated 60 000 cobia) escaped in 2007 (Benetti *et al.*, 2008). Typhoons in Taiwan, Province of China caused similar effects releasing large numbers of farmed fish thereby leading to a major decline in production in 2001 and 2002 (Liao *et al.*, 2004). Escapes have also resulted from human error during cage maintenance and harvesting activities, collision of ships with net-cage farms, sharks or other predators tearing net-cages (Food and Water Watch, 2009b) and vandalism (D. Angel, personal communication, 1997).

The escape of farmed fish may have detrimental effects on wild fish populations through competition and interbreeding (Naylor and Burke, 2005). This aspect of environmental interaction has been studied in depth in Canadian aquaculture. One of the advantages of offshore farms that are situated far from shore is the potential reduction in vandalism, though there is a need to monitor and guard these offshore facilities. In addition, escaped fish may have a lower impact on the environment that they are introduced into, by virtue of their distance from shore and the pelagic environment that may be the “wrong” habitat for the fish. Thus, despite numerous escape events of large numbers of fish, there are few examples of successful fish introductions in marine environments (Baltz, 1991; Billington and Herbert, 1991). This statement regarding low levels of impact should be accompanied by the caveat that our level of knowledge regarding fish communities and their resilience is rather limited in many parts of the ocean. Application of best practices and technology should limit escape events to a minimum. This may partially be achieved by good site selection, as in the case of aquaculture in Brazil, Belize and Panama which are known for their low frequency of hurricanes and strong storms (Benetti, 2008). In addition, good husbandry, including routine disposal of dead fish should reduce the attraction of predators, such as sharks, thereby reducing the risk of escapes even further. Stronger nets, monitoring systems e.g. motion-detection sensors, and proper planning of farming operations are all readily available solutions to reduce escapes. In this aspect (prevention of escapes), there is no distinguishing feature to differentiate tropical from temperate aquaculture,

though the predators are inherently different (sharks in the tropics versus sea lions in the temperate zone). State of the art information regarding escapes and developments to reduce this problem may be found at the Web site of the European Union project (www.preventescape.eu). It is noteworthy that there are cultural differences with regard to the outlook on escapes, i.e. whether they are detrimental or beneficial. In many western countries, e.g. Canada, United States of America, Norway, escapes (especially salmon) are considered a tremendous detriment to natural stocks as they may dilute the natural gene pool and spread disease. In Asia, there is a lot less concern about the environmental consequences of escapes and in some cases, the escaped fish are considered a good means for restocking natural fisheries.

Despite their distance from shore, offshore farms tend to serve as efficient fish attracting “devices” (FAD). The mechanism underlying this process is not clear, since many coastal species are not known to migrate over great distances, but the facts speak for themselves. Many tropical and subtropical farms are surrounded by large populations of wild (and in some cases feral) fish (e.g. Boyra *et al.*, 2004; Dempster *et al.*, 2002, 2004) which fill different ecological roles. Some of the fish (planktivores) feed on phytoplankton and zooplankton that tend to concentrate around the cages, while others (detritivores) act as “sinks” for lost feed and feces that are released from the cages. Numerous predatory fish are attracted to the cages by the presence of the planktivores and detritivores that congregate around the FADs and others, e.g. sharks and seals are attracted by the caged fish stocks themselves (Tuya *et al.*, 2006). The attraction of large predators to the cages endangers the caged stocks (which could lead to additional escapes) and the farm employees that maintain the cages by diving.

Shark attacks on cages in the Bahamas and in Puerto-Rico have damaged nets. As a consequence of subsequent escapes, the entire economic viability of some farms was compromised (Bennetti *et al.*, 2008). With respect to causes of damage to cages, shark attacks are prevalent in the Caribbean (Bennetti *et al.*, 2008) and in Hawaii (Food and Water Watch, 2009a, b), whereas storm damage was the main problem for cages in such regions as China, Mexico and the Dominican Republic.

In addition to the attraction of pelagic fish to fish farms, benthic enrichment under cage sites may serve as a FAD for benthic detritivores, altering local biogeography and benthic food webs. These changes may have an impact on community composition and nutrient regime shifts may follow.

Potential ecosystem effects

One of the main motivations of marine aquaculture is to supply the marine products (both in terms of rare species and volume) that conventional fisheries can no longer provide. On the ecosystem level, this may ultimately mean reduced pressure on natural fisheries, provided aquaculture can find alternatives to fishmeal and fish oils. A reduction in fishing pressures in areas where aquaculture serves as an alternative supplier should enable the recovery of many benthic and pelagic communities and could have ecosystem-wide ramifications. This is a topic that would greatly benefit from the involvement of policy-makers and politicians.

The transition from coastal aquaculture to offshore practices may have less of an effect on the local-scale, as we increase the dispersal of fish farm effluents at such exposed sites, but greater impact on an ecosystem level. Machias *et al.* (2006) and others have found evidence of regional and ecosystem level effects, e.g. increased fishery landings as a consequence of increased aquaculture production. An increase in dispersal of nutrients from large offshore farms could create a large trophic ripple effect, as anticipated in the models developed in the MARICULT project (Olsen, 2002), though it is not clear whether these would generate desirable or undesirable changes.

In some commercial species, it is difficult or prohibitively expensive to complete the life cycle in captivity and the growout process relies on collection of fingerlings from

wild stocks. This currently happens, for example, with grey mullets in Egypt and places heavy pressure on wild stocks. The same occurs with grouper farming in SE Asia and as it is done in an unregulated manner, wild stocks may be driven to extinction. In some countries in Central and South America, this issue has been addressed and offshore farms are required to construct hatcheries before cage systems are deployed to prevent wild fry fishing. Large efforts are being made to solve this problem for tuna aquaculture in Australia, United States of America, Japan and in the European Union.

There are also problems related to the feed used in fish farms. In many tropical countries carnivorous fish are fed “trash” fish (a term used to describe fish that are not usually eaten or sought after as sport fish or otherwise by fishers). This practice is extremely wasteful, and has a very high feed conversion ratio (FCR). This practice also places greater pressure on a variety of wild species, that are not normally targeted as commercial fish and raises questions with regard to by-catch and whether there should be more or less incentive to use the products of fishery by-catch. Thus, there is concern that by virtue of expansion of the cage aquaculture industry into offshore areas the need for fish feed will have widespread impacts on more wild stocks than are currently targeted and exploited by the fish-feed industry.

Carbon footprint

While offshore farming may mitigate effects on the local ecosystem by moving nutrient, pathogen and chemical sources away from fragile coastal or estuarine waters, the additional energy required for access and transportation to remote farms should be factored in before a net ecological footprint is calculated. Increased fuel costs and carbon emissions from employee access, maintenance, feed delivery, stocking and harvesting must be accounted for, though some of these are certainly offset by energy savings in water oxygenation and filtration when compared with land-based farms.

One of the major factors affecting the carbon footprint of the aquaculture industry is the proximity of feed stocks and the distance to market, the latter being especially important since high-value species (e.g. bluefin tuna) are generally delivered by air when exported. Tropical mariculture projects designed to meet import demand of wealthy countries would have a dramatically larger carbon footprint when compared with projects designed to supply local markets. One way to reduce the carbon footprint of exported high-end species is by establishing and developing local markets as was done with cobia in Taiwan, Province of China (Liao *et al.*, 2004). The market for live food fish is substantial and is increasing, not only in Asia but throughout the world, though records indicate that roughly 40 percent of the trade goes through Hong Kong SAR (Nguyen *et al.*, 2009). In Hawaii, the Kona Blue Water farm rears Hawaiian yellowtail, *Seriola rivoliana*, in open-water cages and targets this fish toward local Hawaiian, and the tourist, market under the brand name “Kona Kampachi”.

Another aspect of the carbon footprint that should be considered is the fish that are used in preparing the farmed fish feed. Feeding with “trash fish” from local fisheries would reduce transportation and processing related emissions when compared with the use of fish meal or fish oil which are produced from species which are fished in the high latitudes, e.g. anchovy and herring. But this would contribute to a greater problem of nutrification, since trash fish are a less efficient food source (lower FCR) (Naylor *et al.*, 2000). In addition, targeted trash fish extraction (as practiced in parts of Southeast Asia, mostly by trawl fisheries) impacts local food webs by removing certain size classes and species (Hall, Alverson and Metzals, 2000), as well as, having severe detrimental effects on benthic habitats (Watling and Norse, 1998).

Policy-makers

In many countries (e.g. Israel, Cyprus, Turkey, United States of America) policy-makers have reacted to the demands of lobbyists and veteran (non-aquaculture) stakeholders

with respect to the coastal zone and have limited the development of aquaculture to non-coastal or off-the-coast sites. This is a source of optimism for offshore aquaculture development, but there are also many obstacles blocking the way, mainly related to governance.

Governance

Addressing the effects of aquaculture on the marine environment requires changes to the broader framework of laws, institutions, and policies that dictate how aquaculture is sited, permitted, and operated in marine waters. This is particularly true if aquaculture moves increasingly offshore into marine waters under national jurisdiction. Two key failings of the current legal regime for marine aquaculture in many countries are the lack of clear national leadership and the lack of standards to protect the marine environment. Numerous federal agencies have responsibility for aspects of aquaculture regulation, but currently no agency is charged to coordinate the overall process. This creates a confusing and cumbersome process for those seeking permits for aquaculture and results in a lack of accountability among the agencies for marine aquaculture activities and its impacts on the marine environment.

A growing need therefore, emerges to establish a marine aquaculture programme that is precautionary, science based, socially and economically compatible with affected coastal communities, transparent in its decision-making, and provides ample opportunity for public input.

Potential socioeconomic effects

There are various socioeconomic ramifications involved in the development of offshore aquaculture in the tropics, as compared to the existent coastal aquaculture industry. Ownership and operation of offshore farms by individual farmers is a substantial economic hurdle due to the large initial investment required. These investments include extensive and massive mooring arrays, seagoing vessels for maintenance and feeding, etc., that are not required in coastal operations. Even if an entrepreneur overcomes the initial capital investment obstacle, the high risks associated with offshore mariculture further discourages smaller operators from entering the industry. Deployment and management of a farm at an offshore setting requires more highly-skilled workers than are needed in coastal aquaculture, since there is a large degree of seamanship and SCUBA divers involved in addition to routine aquaculture husbandry and thus jobs tend to be higher paid. On the positive side, it is highly likely that the success of offshore aquaculture will mark a great expansion in production volume which will generate demand for all of the peripheral industries such as marketing, feed and seed production, processing and other downstream added value industries, and thus, generation of many more jobs. In areas which have high unemployment, this has the potential to boost the economy and help develop ailing communities.

Another possible outcome of moving farms offshore is the increased reliance on automation rather than manpower. This is due to the need for sophisticated systems to address difficult and dangerous weather and sea states and in that case, the number of available jobs at the farms themselves might actually be more limited. Liao (2000) describes the socioeconomic problems that farmers in Taiwan, Province of China face as “high production costs, marketing factors, user conflicts, and lack of infrastructures”. Whereas marketing problems and user conflicts may actually decrease, production costs and lack of infrastructure tend to increase when moving offshore, as described at length in the technical reviews (this volume). Moving farms offshore requires farmers to increase farm volume and focus on more profitable species in order to balance the high production costs with high profit. For Southeast Asia, this mandates growing larger, more predatory species fit for the Japanese Sashimi market, for example (Liao, 2000). Since feed is still the major cost component in farm expenses, the choice is between

cheaper, low FCR trash fish, which are also more detrimental to the environment, and the more expensive pelleted feed.

Additional socioeconomic issues that need to be taken into consideration include: a) Considerably greater technical skills and maritime expertise: offshore farms, especially those in exposed sites, involve skilled seamanship, SCUBA diving in difficult conditions and greater “farming-in-extreme-conditions” skills as compared to mariculture near the coast; b) user conflicts, including competition with fishers, shipping lanes, offshore mining, communication cables, underwater gas lines, etc.; c) socio-economic sustainability. Because offshore farms are more of a debate than a reality in many countries, this aspect of offshore aquaculture is really only emerging at the present time, but it is an area that is essential to the industry and needs to be explored with regard to the feasibility of offshore aquaculture.

NGO response and organic label debate

Various NGOs are opposed to offshore aquaculture, though their motivations are often not very clear. One of the patterns that recur in some of the NGO statements is a blanket statement regarding the negative effects of aquaculture on the environment without actually addressing the differences between coastal and offshore aquaculture. Food and Water Watch (FWW) is opposed to sea-based aquaculture and is concerned that offshore producers will seek an organic label (“green” seafood) based on the premise that offshore enterprises may cause less environmental damage. The National Coalition for Marine Conservation is another NGO that is opposed to offshore aquaculture yet their document does not really address the conditions and issues in offshore waters. Naylor (2006) has covered some of the prime issues that the aquaculture sector must address in developing an environmentally acceptable and sustainable industry. One of the strong claims of NGOs is related to the aesthetic damage caused by coastal fish farms (also known as NIMBYism = Not-In-My-Back-Yard), but this is generally associated with wealthy land and home owners. Because many of the communities in tropical (developing) areas are poor, it is anticipated that offshore aquaculture will not address many NGO concerns related to aesthetics. Despite the many advantages conferred by offshore aquaculture, the increased carbon emissions related to the carbon footprint (described above) may offset some of the ecological benefits.

Mitigating factors for offshore aquaculture

Integrated aquaculture potential

Whereas the norm in mariculture is monoculture, the cultivation of one species, farms that rear fish, shellfish and seaweeds in bays and lagoons have operated in the Pacific and Indian oceans for many years (Neori *et al.*, 2004), especially in mainland China. Because of the logistical difficulties involved in offshore systems, it would appear that the optimal type of integrated culture is polyculture of different, yet compatible species in cages. Simultaneous, sequential or temporal integration are also possible depending on cultured species and the desired outcome.

Both integrated and offshore mariculture seek to solve nutrification problems caused by conventional coastal mariculture, but they do so via two different mechanisms. Whereas integrated systems diversify production to induce biofiltration, offshore farms shift the nutrient load to environments with a higher carrying capacity and greater flushing rates. Troell (2009) reviewed the potential of farm diversification and integration of different species of organisms in the tropics in order to benefit from the synergy. Out of nearly 100 studies of integrated systems that he reviewed, 16 percent dealt with open water integration; most of these included seaweeds. The main objective of integrating fish or shrimps with seaweeds or mussels is for the latter to act as a biofilter and mitigate eutrophication effects of the farms. Although such systems make ecological “sense”, a proper balance between the cultured components in

such an operation is a pre-requisite for successful, efficient and profitable production. Most studies were performed on a small, experimental scale but did not include an economic analysis, to calculate feasibility and profitability. The combination of moving farms offshore and integration of systems requires that several demands are met: a) there must be sufficient dissolved and particulate matter in the water column to support the lower trophic levels; b) the seaweeds or mussels surrounding a fish farm must be adjusted to higher energy fluxes that exist in offshore surroundings; c) if submersible systems are used, changes in light penetration and ambient pressure must not affect growth and survival of the integrated organisms.

Oyster and seaweed co-cultures are practiced in many off-the-coast operations, mainly in China, and are the most common type of integrated systems in open waters. Nevertheless, these are mostly practiced in protected bays and shallow coastal waters. Several examples of integrated open farms already exist in the tropics: oyster-seaweed systems in China, an experimental system for *Trochus* and giant clam restocking in the Solomon Islands and shrimp and seaweed systems in the Philippines (Lombardi *et al.*, 2006).

Recent studies have shown that corals growing adjacent to finfish net cages have higher growth rates than corals growing at pristine reference sites and on coral reefs (Bongiorni *et al.*, 2003; Bosc, 2004; Shafir, Rijn and Rinkevich, 2006). These findings may enable the integrated cultivation of corals with aquaculture for the marine aquarium trade, remediation and restocking of natural reefs or alleviation of diving pressure on natural reefs.

Troell (2009) notes that the key difference in the approach toward integrated systems in tropical versus temperate zones stems from lack of environmental awareness to waste mitigation in the tropics. This lack of awareness may prove a decisive factor in the overall deployment of offshore systems in the tropics, as high cost of offshore farms often obscures the benefits of mitigations.

Whereas offshore aquaculture may offer solutions to some of the problems that characterize coastal farms, other issues, such as biofouling, predators and stress-related disease are often just as much a problem in offshore farms. Oronti and Thiago (2009) propose a low cost solution to these problems by mimicking natural marine processes. They suggest that an artificial ecosystem may be created within the cages that would include the various trophic levels needed to maintain a clean and healthy growth environment. This would include: herbivorous species, such as rabbitfish, that would keep algal fouling of the nets to a minimum, detritivores, e.g. crustaceans or sea cucumbers to consume uneaten fish feed and faeces, scavengers to consume dead fish and even cleaner fish to improve overall fish health. This concept is somewhat utopian since it assumes that the organisms representing the various trophic levels will co-exist harmoniously, but it is worthwhile examining.

Synopsis of ongoing offshore aquaculture activities in tropical regions

The majority of tropical offshore aquaculture activity is concentrated in two regions, the Far East and the Caribbean/USA-Hawaii. Off-the-coast and offshore aquaculture in the Far East is dominated by China and Taiwan, Province of China which have already achieved commercial scale activities. Lucrative predatory fish prices from regional markets in Hong Kong Special Administrative Region and Japan and limited space in overcrowded bays and coastal lagoons are driving aquaculture companies offshore and are attracting poorer neighboring countries, such as Viet Nam into the practice. The paucity of offshore systems in countries with considerable experience in mariculture such as the Philippines, Malaysia, Indonesia or Thailand is surprising, and can probably be explained by a lack of private investment and governmental support. In comparison, there is obvious government involvement in offshore farms in Taiwan, Province of China (Liao *et al.*, 2004) and in China (Feng *et al.*, 2005).

Most Chinese mariculture operates in shallow seas, mud flats and protected bays. The main production types of coastal and off the coast aquaculture are floating and semi-floating raft culture, net cage culture, seabed seeding, vertical (hanging) culture and ponds in tidal areas (Cao *et al.*, 2007). High organic nutrient loading may lead to environmental degradation, especially when trash fish are used (Wu, 1995) because of the high FCR of this practice as Chinese coastal waters are shallow.

The development of deep-water offshore cages in China was initiated in the late 1990s. In 1998 the first offshore cages (four cages, 40 and 50 m in perimeter) were introduced into Hainan Province from Norway. Another 32 offshore cages were introduced and installed in coastal provinces including Shandong, Zhejiang, Guangdong and Fujian since 2000. From then on, developing and extending offshore cages has been confirmed as a priority of marine fish farming by the Chinese government and relevant authorities (Lovatelli *et al.*, 2008). Pompano is the main cultured species in the southern provinces (Cremer *et al.*, 2006).

Seed for the high-end offshore species in China and Taiwan, Province of China is almost exclusively hatchery reared and feed is mostly pellets, with some trash fish still used. Despite this, Chen *et al.* (2007) argue that the prospects of widespread development of offshore systems in Asia is unlikely and is hampered by the lack of investment capital and by the hydrography of the surrounding shallow seas, making adoption of technology available elsewhere difficult.

The second region where substantial offshore activities are recorded is Hawaii (USA) and the Caribbean (mainly Puerto Rico and Bahamas), where the United States of America is the major force driving the development of experimental systems. A growing interest is also emerging among aquaculture companies based in other central America countries, including Panama, Belize, Mexico, Costa Rica and others. The emphasis in the Caribbean is still on development of technology and the shift to commercial scale production is expected to take place in the coming decade.

In both the Far East and the Caribbean, the trend is generally toward rearing of pelagic fish, with cobia and snapper the primary aquaculture species.

Isolated tropical ventures also exist in the French influenced islands of Martinique and Mauritius, Mayotte and La Reunion in the Western Indian Ocean. There is also an Omani farm growing seabream and seabass using the “Mediterranean model”, some Australian offshore Barramundi farms and an experimental offshore sponge ranch.

Many of the countries in the tropical region have plans to develop or are in early stages of development of their aquaculture industry. Because this is a highly dynamic industry with large potential, yet many risks, aquaculture ventures rapidly rise and fall and only some (usually the successful) companies in selected countries are accompanied by monitoring or research that eventually yields reports and publications. A few of these developments are described below.

In Papua New Guinea, a barramundi sea cage farm was established off-the-coast of the Madang Province, as a community program. It is in a somewhat protected area and reached 100 tonnes at its peak. The farm sustained storm damage and is scheduled to be reopened, following repairs during 2010. Fry is locally produced and feed is locally gillnetted trash fish (Middleton, 2004).

There are only three barramundi sea cage farms in Australia and two of these are located in high energy environments. The Northern Territory farm is subject to tidal amplitudes, up to 8 m, while the Queensland farm is situated in an estuary with lower tides (up to 3.5 m) but with high velocity currents during strong tides. The strong currents that the farms are exposed to have resulted in both farms moving away from traditional mesh cages to more rigid designs utilizing steel or plastic mesh cages. Barramundi are fed pellet diets, and there has been much research done on developing cost-effective diets, including high-energy diets. Although automated feeding systems have been used on the large-scale sea cage farms, most barramundi farmers feed

manually. Food conversion ratios for cage culture of barramundi vary widely, ranging from 1.3:1 to 2.0:1 during the warmer months, and increasing during winter.

Table 2 provides a non-comprehensive overview of information on current off-the-coast and offshore aquaculture in the tropical regions (between the Tropics of Cancer – 23.5 N and Capricorn – 23.5 S).

STATUS OF OFFSHORE AQUACULTURE IN TROPICAL REGIONS

The initial challenge in moving aquaculture offshore was technological, as traditional methods were suitable for sheltered, low-energy environments. Despite some storm damage the offshore systems employed have thus far passed the physical tests the ocean has put them through, and must now face other feasibility issues. In Southeast Asia, governmental subsidy and entrepreneurship as well as spatial constraints have propelled offshore aquaculture to full commercial scale. China and Taiwan, Province of China have thousands of years of experience in aquaculture, therefore skilled labor is never hard to find. Moreover, producers have considerable biological and operational know-how regarding hatcheries, nurseries, feed and growout technology. Consumers in these and neighboring countries (mostly Japan and Republic of Korea) constitute an almost insatiable market for mariculture products. Furthermore, new capital is readily available and governments are eager to invest or subsidize the mariculture sector. There are national aquaculture plans in China and in Taiwan, Province of China to expand the sector and this is bound to aid in further development of offshore aquaculture. This favourable “climate” is such that in these countries user conflicts or environmental criticism is not likely to interfere with offshore development.

Constraints in Southeast Asia are mostly hydrographic and some researchers (Chen *et al.*, 2007) claim they will limit production considerably. Viet Nam is a new player in the offshore aquaculture industry with credentials in the freshwater and inshore marine sector. Viet Nam also fosters a government-backed offshore plan and is expected to become a major contributor to mariculture yields in the near future. Other Southeast Asian countries with aquaculture experience are expected to venture offshore in the future as demands and prices increase and provided the risks are reduced, but they are currently not developing in this direction.

The Caribbean region is a different story. Here, technology is scrutinized in detail before licenses are granted, governments subsidize and companies invest. The climate is still one of pioneering and trial and error and thus great plans are drawn but have so far remained mostly on paper.

This is especially true for cobia, hailed as the main culture species of offshore systems. In 2005, 80 percent of the 32 000 tonnes grown worldwide were produced in China and the rest in Taiwan, Province of China (Morales and Morales, 2005). Bennetti *et al.* (2007) predicted exponential growth rates for Caribbean cobia: from 50 tonnes to 1 000–3 000 tonnes in 2010 and 5 000–10 000 tonnes in 2012 for the offshore farm industry. These predictions were not met. This growth estimate was based on the assumption that foreign investment would enable rapid development, but that did not happen. Whether or not this growth will eventually occur remains hard to predict. User conflicts, environmental criticism and sluggish governmental involvement and backing still hamper individual efforts of companies. Nevertheless, the way forward has been plotted and many countries in Latin America appear to be potential growers, with hatcheries and onshore facilities already installed in most of them. The Hawaiian (USA) experience, despite its relative success, is also still more of a feasibility study than a successful business at commercial scale.

Australia is another country with a long tropical coastline. The main cultured species is barramundi and the few offshore farms are still isolated cases, rather than a large scale-up. Here as well it seems that legal and environmental constraints will delay production. Other ventures, such as those in Oman or the Islands of Reunion

TABLE 2

A regional synopsis of off the coast and offshore aquaculture in the tropical regions. Column headings include: country (or region)¹, major species and production levels², site exposure level (despite distance from shore and water depth, the degree of exposure will determine the level of investment required to withstand rough seas)³, currents and waves (related to “exposure”)⁴, trophic state of the water and bottom type (variables that will affect how sensitive the environment will be to farm effluents)⁵, system type (technical specifications of the farm)⁶, integrated potential (potential to establish integrated aquaculture to enhance sustainability of farms)⁷, feed and seed source (relates to ecosystem effects)⁸, product destination (relates to carbon footprint of the sector)⁹, user conflicts (conflict with other users of the lease area, e.g. fishers)¹⁰, escapes (one of the major problems at exposed sites is physical damage to fish cages and related fish escapes)¹¹, references from the literature¹² and status (whether offshore aquaculture is in planning stages or exists)

Country	Species and production level	Site exposure level	Currents and waves	Trophic state of the water and bottom type	System type	Integrated potential	Feed and Seed source	Product destination	User conflicts	Escapes	References	Status
China - Tropical China (4 Southern provinces)	~900 offshore cages in the Chinese tropics. Main Species are: cobia, amberjack, Japanese seaperch, red seabream, black porgy, tongue sole (Indigenous), red drum, derbio and southern flounder (Introduced). Production is expected to reach 500 000 mt by 2010.	Mostly inside the 40 m isobath. Many in more sheltered environments. Some exposed to typhoons and full open ocean conditions – only 13 submersible and 36 other offshore cages were deployed by 2000.	Farms are located from several hundred thousand metres offshore but mostly in shallow waters (15–20 m). Systems were tested at currents of 0.5–2 knots and submersible systems withstood typhoons with waves of >5 m.	Mostly eutrophic. In Hainan Island Province water quality is better than the mainland. Many of the bays where exposed and semi-exposed farms are located suffer from and contribute to coastal pollution. Some farms are subjected to runoff. Bottom is mostly muddy. Especially near estuaries and in sheltered bays. Some sand and silt but in shallow seas under further offshore cage systems - mud flats.	Six main cage types – HDPE circles (first imported and then adapted) are now locally produced and are commonest. floating rope cage, metal gravity cage, dish shape submersibles (imported and then adapted from Oceanspar, PDW submersible (for flatfishes), SLW submersible (spherical or cylindrical). In Hainan, 800 submersible HDPE cages have a 500 m ³ volume and produce 20–40 mt of Derbyio annually.	Mainly seaweed-shellfish cultures.	Feed is mostly trash fish. Seed is mostly locally produced in hatcheries but some is imported or caught.	The more expensive, offshore grown species are mostly shipped to Japan, Taiwan Province of China, Hong Kong SAR, USA, Canada and Europe.	-	There is little quantitative information on the numbers of animals that escape from aquaculture operations.	Lovatelli <i>et al.</i> (2008); Feng <i>et al.</i> (2005); Cao <i>et al.</i> (2007).	Most farms are operational. Many of the further offshore projects in planning stages.

TABLE 2 (CONTINUED)

Country	Species and production level	Site exposure level	Currents and waves	Trophic state of the water and bottom type	System type	Integrated potential	Feed and Seed source	Product destination	User conflicts	Escapes	References	Status
Taiwan, Province of China	Cobia indigenous 3 000 mt in 2001, 1 000 mt in 2002.	Family owned operations are protected in bays. company owned – in open water (Liu Chiu) or protected lagoon (Pengou)	Pengou is sheltered - 0.8–1.7 m waves. Liu Chiu is in higher energy environments and waves surpass 3 m. Tidal currents of up to 2 knt in Taiwan, Province of China strait.	The water is mostly oligotrophic. Bottom: Sand/Mud in sheltered inshore areas. Mud/silt in offshore farms	Square net cages in Pengou. Round HDPE cages in Liu Chiu.	In Pengou cobia are integrated with oysters.	Local seed. Pellet feed – partially locally made.	Japanese or local markets.	–	No record but some damage was caused to cages by typhoons. Other damages by poaching and vandalism.	Liao et al. (2004); Liao, 2000; Latanich, 2009.	Operational
Viet Nam	Cobia (10 000 mt), red drum and seabass. Some <i>Kappaphycus</i> is being cultivated in semi-protected areas using floating rafts.	Semi-protected in lagoons and estuaries. 1 000 mt in 25 circle cages in Nha Trang Bay.	The South China Sea has strong bottom currents but waves get high only during typhoons.	Coastal waters strongly affected by terrestrial runoff. Mostly muddy bottoms.	Norwegian imported and locally made round HDPE cages.	Some siganids are raised in Viet Nam, which can potentially be integrated with predators for cage cleaning.	Cobia, red drum and seabass seeds are hatchery reared. Almost all feed is trash fish.	Export to Japanese and US markets.	–	No record	FAO NASO, Marine Farms Ltd.; Merican, 2006, Tong, Hoang and Nguyen, 2005.	Coastal and protected cages operational. Exposed cages planned.
Mauritius	Seabream and seabass, red drum and siganids. All indigenous. 370 mt of red drum produced in 2006. total expected to reach ~1000 mt by 2010	Semi-protected – in a lagoon.	Relatively low waves and currents in the lagoon.	Oligotrophic waters. bottoms sandy or sand/silt.	Round HDPE cages in the lagoon.	Siganid culture can be integrated to clean cages from algae.	Local seed. Use of local trash fish for feed.	Export. Mainly to Japan	–	No record	Ministry of Agro-Industry and Fisheries of Mauritius (2007).	Operational

TABLE 2 (CONTINUED)

Country	Species and production level	Site exposure level	Currents and waves	Trophic state of the water and bottom type	System type	Integrated potential	Feed and Seed source	Product destination	User conflicts	Escapes	References	Status
Reunion and Mayotte (France)	Drum and cobia (indigenous) – 200 mt in Mayotte in 2007. 45 mt of drum	Mayotte farm is semi-protected, within the Mayotte lagoon. Reunion farm across from St. Paul is in open water. Both are impacted by typhoons.	–	Water is oligotrophic and bottoms are mostly sandy.	N/A	N/A	Seed imported from Taiwan, Province of China.	Export to EU, mainly France.	–	No record of escapes or damage to cages.	Dabaddie (2009).	operational. Target is 1-10000mt
Belize	Cobia (future plans - Pompano) indigenous. Projected to reach 5 000 mt in 2011.	Semi-Protected in barrier reef lagoon, but still exposed to hurricanes.	Cages located in areas with >0.1m/sec currents for nutrient dispersal.	Water: oligotrophic. Bottom: sand with some corals.	Gravity HDPE cages.	N/A	Seed initially from the United States of America, but expected to be local from 2009. Pellet feed	Export to the United States of America.	Possible friction with marine-mammal tourism (manatees)	No record yet.	Benetti et al. (2006), Benetti et al. (2008).	Operational
Bahamas and Puerto-Rico	Cobia and snapper (<i>Lutjanus analis</i>). 50 mt each farm (demonstration phase) but with plans to expand to 750 mt.	Exposed site in Puerto Rico. Semi-protected in Bahamas.	Current - 0.5–1.5 km. depth – 25–30 m.	Water oligotrophic. Bottom: sand (no coral reefs nearby).	Submersible nets systems 3000 by Oceanspar.	N/A	Fingerlings provided by foreign hatcheries. Imported pellet feed.	Export to the United States of America.	N/A (submersible cages).	Shark attacks led to escapes in all Caribbean region operations.	Benetti et al. (2008).	Experimental phase
Hawaii	Pacific threadfin (Moi) in Oahu – 750 mt. Plans to expand to 7 000 mt. <i>Seriola rivolina</i> in Kona – 650 mt.	Exposed sites - 2 nm off the coast at Oahu and 0.5 nm off the coast at Kona at 30 m depth.	Up to 1.5 km at Kona.	Oligotrophic	Submersible cages – Oceanspar. Plan to deploy 12 Oceanspheres by 2014.	N/A	Local seed. Imported pellet feed.	Either local markets (Moi) or mainland United States of America.	–	Several thousand fish escaped from Kona Blue Farms in Hawaii (USA).	Borgatti and Buck (2004, 2006).	Operational

and Mauritius, have small governmentally backed pilot operations which are only semi-commercial. In December 2007, the Ministry of Agro-Fisheries of Mauritius identified numerous sites suitable for offshore aquaculture and estimated a production potential of 15 000 tonnes, however this was not translated to the development and installation of farms. Such surveys are not uncommon; as several tropical countries (including India; Bhat and Vinod, 2008) have mapped and demarcated possible sites suitable for offshore mariculture and declared plans for production. Despite this, many still seem to wait for an economic incentive that would establish the profitability of the business. In Bangladesh, the poorest of Asian countries, we may find such an example, of the gap between the only available resource – the sea itself, and the required additional resources. The Bangladesh fishery department identified the potential of the aquaculture industry and requested aid, naming their major constraints: a lack of awareness, technology, infrastructure, hatcheries, skilled manpower, markets, legislation or financing (Kabir, 2006). It stands to reason therefore, that until external drivers force initial investment costs downwards and enable a sufficient amount of knowledge to accumulate, offshore aquaculture will continue to stall or grow slowly in these regions. It seems, however, that excluding Southeast Asia, at the onset of the second decade of the 21st Century tropical countries are still dragging their feet with regard to offshore mariculture development.

RECOMMENDATIONS

- Need to lobby for greater development of offshore aquaculture, which should address permitting issues and include government subsidies and financial support.
- To enhance the sustainability of offshore aquaculture, need to select species on the basis of trophic level, with preference for herbivorous fish, shellfish and algae.
- Proper site selection guidelines, using models where needed; prefer sites with good flushing rates to maximize fish health; need to balance depth with ecological impact/logistical considerations.
- Must balance distance from shore with carbon footprint/tourism/NIMBY/distance travelled by farm workers.
- Site preference – as close as possible to hatchery, processing plant, marketing; as far as possible from ecologically sensitive areas (reefs, seagrass beds, etc.); consider proximity to other farms (flow disruption, disease, nutrient buildup).
- Need to develop suitable and feasible protocols for monitoring farm management and the environment around the farms.

CONCLUSIONS

Tropical offshore mariculture is a growing industry with much to offer. When comparing offshore mariculture to land-based aquaculture, the potential benefits clearly outweigh the costs in terms of profitability, land use and ecosystem preservation (Troell *et al.*, 2003; Bennetti *et al.*, 2006). That said, in the tropical regions the benefits and costs are not strictly comparable, since pond aquaculture can be (and is) developed as a low-tech, extensive agricultural system that benefits the rural poor, whereas offshore mariculture is restricted to corporate initiatives capable of large capital investments, technological imports, and the assumption of significant risk. The ecological effects of intensive coastal mariculture have reduced its potential for expansion and fostered increasing opposition to existing projects. While offshore mariculture is more costly, risky (as a result of high exposure to the elements) and logistically difficult than coastal mariculture, properly planned offshore facilities can avoid many of the environmental problems of sheltered systems while maintaining high production levels. The growth of this industry in the tropics will require major investment of capital, knowledge and planning resources to underdeveloped nations. Moreover, it is important to examine the suitability of current

commercial species and new species for offshore rearing and to explore the feasibility of polyculture and integrated aquaculture systems in highly-exposed sites.

REFERENCES

- Abellán, E. & Basurco, B., eds. 1999. Marine finfish species diversification: Current situation and prospects in Mediterranean aquaculture. *Options Mediterranees Series B* 24. 138 pp.
- Al-Yahyai, S. 2008. Sultanate of Oman: National review on marine cage aquaculture. Aquaculture Centre, Ministry of Fisheries. 28 pp.
- Alston, D.E., Cabarcas, A., Capella, J., Benetti, D.D., Keene-Meltzoff, S., Bonilla, J. & Cortes, R. 2005. Environmental and social impact of sustainable offshore cage culture production in Puerto Rican waters. NOAA – National Sea Grant. University of Puerto Rico at Mayagüez, P.R. 207 pp.
- Apostolaki, E., Tsagaraki, T., Tsapakis, M. & Karakassis, I. 2007. Fish farming impact on sediments and macrofauna associated with seagrass meadows in the Mediterranean. *Estuarine, Coastal and Shelf Science*, 75: 408–416.
- Atkinson, M.J., Birk, Y. & Rosenthal, H. 2001. Evaluation of pollution in the Gulf of Eilat. Report for the Ministries of Infrastructure, Environment and Agriculture of Israel. 44 pp.
- Aure, J. & Stigebrandt, A. 1990. Quantitative estimates of eutrophication effects on fjords of fish farming. *Aquaculture*, 90: 135–156.
- Avise, J.C., Hubbell, S.P. & Ayala, F.J. 2008. In the light of evolution II: Biodiversity and extinction. *Proceedings of the National Academy of Sciences USA*, 105: 11453–11457.
- Baltz, D.M. 1991. Introduced fishes in marine systems and inland seas. *Biological Conservation*, 56: 151–177.
- Bannister, R., Brinkman, R.M., Wolff, C.W.W., Battershill, C.N. & De Nys, R. 2007. The distribution and abundance of dictyoceratid sponges in relation to hydrodynamic features: identifying candidates and environmental conditions for sponge aquaculture. *Marine and Freshwater Research*, 58: 624–633.
- Barracough, S. & Finger-Stich, A. 1996. *Some ecological and social implications of commercial shrimp farming in Asia*, United Nations Research Institute for Social Development (UNRISD) Discussion Paper No. 74.
- Beltrán-Rodríguez, D.M. 2007. *Spatio-temporal variation in organic nitrogen and carbon in sediments associated with tropical submerged cage aquaculture*. University of Puerto-Rico, Mayaguez Campus. (M.Sc. dissertation). 94 pp.
- Benetti, D. 2008. Cobia aquaculture, expanding in Americas, Caribbean. *Global Aquaculture Advocate*, Mar/Apr 08 issue. 46–47 pp.
- Benetti, D.D. & Watchinson, W. 2000. Offshore cage aquaculture of southern bluefin tuna (*Thunnus maccoyii*) in South Australia. *Global Aquaculture Alliance Technical Magazine*, 3(4): 28–29.
- Benetti, D., Brand, L., Collins, J., Orhun, R., Benetti, A., O’Hanlon, B., Danylchuk, A., Alston, D., Rivera, J. & Cabarcas, A. 2006. Can offshore aquaculture of carnivorous fish be sustainable? Case studies from the Caribbean. *World Aquaculture*, 37(1): 44–47.
- Benetti, D.D., Orhun, M.R., Sardenberg, B., O’Hanlon, B., Welch, A., Hoenig, R., Zink, I., Rivera, J.A., Denlinger, B., Bacoat, D., Palmer, K. & Cavalin, F. 2008. Advances in hatchery and grow-out technology of cobia *Rachycentron canadum* (Linnaeus). *Aquaculture Research*, 39: 701–711.
- Bhat, B.V. & Vinod, P.N. 2008. Development of seafarming in India – an export perspective. In A. Lovatelli, M.J. Phillips, J.R. Arthur & K. Yamamoto, eds. *FAO/NACA Regional Workshop on the Future of Mariculture: a Regional Approach for Responsible Development in the Asia-Pacific Region*. Guangzhou, China, 7–11 March 2006, pp. 301–306. FAO Fisheries Proceedings No 11. Rome, FAO. 325 pp (also available at www.fao.org/docrep/011/i0202e/i0202e00.htm).

- Billington, N. & Herbert, P.D.N. 1991. The ecological and genetic implications of fish introductions. *Canadian Journal of Fisheries and Aquatic Sciences*, 48(S1): 80–94.
- Bongiorni, L., Shafir, S., Angel, D.L. & Rinkevich, B. 2003. Survival, growth and reproduction of hermatypic corals subjected to *in situ* fish farm nutrient enrichment. *Marine Ecology Progress Series*, 253: 137–144.
- Borgatti, R. & Buck, E.H. 2004. Open Ocean Aquaculture. CRS Report for Congress RS21914. 6 pp.
- Borgatti, R. & Buck, E.H. 2006. Open ocean aquaculture. Congressional Research Service, Washington, DC. (available at <http://ncseonline.org/nle/crsreports/06apr/RL32694.pdf>).
- Bosc, P. 2004. Programme d'évaluation des perspectives de développement de l'élevage d'ombrine (*Sciaenops ocellatus*) en cage en Baie de Saint-Paul – Contribution à l'étude de la structure des coûts de production. Rapport ARDA – Région Réunion – Union Européenne.
- Boyra, A., Sanchez-Jerez, P., Tuya, F., Espino, F. & Haroun, R. 2004. Attraction of wild coastal fishes to Atlantic subtropical cage fish farms, Gran Canaria, Canary Islands. *Environmental Biology of Fishes*, 70: 393–401.
- Bridger, C.J. 2004. The Gulf of Mexico Offshore Aquaculture Consortium. In C.J. Bridger, ed.. *Efforts to develop a responsible offshore aquaculture industry in the Gulf of Mexico: A compendium of offshore aquaculture consortium research*. pp. 11–21. Mississippi-Alabama Sea Grant Consortium, Ocean Springs, MS.
- Cao, L., Wang, W., Yang, Y., Yang, C., Yuan, Z., Xiong, S. & Diana, J. 2007: Environmental Impact of Aquaculture and Countermeasures to Aquaculture Pollution in China. *Environmental Science and Pollution Research*, 14(7): 452–462.
- Chamberlain, J., Fernandes, T.F., Read, P., Nickell, T.D. & Davies, I.M. 2001. The surrounding surficial sediments. *ICES Journal of Marine Science*, 58: 411–416.
- Chen, J., Guang, C., Xu, H., Chen, Z., Xu, P., Yan, X., Wang, Y. & Liu, J. 2007. A review of cage aquaculture in China. In M. Halwart, D. Soto & J.R. Arthur, eds. *Cage aquaculture – Regional reviews and global overview*, pp. 53–66. FAO Fisheries Technical Paper. No. 498. Rome, FAO. 241 pp. (also available at www.fao.org/docrep/010/a1290e/a1290e00.htm).
- Chen, J., Guang, C., Xu, H., Chen, Z., Xu, P., Yan, X., Wang, Y. & Liu, J. 2008. Marine fish cage culture in China. In: Lovatelli, A.; Phillips, M.J.; Arthur, J.R. & Yamamoto, K., eds. *FAO/NACA Regional Workshop on the Future of Mariculture: a Regional Approach for Responsible Development in the Asia-Pacific Region. Guangzhou, China, 7–11. March 2006*. FAO Fisheries Proceedings No. 11. Rome, FAO. 325 pp. (also available at www.fao.org/docrep/011/i0202e/i0202e00.htm).
- Cheng, T., Molenaar, M. & Stein, A. 2009. Fuzzy Approach for Integrated Coastal Zone Management. In X. Yang, ed. *Remote Sensing and Geospatial Technologies for Coastal Ecosystem Assessment and Management*, Lecture Notes in Geoinformation and Cartography, 67–90.
- Costello, M.J. 2006. Ecology of sea lice parasitic on farmed and wild fish. *Trends in parasitology*, 22: 475–483.
- Cremer, M.C., Lan, H.P., Schmittou, H.R. & Jian, Z. 2006. Commercial scale production of Pompano *Trachinotus ovatus* in off-shore ocean cages: results of 2004 and 2005 production tests in Hainan, China, by ASA-IM/USB. In Book of Abstracts, 2nd International Symposium on Cage Aquaculture in Asia (CAA2), 3–8 July 2006, Hangzhou, China.
- Dabbadie, L. 2009. Aquaculture Notes. Aquaculture in Africa (also available at: <http://aquaculture-notes.blogspot.com/2009/08/aquaculture-in-africa.html>).
- De Silva, S.S. 1998. Tropical mariculture: current status and prospects. In S.S. De Silva, ed. *Tropical Mariculture*, pp. 1–17. Academic Press, London.
- De Silva, S.S. & Phillips, M.J. 2007. A review of cage aquaculture: Asia (excluding China). In M. Halwart, D. Soto & J.R. Arthur, eds. *Cage aquaculture – Regional reviews and global overview*, pp. 18–48. FAO Fisheries Technical Paper. No. 498. Rome, FAO. 241 pp. (also available at www.fao.org/docrep/010/a1290e/a1290e00.htm).

- Dempster, T., Sanchez-Jerez, P., Bayle-Sempere, J.T., Giménez-Casalduero, F. & Valle, C. 2002. Attraction of wild fish to sea-cage fish farms in the south-western Mediterranean Sea: spatial and short-term temporal variability. *Marine Ecology Progress Series*, 242: 237–252.
- Dempster, T., Sanchez-Jerez, P., Bayle-Sempere, J. & Kingsford, M. 2004. Extensive aggregations of wild fish at coastal sea-cage fish farms. *Hydrobiologia*, 525: 245–248.
- Diamant, A. & Paperna, I. 1995. Protozoan diseases of fish in Mediterranean marine aquaculture. 2nd European Congr. Protistology and 8th Europ. Conf. On Ciliate Biology, July 21–26, Clermont Ferrand, France. *European Journal of Protistology*, 31: 402–476.
- Du, Q., Zhang, Y.T., Gao, L., Qian, X.M. & Xu, C.Y. 2002. Features and countermeasures of red tides in Fujian sea area in recent years. *Journal of Fujian Fisheries*, 4:32–37 (in Chinese).
- Duckworth, A.R. & Wolff, C. 2007. Bath sponge aquaculture in Torres Strait, Australia: Effect of explants size, farming method and the environment on culture success. *Aquaculture*, 271: 188–195.
- Eklöf, J.S., de la Torre-Castro, M., Adelsko, L., Jiddaawi, N.S. & Kautsky, N. 2005. Differences in seagrass and macrofaunal assemblages in seagrass beds with and without seaweed farms. *Estuarine, Coastal and Shelf Science*, 63: 385–396.
- Eklöf, J.S., Henriksson, R. & Kautsky, N. 2006a. Effects of tropical open-water seaweed farming on seagrass ecosystem structure and function. *Marine Ecology Progress Series*, 325: 73–84.
- Eklöf, J.S., de la Torre-Castro, M., Nilsson, C. & Rönnbäck, P. 2006b. How do seaweed farms affect local fish catches in a seagrass-associated setting? *Aquatic Living Resources*, 19: 137–147.
- FAO. 1998. *Developing participatory and integrated watershed management*. Community Forestry Case Study Series, No. 13. Rome, FAO.
- Feng, Y.Y., Hou, L.C., Ping, N.X., Ling, T.D. & Kyo, C.I. 2005. Development of mariculture and its impacts in Chinese coastal waters. *Reviews in Fish Biology and Fisheries*, 14: 1–10.
- Food & Water Watch. 2009a. Kona Blue's Ocean Aquaculture: Marketing the Myth of Sustainability. Fact Sheet, June 2009.
- Food & Water Watch. 2009b. Fishy farms: the problems with open ocean aquaculture. Report, September 2009.
- Goldburg, R. & Naylor, R. 2004. Future seascapes, fishing, and fish farming *Frontiers in Ecology and the Environment*, 3: 21–28.
- Hall, M.A., Alverson, D.L. & Metzuzals, K.I. 2000. By-Catch: Problems and Solutions. *Marine Pollution Bulletin*, 41(1–6): 204–219.
- Halwart, M. & Moehl, J.F. (eds.). 2004. *FAO Regional Technical Expert Workshop on Cage Culture in Africa*. October 2004. Entebbe, Uganda.
- Halwart, M.; Soto, D.; Arthur, J.R. (eds.). 2007. Cage aquaculture – Regional reviews and global overview. *FAO Fisheries Technical Paper* No. 498. Rome, FAO. 241 pp. (also available at www.fao.org/docrep/010/a1290e/a1290e00.htm).
- Helsley, C.E. 2006. Environmental Observations around Offshore Cages in Hawaii. In Lee, C.S. & O'Bryen P.J., eds. *Open Ocean Aquaculture – Moving Forward*. Aquaculture Interchange Program (AIP) Workshop, Honolulu, Hawaii. 4 pp.
- Hincapié-Cárdenas, C. 2007. Macrobiofouling on open-ocean submerged aquaculture cages in Puerto Rico, University of Puerto Rico, Mayaguez Campus, P.R. 38 pp. (M.Sc. dissertation).
- Iitembu, J.A. 2005. Analysis of Marine Aquaculture Developments in Namibia: Environmental, Economic and Legislative considerations.. Norwegian College of Fishery Science, University of Tromsø, Norway. 63 pp. (M.Sc. dissertation).
- Kalantzi, I. & Karakassis, I. 2006. Benthic impacts of fish farming: Meta-analysis of community and geochemical data. *Marine Pollution Bulletin*, 52: 484–493.

- Kam, L.E., Leung, P. & Ostrowski, A.C.** 2003. Economics of offshore aquaculture of pacific threadfin (*Polydactylus sexfilis*) in Hawaii. *Aquaculture*, 223: 63–87.
- Karakassis, I., Hatziyanni, E., Tsapakis, M. & Plaiti, W.** 1999. Benthic recovery following cessation of fish farming: a series of successes and catastrophes. *Marine Ecology Progress Series*, 184: 205–218.
- Kent, D.B.** 2003. Offshore non-salmon aquaculture: Tuna culture as a demonstration of commercial-scale production. Presentation of Pacific States Marine Fisheries Commission, 2003 Marine Aquaculture Conference. Portland, Oregon. 55 pp.
- Latanich, C.** 2009. Seafood Watch farmed cobia report. Monterey Bay Aquarium. 68 pp.
- Lee, H., Bailey-Brock, J. & McGurr, M.** 2006. Temporal changes in the polychaete infaunal community surrounding a Hawaiian mariculture operation. *Marine Ecology – Progress Series*, 307: 175–185.
- Liao, I.C.** 2000. Socioeconomic aspects of cage aquaculture in Taiwan. In I.C. Liao & C.K. Lin, eds. Cage Aquaculture in Asia; Proceedings, Manila (Philippines): AFS; WAS-SC, 2000. 318 pp.
- Liao, I.C., Huang, T.S., Tsai, W.S., Hsueh, C.M., Chang, S.L. & Leñaño, E.M.** 2004. Cobia culture in Taiwan: current status and problems. *Aquaculture*, 237: 155–165.
- Lin, D. & Bailey-Brock, J.** 2008. Partial recovery of infaunal communities during a fallow period at an open-ocean aquaculture. *Marine Ecology – Progress Series*, 371: 65–72.
- Livingstone, M.W., Smith, R.V. & Laughlin, R.J.** 2000. A spatial study of denitrification potential of sediments in Belfast and Strangford Lough and its significance. *Science of the Total Environment*, 251/252: 369–380.
- Lombardi, J.V., Marques, H.L.A., Pereira, R.T.L., Barreto, O.J.S. & de Paula, E.J.** 2006. Cage polyculture of the Pacific white shrimp *Litopenaeus vannamei* and the Phillipines seaweed *Kappaphycus alvarezii*. *Aquaculture*, 258(1–4): 412–415.
- Lovatelli, A., Phillips, M.J., Arthur, J.R. & Yamamoto, K., eds.** 2008. FAO/NACA Regional Workshop on the Future of Mariculture: a Regional Approach for Responsible Development in the Asia-Pacific Region. Guangzhou, China, 7–11 March 2006. *FAO Fisheries Proceedings*. No. 11. Rome, FAO. 2008. 325 pp. (also available at www.fao.org/docrep/011/i0202e/i0202e00.htm).
- Machias, A., Giannoulaki, M., Somarakis, S., Maravelias, C.D., Neofitou, C., Koutsoubas, D., Papadopoulou, K.N. & Karakassis, I.** 2006. Fish farming effects on local fisheries landings in oligotrophic seas. *Aquaculture*, 261: 809–816.
- Mantzavarakos, E., Kornaros, M., Lyberatos, G. & Kaspiris, P.** 2007. Impacts of a marine fish farm in Argolikos Gulf (Greece) on the water column and the sediment. *Desalination*, 210(1–3): 110–124.
- Mazur, N. & Curtis, A.** 2008. Understanding community perceptions of aquaculture: lessons from Australia. *Aquaculture International*, 16: 601–621.
- McVey, J.P.** 2006. The Role of Offshore Aquaculture in Ecosystem-Based Approaches to Coastal Management. In C.S. Lee, & P.J. O’Byrne, eds. *Open Ocean Aquaculture – Moving Forward*. Aquaculture Interchange Program (AIP) Workshop, Honolulu, Hawaii. 6 pp.
- McVicar, A.H.** 1997. Interaction of pathogens in aquaculture with wild fish populations. *Bulletin of the European Association of Fish Pathology*, 17: 197–200.
- Merican, Z.** 2006. Marine finfish cage culture – Industry Review. *Aqua Culture Asia Pacific*, 2(2): 22–24.
- Middleton, I.** 2004. Commercial barramundi *Lates calcarifer* farming with rural villagers along the north coast of Madang, Papua New Guinea. In Proceedings of Australasian Aquaculture 2004, Sydney Convention Centre, Sydney, Australia. 206 pp.
- Ministry of Agro Industry & Fisheries (Fisheries Division).** 2007. Potential for sustainable aquaculture development in Mauritius. Port Louis Republic of Mauritius. 11 pp.
- Morales Núñez, A.G.** 2005. Temporal and spatial characterization of tropical benthic macroinfauna around submerged cages for open sea fish farming, Department of Biology, University of Puerto Rico, Mayaguez Campus (M.Sc. dissertation).

- Morales Q., V.V.; Morales R., R. 2006. *Síntesis regional del desarrollo de la acuicultura. 1. América Latina y el Caribe – 2005/Regional review on aquaculture development. 1. Latin America and the Caribbean – 2005*. FAO Circular de Pesca/FAO Fisheries Circular. No. 1017/1. Roma/Rome, FAO. 177 pp. (also available at <ftp://ftp.fao.org/docrep/fao/009/a0615b/a0615b00.pdf>).
- Muir, J. 2004. Potential of Mediterranean marine fish aquaculture, Pres. Annual meeting of EAS “biotechnologies for quality”, Barcelona, Spain, 20–23 October 2004.
- National Research Council. 1992. Review of World Aquaculture. U.S. Department of Commerce, Washington, D.C.
- Naylor, R.L. 2006. Environmental safeguards for open-ocean aquaculture. *Science*, 313: 1363.
- Naylor, R. & Burke, M. 2005. Aquaculture and ocean resources: raising tigers of the sea. *Annual Review of Environment and Resources*, 30: 185–218.
- Naylor, R.L., Goldburg, R.J., Primavera, J.H., Kautsky, N., Beveridge, M.C.M., Clay, J., Folke, C., Lubchenco, J., Mooney, H. & Troell, M. 2000. Effect of aquaculture on world fish supplies. *Nature*, 405: 1017–1024.
- Neori, A., Chopin, T., Troell, M., Buschmann, A.H., Kraemer, G.P., Halling, C., Shpigiel, M. & Yarish, C. 2004. Integrated aquaculture: rationale, evolution and state of the art emphasizing seaweed biofiltration in modern mariculture. *Aquaculture*, 231: 361–391.
- Nguyen, T.T.T., Davy, B.F., Rimmer, M.A. & de Silva, S.S. 2009. Use and exchange of genetic resources of emerging species for aquaculture and other purposes. *Reviews in Aquaculture*, 1: 260–274.
- Ólafsson, E., Johnstone, R.W. & Ndaro, S.G.M. 1995. Effects of intensive seaweed farming on the meiobenthos in a tropical lagoon. *Journal of Experimental Marine Biology and Ecology*, 191: 101–117.
- Olsen, Y. 2002. MARICULT Research Programme: background, status and main conclusions. *Hydrobiologia*, 484: 1–10.
- Oronti, A. & Thiago, S. 2009. Investigating an ecosystem approach to sustainable rearing of fish in offshore aquaculture system *Annual meeting of the International Marine Conservation Congress, George Madison University, Fairfax, Virginia, May 20, 2009*.
- Ottolenghi, F. 2008. Capture-based aquaculture of bluefin tuna. In A. Lovatelli & P.F. Holthus, eds. *Capture-based aquaculture. Global overview*, 169–182. FAO Fisheries Technical Paper. No. 508. Rome, FAO. 298 pp. (also available at www.fao.org/docrep/011/i0254e/i0254e00.htm).
- Pitta, P., Apostolaki, E., Tsagaraki, T., Tsapakis, M. & Karakassis, I. 2006. Fish farming effects on chemical and microbial variables of the water column: A spatiotemporal study along the Mediterranean Sea. *Hydrobiologia*, 563: 99–108.
- Pitta, P., Tsapakis, M., Apostolaki, E.T., Tsagaraki, T., Holmer, M. & Karakassis, I. 2009. ‘Ghost nutrients’ from fish farms are transferred up the food web by phytoplankton grazers. *Marine Ecology Progress Series*, 374: 1–6.
- Pitta, P., Karakassis, I., Tsapakis, M. & Zivanovic, S. 1999. Natural vs. mariculture induced variability in nutrients and plankton in the Eastern Mediterranean. *Hydrobiologia*, 391: 181–194.
- Poynton, S.L. 2006. Regional review on aquaculture development. 2. Near East and North Africa – 2005. FAO Fisheries Circular No. 1017/2. Rome, FAO. 79 pp. (also available at <ftp://ftp.fao.org/docrep/fao/009/a0635e/a0635e00.pdf>).
- Rajan, J.P.R., Lopez, C., Lin, J.H.Y. & Yang, H.L. 2001. *Vibrio alginolyticus* infection in cobia (*Rachycentron canadum*) cultured in Taiwan. *Bulletin of the European Association of Fish Pathology*, 21: 228–234.
- Rawson Jr., M.V., Chen, C., Ji, R., Zhu, M., Wang, D., Wang, L., Yarish, C., Sullivan, J.B., Chopin, T. & Carmona, R. 2002. Understanding the interaction of extractive and fed aquaculture using ecosystem modeling: 263–296. In R.R. Stickney, & J.P. McVey, eds. *Responsible Aquaculture*. CABI Publishing, Oxon, 391 pp.

- Report of the Marine Aquaculture Task Force.** 2007. Sustainable Marine Aquaculture: fulfilling the promise; managing the risks. 142 pp.
- Rimmer, M.A. & Ponia, B.** 2007. A review of cage aquaculture: Oceania. In M. Halwart, D. Soto & J.R. Arthur, eds. *Cage aquaculture – Regional reviews and global overview*, pp. 208–231. FAO Fisheries Technical Paper No. 498. Rome, FAO. 2007. 241 pp. (also available at www.fao.org/docrep/010/a1290e/a1290e00.htm).
- Rojas, A. & Wadsworth, S.** 2007. A review of cage aquaculture: Latin America and the Caribbean. In M. Halwart, D. Soto & J.R. Arthur, eds. *Cage aquaculture – Regional reviews and global overview*, pp. 70–100. FAO Fisheries Technical Paper. No. 498. Rome, FAO. 241 pp. (also available at www.fao.org/docrep/010/a1290e/a1290e00.htm).
- Shafir, S., Rijn, J.V. & Rinkevich, B.** 2006. Steps in the construction of underwater coral nursery, an essential component in reef restoration acts. *Marine Biology*, 149: 670–687.
- Soto, D., Aguilar-Manjarrez, J. & Hishamunda, N., eds.** 2008. Building an ecosystem approach to aquaculture. FAO/Universitat de les Illes Balears, Expert Workshop. 7–11 May 2007, Palma de Mallorca, Spain. *FAO Fisheries and Aquaculture Proceedings*. No. 14. Rome, FAO. 2008. 221 pp.
- Stemler, C.** 2009. Open Sea Aquaculture in Panama: An Assessment of Cobia Production by Pristine Oceans. Smithsonian Tropical Research Institute. Presented to Dr. Rafael Samudio at the Smithsonian Tropical Research Institute & Dr. Stanley Heckadon-Moreno at Punta Galeta As part of The McGill Panama Field Study Semester. 29 pp.
- Stenton-Dozey, J.M.E., Jackson, L.F. & Busby, A.J.** 1999. Impact of mussel culture on macrobenthic community structure in Saldanha Bay, South Africa. *Marine Pollution Bulletin*, 39: 1–12.
- Tenore, K.R., Corral, J. & Gonzales, N.** 1985. Effects of intense mussel culture on food chain patterns and production in coastal Galicia, North Spain. *ICES CM* 62, 9 pp.
- Thompson, N.** 1996. Offshore aquaculture development in Australasia, four issues to overcome. In M. Polk, ed., *Open ocean aquaculture. Proceedings of an International Conference*, May 8–10, 1996, Portland, Maine. New Hampshire/Maine SeaGrant College Program. 62 pp.
- Tong, P., Hoang, S. & Nguyen, T.A.** 2005. The temporal and spatial variation of environmental ecological parameters in southern part of Vietnam Sea from MODIS image series. *ACRS Proceedings*.
- Troell, M., Halling, C., Neori, A., Chopin, T., Buschmann, A.H., Kautsky, N. & Yarish, C.** 2003. Integrated Mariculture: asking the right questions. *Aquaculture*, 226: 69–90.
- Troell, M.** 2009. Integrated marine and brackishwater aquaculture in tropical regions: research, implementation and prospects. In D. Soto, ed. *Integrated marine aquaculture: a global review*. FAO Fisheries and Aquaculture Technical Paper No. 529. Rome. FAO. 183 pp. (also available www.fao.org/docrep/012/i1092e/i1092e00.htm).
- Tuya, F., Sanchez-Jerez, P., Dempster, T., Boyra, A., & Haroun, R.** 2006. Changes in demersal wild fish aggregations beneath a sea-cage fish farm after the cessation of farming. *Journal of Fish Biology*, 69: 682–697.
- Watling, L. & Norse, E.** 1998. Disturbance of the seabed by mobile fishing gear: a comparison to forest clearcutting. *Conservation Biology*, 12: 1180–1197.
- WHOI (Woods Hole Oceanographic Institute).** 2007. Sustainable marine aquaculture: fulfilling the promise; managing the risks. Report of the Marine Aquaculture Task Force. 142 pp.
- Wu, R.S.S.** 1995. The environmental impact of marine fish culture: towards a sustainable future. *Marine Pollution Bulletin*, 31(4–12): 159–166.
- Wu, R.S.S., Lam, K.S., MacKey, D.W., Lau, T.C. & Yam, V.** 1994. Impact of marine farming on water quality and bottom sediment: A case study in the sub-tropical environment. *Marine Environmental Research*, 38: 115–145.