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A REVIEW OF THE LITERATURE ON THE ENVIRONMENTAL IMPACTS OF MARINE FISH CAGE CULTURE

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ABSTRACT

A review of the literature is presented that covers current knowledge of documented environmental impacts that result from cage-culture of fish in coastal waters. Little work has been done that document these types of impacts in tropical environments therefore selected topics taken from studies on salmon net-pen culture will be briefly reviewed. The areas covered include: a) concerns related to eutrophication in coastal areas, b) information on feed utilization and waste production in salmon net-pen culture, c) the extent and nature of observed impacts on benthic communities, d) possible effects on local fish communities and e) concerns related to the use of chemicals in intensive fish culture. The development of simulation models to describe and predict impacts from coastal fish farming is discussed. Recommendations for future research are also made.

RESUMEN

Se presenta una revisión comprensiva de la literatura relacionada con los impactos ambientales producidos por el cultivo de peces marinos en jaulas. Es poca la investigación que se ha realizado sobre este tipo de impacto en ambientes tropicales, por lo que se presentan resultados de estudios realizados sobre el cultivo de salmón en zonas templadas. Los temas incluyen: a) aspectos relacionados con la eutroficación de las areas costeras b) información sobre los regímenes de alimentación y la producción de desechos en el cultivo de salmón, c) características y extensión de los impactos observados sobre las comunidades del fondo del mar, d) posibles efectos en comunidades locales de peces, y e) preocupaciones relacionadas con el uso de sustancias químicas en el cultivo intensivo de peces. Con base en la literatura revisada se formulan sugerencias para el desarrollo de modelos tendientes a representar y pronosticar impactos derivados del cultivo de peces en jaulas. También se hacen recomendaciones para futuros trabajos de investigación en este tema.

INTRODUCTION

The marine fisheries have been subjected to steadily increasing exploitation during the last half-century due to improvements in fishing technology and expansion of the world's fishing fleet. Fisheries stocks are also impacted in some locations by environmental degradation resulting from the discharge of agricultural and industrial wastes into rivers and coastal areas. Not surprisingly, many fish stocks are currently over-exploited and some have crashed altogether. While there may be a few stocks in the deeper parts of the ocean that can still be exploited, a growing consensus exists that substantial increases are unlikely to occur in the world's capture fisheries yields in the future (NEW 1997). Recognition of natural fisheries limitations has been one of the major factors leading to the development of fish farming and other forms of aquaculture.

Rising from obscurity, the rapidly expanding aquaculture industry has been growing at 10% per year in the last ten years (FAO 1996). In 1996, aquaculture contributed over a quarter of all fish consumed by humans and will doubtless produce a greater and greater share of this important source of animal protein. Much of this expansion is taking place in developing countries where the production of seafood for export represents a practical means to acquire foreign exchange. However, like with many other industries, rapid expansion combined with an intensification of production methodologies has led to concern about the sustainability of some aquaculture production activities. For example, considerable controversy surrounds the culture of high value, carnivorous species such as shrimp and salmon, due to the demands placed on natural resources and subsequent environmental cost associated with their production (GOLDBURG y TRIPLETT 1997, NAYLOR *et al.* 1998).

When aquaculture development occurs without recognition of important constraints such as resource limitations or the potential for long-term environmental impacts, public opinion and political pressure can lead to regulatory decisions that restrict aquaculture activity (MUIR 1996). Therefore, it is important for the aquaculture industry to take a proactive approach that acknowledges these constraints and the external costs associated with ecosystem services that are utilized in many production activities. Developing more efficient, better-managed aquaculture production methodologies that reduce detrimental environmental impacts and that optimize the use of natural resources is an important research goal.

As the demand for seafood continues to rise, current research programs to improve marine fish husbandry techniques will permit the expansion and further intensification of cage and net-pen culture of marine fish in many parts of the world. It is likely that this sort of enterprise will occur in developing countries of the tropics to increase production of indigenous high-value marine fish species. Adequate management of an expanding coastal cage or net-pen fish farming industry requires that we develop a better understanding of how these activities impact coastal environments. For example, improved understanding of how coastal ecosystems assimilate aquaculture wastes might allow for the development of operational criteria that can be used to appropriately regulate coastal aquaculture development. GOWEN (1991) suggests that careful evaluation of the potential for environmental change is especially important for aquaculture development due to the possible adverse effects that such change, either natural or self-induced, might have on the long-term viability of the industry. The objective of this paper is to review the literature that addresses various impacts caused by marine fish cage or net-pen culture in the marine environment. Although most studies that examine how cage or net-pen culture affects the environment focus on salmon culture in temperate regions, recent studies have begun to address impacts from fish farms in other parts of the world. However, in total, relatively little information exists on how cage culture impacts tropical marine environments, therefore priority areas for research will be presented based on presumed differences between temperate and tropical coastal ecosystems with respect to their ability to assimilate aquaculture wastes.

Intensive cage culture production of salmonids expanded rapidly in northern Europe beginning in the late 1970's, reaching an estimated 1998 annual production that exceeds 500,000 metric tons of fish. Export of salmonid culture technology to Chile has also led to the establishment of an expanding industry in South America that now produces about 200,000 metric tons annually (LINDBERGH 1999). In addition to salmon culture, net-pen culture of seabream and seabass in the Mediterranean region has been expanding rapidly, doubling in the last 5 years to an estimated annual production of approximately 34,000 metric tons (FAO 1997). In Asia, cage and net-pen culture of several high value fish species such as groupers (*Epinephelus spp.*), snappers (*Lutjanus spp.*), yellowtail (*Seriola quinqueradiata*) and seabream (Pagrus spp. and sparids) amounted to over 350,000 metric tons in 1994 (BEVERIDGE *et al.* 1997).

Useful reviews on the subject of how marine fish net-pen or cage culture affects coastal ecosystems are those by GOWEN and BRADBURY (1987), WU (1995) and WESTON and co-authors (1997). In general, environmental impacts due to marine fish culture tend to fall into specific areas of concern. Those that will be addressed here include:

Eutrophication of local receiving waters
Impacts on benthic communities near cage sites
Impacts on local fish communities
Concerns related to the release of anti-bacterial and other chemical used in cage farming
General concerns related to overall sustainability of production activities

Impacts on water quality - is there evidence for eutrophication?

While it is certain that significant quantities of nutrients are released into surrounding water in intensive fish farming operations, how or whether this alters the ecological balance in a given location is less certain. Possible consequences that might occur due to hypernutrification near fish farms include increased algal biomass, changes in phytoplankton species composition, increased frequency of algal blooms, fluctuations in dissolved oxygen, or even de-oxygenation in low energy environments (GOWEN 1991). However, in most instances, marine fish farms appear to have minimal impact on coastal water quality, especially when nutrient inputs from fish farms are viewed as the proportion of the total input of nutrients released into coastal waters. For example, ACKEFORS and ENELL (1990) suggest that the nitrogen and phosphorus released from Swedish aquaculture represent only 0.02% and 0.05% respectively of the total input of these nutrients to Swedish coastal waters. In general, although higher than normal ammonia levels are observed near fish cage farms sites, no evidence directly links increased nutrient levels from aquaculture to eutrophication in the marine environments, per se. WESTON and co-authors (1997) suggest three reasons for this lack of evidence. First, few measurements have been made of primary productivity near cage sites, second, other factors may be limiting phytoplankton growth besides nitrogen and phosphorus at a given site, and third, nutrient dilution occurs rapidly and is typically faster in the marine environment than the time required for increased algal biomass production to take place.

Nevertheless, observable local effects from fish farming are possible when farm sites are located in semi-enclosed embayments where poor flushing leads to relatively long water residence times. RUOKOLAHTI (1988) found evidence of hypernutrification near fish farms located in sheltered bays in the Baltic Sea based on differences in biomass, chlorophyll a content and morphology of macroalgal (*Cladaphora glomerata*) samples. And while ENG and co-authors (1989) suggest that the environmental impact of cage culture in Southeast Asia is less severe than in Northern Europe due to lower stocking densities and small farm sizes, localized effects are inevitable as farming intensifies. For example, increased biological oxygen demand (BOD) and decreased oxygen levels due to organic loading were observed in a fish culture zone located in a poorly flushed subtropical region, although oxygen levels increased rapidly to normal levels with distance from the farm (WU *et al.* 1994). ARULAMPALAM and coworkers (1998) found nutrients from trash fish fed to cage-cultured seabass (*Lates calcarifer*) in Malaysia increased levels of opportunisitic pathogens in the water column and the sediment immediately under the cage farm in contrast with a site100 meters away. Based on their study, the authors suggest that increased nutrient levels near cage farms may increase the abundance of *Vibrio* spp. and other harmful bacteria, which can cause disease in cultured fish.

In many parts of the world, fish farms and other types of aquaculture operations have been subjected to mortality caused by toxic algal blooms (DALE *et al.* 1987). Concern exists that a greater prevalence of toxic "red tide" algal blooms (SHUMWAY 1990) might be associated with aquaculture effluent, however, definitive evidence to indicate a causal connection is lacking. One possible mechanism for how this might occur is that anaerobic conditions in the sediment caused by organic loads from fish farms may increase the availability of manganese, iron and phosphorus and other growth promoting factors that can enhance dinoflagellate growth (KIMURA *et al.* 1992). Other compounds leaching from feeds such as vitamins may also have stimulatory effects on dinoflagellates (GOWEN and BRADBURY 1987). The species composition of algal samples collected at a eutrophic site in Hong Kong showed a greater dominance of dinoflagellates, including toxic red tide species, compared to samples collected at non-eutrophic sites that were dominated by diatoms (Wu *et al.*, 1994). Understanding the factors that promote toxic algal bloom formation is an important focus of research in order to reduce the detrimental effects such events can have on coastal aquaculture.

Several authors have developed mass balance relationships to describe the fate of nutrients supplied as feeds in net-pen salmonid culture (WALLIN and HAKANSON 1991, HALL *et al.* 1991, HOLBY and HALL 1991, HALL *et al.* 1992, ACKEFORS and ENELL 1994). For example, HALL and coauthors (1992) constructed a mass-balance budget for nitrogen for a trout cage farm located in a fjord in western Sweden based on feed input, fish harvest weight, and measurements of the nitrogen found in the sediment below the cages (figure 1). They found that 27-28% of the total nitrogen supplied as fingerlings and feed combined was retained in the harvested fish, approximately 48% was released as dissolved nitrogen compounds and about 23% was found in the sediment, a small proportion of which re-entered the wate r column as dissolved nitrogen.

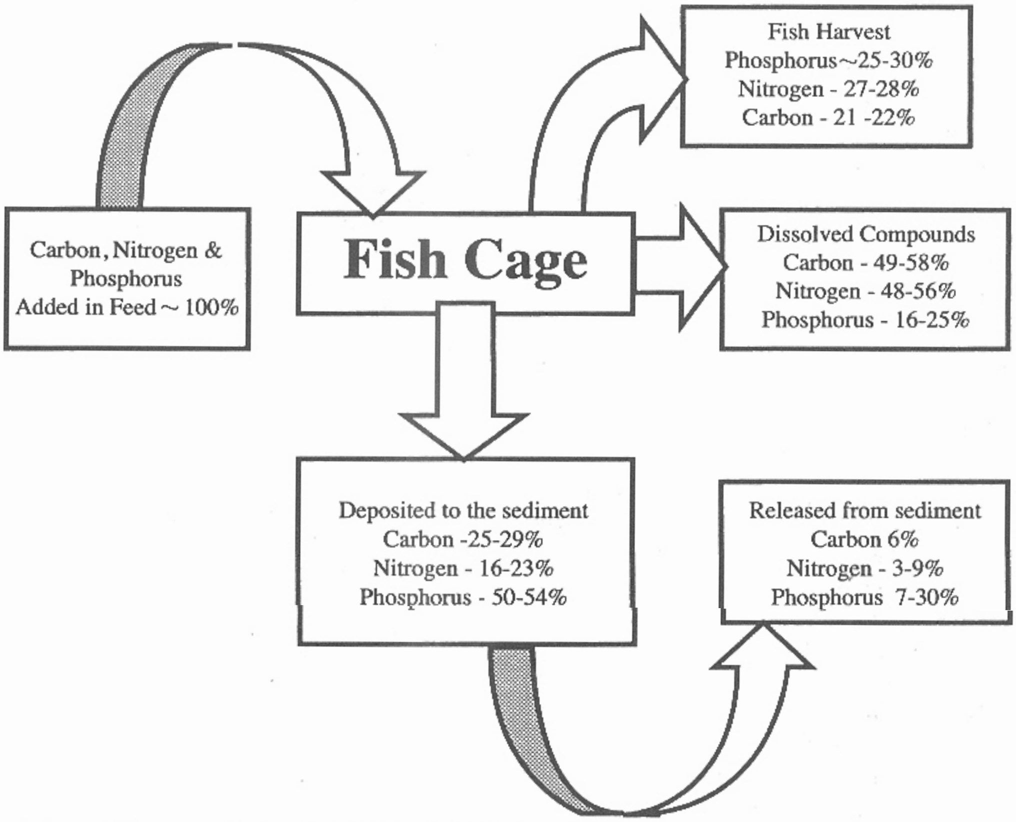

Figure 1. A mass balance model of carbon, nitrogen and phosphorus flux through a salmon net-pen farm. Data from ACKEFORS and ENELL (1990), HOLBY et al. (1990), HALL et al. (1990) and HALL et al. (1992).

In the case of phosphorus, 25% was retained in the fish, 25% entered the environment in the dissolved phase, and 50% was deposited onto the sediments (HOLBY and HALL 1991). Overall, ACKEFORS and ENELL (1994) estimate that for every ton of fish produced, 60 kg of nitrogen and 10 kg of phosphorus are released into the environment in salmon net pen culture. Of course, nutrient loads will vary depending on the feed conversion and the phosphorus and nitrogen content of the feed. In recent years, adjustments in digestible protein to energy ratios and reductions in phosphorus content of feeds has lowered feed conversion ratios and has resulted in reduced nutrient loading from net-pen salmon farming operat ions (TALBOT and HOLE 1994). Along with improved feed formulation, optimization of feed delivery is another important way to reduce waste production from cage fish farming. Though by far the most labor intensive, hand-feeding appears to be the most effective means to provide feed with minimal waste compared to demand feeders or automatic feeders (WESTON 1997). Feed wastage is an even greater problem in the marine fish farming industry in Asia where trash fish continues to be the most commonly used feed (BEVERIDGE *et al.* 1997). Growth of the industry in Asia will depend upon the adoption of new feeding methodologies in order to overcome environmental constraints imposed by current feeding practices.

Impacts on benthic communities near cage sites

There are various factors that determine the extent to which marine cage fish farming impacts benthic communities. Not surprisingly, physical factors such as tidal flushing, bottom characteristics and depth are important determinants of benthic impact (WU *et al.*, 1994) as are farm production characteristics, feed composition and feed management. Different methods have been used to study benthic impacts from marine fish farming that include the measurement of sedimentation rate (HALL *et al.* 1992, ANGEL *et al.* 1994), comparative analysis of the biotic community and chemical composition in sediment cores and grab samples taken from cage and control sites (WESTON 1990, LAUREN-MAATTA *et al.* 1991, KROST 1994, WU *et al.* 1994, FINDLAY *et al.* 1995), in situ video imaging (ANGEL *et al.* 1994, KROST *et al.* 1994), stable isotope techniques (YE *et al.* 1991, HANSEN *et al.* 1994) and flux chambers operated in situ at the sediment surface to measure gaseous exchange (HALL *et al.* 1992, ANGEL *et al.* 1994). Investigators have also studied changes in nitrification and denitrification rates below cages (KASPAR et al. 1988), and the effect of anti-bacterial deposition on sediment microbial communities (KERRY *et al.* 1994).

In general, benthic communities directly beneath and nearby fish cages in both freshwater and marine environments are organically enriched due to the sedimentation of fecal material and feed wastes originating from the cages, although such deposition may be negligible at more exposed marine sites (GOWEN and BRADBURY 1987, ANGEL *et al.* 1994, WESTON 1997). Organic enrichment often leads to anaerobic conditions at the sediment surface due to increased sediment oxygen demand that can result in ebullition of reduced gaseous compounds such as hydrogen sulfide and methane from the sediment to the water column (KROST *et al.* 1994, ANGEL *et al.* 1994). Such gaseous release can adversely affect cultured fish especially in shallow water since lethal levels of hydrogen sulfide have been observed nine meters above the sediment surface (SAMUELSON *et al.* 1988). Marine fish culture operations are more likely to suffer adverse effects from hydrogen sulfide than freshwater farms due to higher sulfate availability in the marine environment. In general, sulfate reduction contributes more to anaerobic decomposition below fish cages than methanogenesis in the marine environment (ANGEL *et al.* 1994).

Video has been used to observe microbial mats below fish cages which appear as dark, fluffy sediment covered with sulfide-oxidizing bacterial mats composed of *Beggiatoa spp* (KROST *et al.* 1994). Images taken below fish cages in the Red Sea with a remotely operated vehicle show a "living crust" composed of a variable assemblage of filamentous bacteria, algae, ciliates, autotrophic and heterotrophic nano-flagellates, nematodes and other meiofauna (ANGEL *et al.* 1994). During the summer, microbial mats contain large populations of filamentous cyanobacteria and eukaryotic algae in addition to sulfur-oxidizing *Beggiatoa* spp, as well as an unusually rich population of phototrophic bacteria not documented before at cage sites, as evidenced by the red, brown, green and lilac pigmentation patches observed in the mats. The presence of photosynthetic bacteria is thought to be due to the deep penetration of light in the oligotrophic waters of the Red Sea (ANGEL *et al.* 1994). An even more interesting observation was the rapid regeneration of the mats that followed their dispersal by intense feeding activity of wild fish communities under the cages. When not subjected to further disturbance, the microbial community reassembled and formed new mats within hours. The regions below the cages did not support plants, such as seagrass, or benthic animals found in the surrounding, undisturbed areas.

Typically, organic enrichment reduces the species diversity of the benthic community below cage sites. The area under cages may be completely azoic (GOWEN and BRADBURY 1987) or be inhabited by opportunistic species such as the polychaete *Capitella capitata* (WESTON 1990). However, the impact of cage culture on the benthic community drops off rapidly with distance from the cage. In most cases, studies of salmonid farms indicate that benthic communities do not show appreciable impact 25-150 meters away from the cage site (WESTON 1990, YE *et al.* 1991). However, the degree of benthic impact largely depends on physical characteristics of the farm site. A study on the impact of marine fish farming in a small cove in Japan found that seasonal cycles of defaunation and recolonization of the benthos took place near net-pens that were caused by summertime oxygen depletion associated with fish farm effluent (TSUTSUMI 1995). The author stressed the importance of monitoring oxygen levels in the water column near cage sites in order to avoid potential problems that could result if such a "dead water" mass reached the level of the net pens.

In a sub-tropical marine environment, WU and co-workers (1994) examined four fish culture sites in Hong Kong characterized by different hydrographic and culture conditions. Two of the sites had fairly high average current speeds (e.g. 0.5 - 2.0 m/s) while the other two sites had lower speeds (0.01-0.05 m/s) indicative of poor flushing, while all four of the sites were relatively shallow (i.e. < 10 meters). In all but the most well flushed fish farm site, sediment oxygen demand was higher at cage sites compared to control sites. Nitrogen also tends to accumulate in the sediment below cages due to anaerobic conditions. WU and coauthors (1994) suggest that the absence of bioturbation from macrobenthos due to anoxic conditions under cages might slow the rate at which mineralization and release of ammonia-N, nitrate or nitrite from the sediment takes place. The accumulation of nitrogen in sediment can lead to a slow, continuous release of dissolved nitrogen compounds that could impact water quality over a relatively long time. In general, leaching of soluble components of feed wastes and nutrients released from the sediment combined with low oxygen levels can cause self-pollution at farm sites that can lead to poor fish growth or mortality. Some fish farm sites in Japan have been abandoned due to degraded conditions (KADOWAKI 1994).

Effects on local fish communities

The composition and abundance of local fish communities can be altered due to aggregation of fish near cage sites. For instance, there is evidence from both freshwater and marine cage culture to suggest that increased recruitment of wild fish populations may occur near cages due to enhanced growth and survival that results from increased food availability (KILAMBI *et al.* 1978, HENRIKSSON 1991). Observations made at cage sites in the Red Sea showed increasingly greater aggregation over time of both fish and other species. Schools of goatfish (*Parupeneus forsskalii*) and rabbitfish (*Siganus rivulatus*) numbering in the hundreds and thousands were observed actively grazing the organic sediment in search of food (ANGEL *et al.* 1994). A study conducted in a lake in Sweden showed how foraging by wild fish near cage sites alters the pattern of waste deposition from the cage by distributing the farm emissions over a larger area (JOHANSSON *et al.* 1998).

While it appears that cage farms can have positive impacts on local fish communities, the potential also exists for the loss of sensitive species to occur if environmental impacts caused by fish farms lead to changes in community structure, however this has not been documented. Adverse impacts to local wildlife may result from increased activity and noise at remote cage farm sites (BEVERIDGE 1996). The potential also exists for negative impacts on populations of predatory species, such as marine mammals and birds, which are attracted to fish farms due to increased food availability. Exclusion nets or deterrents such as sirens or whistles that scare away predators have been used in salmon farms, however habituation can occur that reduces the effectiveness of these methods. Few studies exist that quantify impacts to predator populations, nor have industry losses due to predation been studied in detail. In Chile, mortalities of sea-lions and birds have created controversy between farmers and some sectors of society (BUSCHMANN *et al.* 1996). In Scotland, wildlife conservation bodies and fish farmers have developed guidelines to minimize the loss of predatory birds and mammals (HOWELL and MUNFORD 1991). BEVERIDGE (1996) suggests that while impacts on wildlife are unlikely to be important on a global scale, they may be of local significance.

The salmon farming industry relies exclusively on hatchery production of seedstock, however the cultivation of tropical species, such as milkfish, snapper and grouper, currently depends on the collection of wild fry to stock ponds and cages. This is because seed production methodologies for most tropical species are either technically difficult or uneconomical (BEVERIDGE *et al.* 1997). Although the impact that wild fry collection has on local target and non-target larval populations has not been quantified, such impacts may be significant. Furthermore, as marine fish farming intensifies, shortages of wild fry can limit production capabilities. For example, wild grouper fry (*Epinephelus* spp.) populations are insufficient to supply local demand from cage fish farmers in Malaysia where the fry are collected and sold for export to buyers from Thailand (SALEH *et al.* 1992). In general, wild fry collection is considered wasteful due to the high mortality and the large by-catch associated with such collection practices (BEVERIDGE 1996). Negative impacts to non-target larval aquatic animals populations are likely to result from the increased pressure on wild fry populations associated with intensification of cage fish farming.

A controversial topic related to the salmon industry is whether interbreeding between escaped farmed fish and wild native fish stocks adversely impacts wild fish population. Clear genetic differences exist between farmed salmon, whose genetic make-up has been altered due to domestication, and wild stocks of salmon, whose genetic heterogeneity results from adaptation to local watershed characteristics. Farmed salmon behave differently and are more risk prone compared to wild salmon due to a relaxation of selection against predator-vulnerable phenotypes in culture facilities during early life history stages (FLEMING and EINUM 1997). Concern exists that the net result of year after year introgression of farmed salmon might be a loss of fitness in the wild population due to the infusion of possibly maladapted genetic traits through interbreeding. While the magnitude of this problem remains unclear, in the case of salmon, that fish do escape from farms and hatcheries and spawn in the wild is undeniable (CARR *et al.* 1997). At present, such problems in tropical fish culture are less critical because wild-caught rather than hatchery reared fry are typically used. However, as larval husbandry for tropical marine fish species improves and genetic divergence occurs between wild and farmed fish stocks, these problems may be of concern in the future.

Another topic of concern is how escaped exotic species used in aquaculture impact local biotic communities since in many parts of the world non-indigenous fish species are used in commercial net-pen culture. For example, the salmon industry in both Chile and British Columbia utilize non-indigenous Atlantic salmon. BUSCHMANN and co-authors (1996) suggest that in the case of Chile, because salmon and trout were introduced into Chilean aquatic ecosystems early in the century, it is difficult to assess current environmental impacts caused by their introduction. Even though no direct evidence indicates that introduced exotic species have eliminated indigenous species, potential adverse effects include disruption of community structure through increased competition or predation (BEVERIDGE 1996). Furthermore, many features common to fish species suitable for aquaculture, such as wide environmental tolerance and flexible phenotypes, are also characteristic of invasive species (BEVERIDGE 1996). The development of sterile fish stock is currently being investigated for many species as a way to reduce impacts from exotic species (BEVERIDGE 1996).

The possibility that parasites and disease may be transmitted between farmed fish and wild populations also is a matter of concern, especially where farming of non-indigenous species takes place. WESTON and co-authors (1997) suggest that although pathogens have been introduced with the transfer of farmed salmonids from North America to Europe, there is little evidence that these introductions have caused increased disease in wild fish stocks. However, problems have occurred in the past such as the spread of furunculosis early in the century in the UK and the spread of the parasite *Gyrodactylus salaris* from the Baltic to western Norway (MCVICAR 1997). Importation of larval fish from other locations is implicated in the introduction of a monogean parasite to wild fish populations in Japan (OGAWA 1996). In general, systematic studies of wild fish diseases in the marine environment are few which makes it difficult to know how disease transmission associated with aquaculture impacts wild fish populations (OGAWA 1996). MCVICAR (1997) considers that the risk posed by fish farming to wild stocks through the introduction of exotic disease can be reduced to acceptable levels with appropriate legislation and codes of practice. Regulations and quarantine procedures are being implemented in many countries in recognition of the possible consequences that can result from indiscriminate movement of fish and other cultured aquatic animals among geographic locations.

Diseases endemic to cage farm sites appear to be more easily transferred to farmed fish than the reverse situation. In the salmon farming industry, infestation of naturally occurring sea lice, which can require pesticide treatment, continues to be a problem. However, it remains unclear how such infestation impacts wild salmonid populations due in part to the lack of historic data on sea lice levels prior to the development of salmon farming (MCVICAR 1997). In Japan, one mode by which disease has been transferred from wild to farmed fish in the past is from feeding parasite-infected fish when fresh anchovies infected with larval cestodes were fed to cage farmed yellowtail (*Seriola* spp.), that became infected themselves (OGAWA 1996). Due to the high cost of pelleted feeds, much of the marine fish culture industry in Asia continues to use trash fish despite the very poor conversion ratios obtained.

Environmental impact of chemicals used in cage fish farming

As marine fish farming intensifies, poor management and the deterioration of local environmental conditions can lead to complex disease "syndromes" that appear to be associated with the increased abundance of opportunistic pathogens (CHUA 1995). For example, the spread of epizootic ulcerative syndrome in both wild and farmed fish populations throughout Asia has caused economic loss to the fish farming industry in the region (SUBASINGHE 1997). In China, disease epidemics that are linked to fish farmers' use of irrationally high stocking densities to achieve high profits have also caused severe economic impacts (YULIN 1995). As intensification leads to a greater need for disease control, anti-bacterial drugs are often being used in aquaculture. While common in terrestrial animal production, the use of anti-bacterial drugs in open aquaculture systems, such as cage fish farming, is a matter of concern because drugs not retained or metabolized by the culture animal are released directly into the aquatic environment. Uncertainty about how aquatic ecosystems respond to anti-bacterials is due in part to the minimal requirement for environmental data associated with their approval and licensing for use in the aquaculture industry (WESTON 1996). In many cases, little regulatory control exists and reliable information on appropriate use is lacking or is limited to recommendations supplied by salespeople. Because anti-bacterials are often administered as feed additives, wastage may be substantial, as diseased fish are likely to exhibit reduced appetite. Even when consumed, some anti-bacterial compounds pass through fish unaltered and are released in the feces. For instance, WESTON (1996) estimated that more than 95% of the oxytetracycline administered to cultured fish is lost in the effluent.

One of the primary concerns related to anti-bacterial use in aquaculture is the potential for pathogenic bacteria to acquire resistance to commonly used anti-bacterial compounds. An increased frequency of anti-bacterial resistance in the microbial community near cage sites, that could occur via the plasmid-mediated transfer of resistance among bacteria, might negatively impact farmed fish (GESAMP 1991). Workers have only begun to investigate the fate and effect of anti-bacterial compounds in marine sediment microbial communities. In a study at a cage farm in Ireland, KERRY and co-workers (1994) found a significant, but transitory, increase in resistance frequency in sediment bacteria up to 50 meters away from the cages. Laboratory and field studies have also shown that the sediment near cage farm sites can serve as a long-term reservoir for drug residues (WESTON 1996). Observations that wild fish feeding near fish cages can accumulate unacceptable levels of anti-bacterial compounds in body tissue suggests other potential problems that might result from persistent drug residues in marine sediment. Another possible consequence of anti-bacterial compounds in marine sediment is the potential for alteration of biogeochemical processes if these compounds reduce bacterial populations that degrade organic material in the sediment (WESTON 1996). Although little work has been done to address this concern, negative impacts on farmed fish due to poor environmental conditions may result if organic degradation processes are slowed below cages. Cage farms sites in Japan begin to show signs of "souring" when the sediment becomes overloaded with organic material (TSUTSUMI 1995), although whether anti-bacterial use might enhance this process remains unclear.

In addition to anti-bacterial compounds, other potentially harmful chemicals associated with construction materials used in cage farming may be introduced into the environment. These include anti-foulants such as tributylin, heavy metals, disinfectants and various compounds contained in plastics (GESAMP 1991, BEVERIDGE 1996). Mortalities in aquaculture have been reported from the leaching of toxic compounds in construction materials, though little is know about how aquatic ecosystems respond to the compounds found in these materials (GESAMP 1991). Pesticide compounds such as dichlorvos, that are used to combat ectoparasitic sea lice infestations in salmonids, may also negatively impact local aquatic communities due to mortality inflicted on non-target larval organisms (GESAMP 1991). More work needs to be done to identify environmental impacts caused by chemical use in cage culture.

Use of models to describe environmental impacts

In an age of ever expanding computing power, the use of simulation models to describe and predict environmental impacts from cage culture represents important new tools for the regulation and management of aquaculture development in the coastal zone. SILVERT and SOWLES (1996) recently reviewed the current state of model development and suggest that even though development is at an early stage, valuable information can already be obtained from relatively simple models. However, as more complex models become available, access to the data needed to use the models becomes a constraint. Some examples of models designed to predict impacts from cage fish farming include models that describe benthic deposition (HEIVA *et al.* 1996), wasteload application (MCDONALD *et al.* 1996), eutrophication in Norwegian fjords (AURE and STIGEBRANDT 1990), the spatial distribution of dissolved oxygen and COD in a bay in Japan (KISHI *et al.* 1994), and nutrient loading in coastal regions (WALLIN and HAKANSON 1991). Models are also being incorporated into management schemes for site selection such as the LENKA program in

Norway (IBREKK *et al.* 1991). LEVINGS and co-authors (1995) describe some of the criteria currently used for siting salmon cage farms in various European and North American countries. Model development is an important area of research due to the ease with which different scenarios can be investigated using simulations, thereby allowing information to be obtained at a relatively low cost. However, in order to use models with any degree of confidence, empirical data needs to be available for adequate validation of model predictions. Most models describe conditions found in temperate zones, however, models that describe impacts of cage culture activities in tropical regions are beginning to be developed. An important area for future research is the identification of how process rates and parameter values differ between tropical and temperate regions.

CONCLUSION

Growth of the marine fish farming industry can be expected to occur in the future as the worldwide demand for seafood increases and yields from capture fisheries stagnate. Much of this growth will take place in tropical regions as improved husbandry techniques for tropical marine fish species become available. Because environmental quality and sustainability are so closely linked in marine fish cage farming, the trend towards intensification of production methodologies needs to be balanced with the recognition of the potential for adverse environmental impacts to result from such intensification. As mentioned earlier, coastal aquaculture development depends upon the maintenance of adequate water quality for its own existence, therefore regulations to manage and control aquaculture development are beneficial to the industry. However, before useful Environmental Quality Standards (EQS) for overseeing marine fish culture activities can be developed, further research is needed to define appropriate operational criteria. For example, HENDERSON and ROSS (1995), in a comparative study of salmon farms in Scotland, found variable and inconsistent relationships between several parameters used to describe impacts caused by organic enrichment near fish farms. In general, while it is widely recognized that an appropriate information base is needed for adequate planning and management of aquaculture development, in most cases such a base is lacking, especially in tropical regions (BARG 1992).

As marine fish farming expands, another problem is conflict that arises between different user groups or stakeholders in the vicinity of the fish farms. Negative interactions based on competition for space or access to coastal areas, or conflicts that arise due to different perceptions of resource use can result in opposition to cage fish farm development. In some instances, conflict arises due to the impact that coastal aquaculture has on the aesthetic quality of a location as a result of visual pollution. Resolution of such conflicts may require a process of environmental mediation that emphasizes consensus building among different user groups (O'SULLIVAN 1991).

Controversy also surrounds issues related to the sustainability of resource use and the externalization of environmental costs associated with intensive aquaculture production, as for example with shrimp and salmon farming (GOLDBURG and TRIPLETT 1997, NAYLOR *et al.* 1998). FOLKE and co-workers (1998) have developed the ecological footprint concept to describe the spatial ecosystem support needed to produce inputs and process wastes from aquaculture production activities. Using this concept, they concluded that intensive monoculture, such as salmon net-pen farming, is ecologically unsustainable. However, even these authors recognize the potential for improvement that exists as new aquaculture practices are developed. Improvements in such areas as management practices, feed formulation, and site selection will all be involved in reaching the goal of reducing environmental impacts and improving the sustainability of resource use in aquaculture. Production methods based on integrated polyculture systems that mimic ecosystem processes, such as the cultivation of filter-feeding molluscs and macroalgae in association with fish production, can optimize resource use and reduce environmental impacts caused by aquaculture (FOLKE 1989, FOLKE *et al.* 1998, WU 1995). Clearly, the demand for seafood in the future can only be met by an evolving aquaculture industry that recognizes environmental constraints and that responds with creative solutions.

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