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Aquatic Polyculture and Balanced Ecosystem Management: New Paradigms for Seafood Production

James P. McVey,[1] Robert R. Stickney,[2]
Charles Yarish[3] and Thierry Chopin[4]

[1]National Sea Grant College Program, SSMC-3,
Room 11829, 1335 East-West Highway, Silver Spring,
MD 20910–3226, USA; [2]Director, Texas Sea Grant College
Program, 2700 Earl Rudder Highway South, Suite 1800,
College Station, TX 77845, USA; [3]Department of Ecology
and Evolutionary Biology, University of Connecticut at
Stamford, 1 University Place, Stamford, CT 06901–2315,
USA; [4]University of New Brunswick, Centre for Coastal
Studies and Aquaculture, PO Box 5050, Saint John,
New Brunswick E2L 475, Canada

Abstract

Chinese aquaculture has employed a balanced ecoystem approach for freshwater aquaculture for several thousand years. Utilizing species that feed at different levels of the food web has permitted China to have the largest freshwater aquaculture production in the world. This production has proved to be sustainable in the long run because there is balance in this system. This concept is just starting to be thought of for broader aquaculture, including marine operations at sea or on land, and fishery communities around the world.

The National Oceanic and Atmospheric Administration has developed a Sustainable Fisheries Implementation Plan that recognizes three key elements – fisheries, aquaculture and coastal communities – for obtaining sustained production of seafood in the United States. The concepts of carrying capacity for biological activities in a hydrographic system; ecological balance between primary producers, primary and secondary consumers; and nutrient flows in ecosystems are essential elements for the future development of world aquaculture and fisheries.

This chapter documents the present status of selected polyculture systems being employed by the aquaculture industry, provides examples of balanced ecosystem approaches to aquaculture and fisheries, and examines the question of how to develop

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models for maximizing the production of seafood through fisheries and aquaculture working in harmony to minimize environmental impacts.

Introduction

Clear signs of overexploitation of important fish stocks, modification of ecosystems, significant economic losses, and international conflicts on management and fish trade threaten the long-term sustainability of fisheries and the contribution of fisheries to the world food supply (FAO, 1997). The collapse of New England fisheries stocks on George's Bank and the economic hardship that this has imposed on coastal communities is a case in point. The National Marine Fisheries Service (2001) estimated that 92 fisheries stocks in the United States are overfished compared with 148 stocks that are not overfished. It is clear that in many fisheries the level of exploitation exceeded the ability of the stocks to replace themselves. Future fishing efforts will have to be at lower levels in New England and throughout the world in order to be sustainable.

Aquaculture is one of the only ways to make up for the reduced fisheries yields that are inevitable in the future. According to FAO (1997), sustainable aquaculture development will need to recognize the diversity of aquaculture practices as well as the social, economic and (we would add) environmental conditions in which they will take place. Aquaculture is taking place in coastal oceans already eutrophied and impacted by human activities. Jewell (1994) stated that a sewage system that serves 10,000 people discharges more than 250 kg of suspended and biodegradable matter daily. Walsh (1988) found that human-related loadings of nitrogen have increased tenfold during the last century. Bouman and van Vuuren (1999) and Smith *et al.* (1999) provided the following statistics: (i) between one-third and one-half of the land's surface has been transformed by human activity; (ii) global production of agricultural fertilizers has increased from less than 10 million tonnes in 1950 to over 80 million tonnes in 1990; (iii) burning of fossil fuels provides the emission of more than 20 million tonnes of nitrogen into the atmosphere on an annual basis; and (iv) phosphorus eroded from the landscape and carried in human wastewater into the world's rivers has increased global fluxes of phosphorus to the oceans almost threefold, from historic levels of about 8 million tonnes to current loadings of about 22 million tonnes per year. Seitzinger and Kroeze (1998) estimated that observed levels of dissolved inorganic nitrogen are due worldwide primarily to agricultural fertilizers (58%), human sewage (24%) and atmospheric deposition (18%). These environmental consequences of human activity were not planned and are seldom taken into account when developing management strategies for coastal ecosystems. The impact of aquaculture relative to the scale of impacts that have already occurred is relatively minor at this time, but it is increasing and needs to be factored into the management strategies that are being proposed for environmental quality and sustainability.

Higher nutrients in estuaries and in coastal locations where deep water upwelling occurs are not inherently bad and, in fact, provide the enrichment necessary for high productivity. Walsh (1988) estimated that 95% of the world's fisheries yield comes from coastal zones because of the nutrient-rich conditions that exist there. The Pacific Ocean averages 1.25 kg ha^{-1} of fishery products annually, but the maximum yield of 280 kg ha^{-1} occurs off Peru where upwelling of nutrient-rich water occurs (Anderson and Gaucher, 1967). This enrichment is the basis for one of the world's most productive fisheries. Only when nutrients outstrip the ability of natural processes to handle them are problems encountered.

Natural aquatic systems have a built-in carrying capacity for handling nutrients, which is dependent on the biological processes that occur in those systems. Christensen *et al.* (2000) observed that denitrification processes in a Norwegian fjord can generally remove 50% of the nitrogen loading from the land. The utilization of nutrients by microbes, phytoplankton, macroalgae, and seagrasses; the consumption of microbes and phytoplankton by filter feeders; and the capture of marine species in fisheries, among other processes, all contribute to the processing or removal of nutrients such as nitrogen and phosphorus from coastal waters.

Considerations for the Balanced Ecosystem Approach

The living resources in coastal waters have a profound influence on the assimilative and recycling capacity for nutrients. Each phylum or species plays a unique role in a productive ecosystem. By ecological function, there are primary producers (phytoplankton, macroalgae, seagrasses), which utilize photosynthesis to capture energy from the sun and fix nitrogen and carbon, secondary consumers (filter-feeding shellfish; filter-feeding fish; herbivorous fish, crustaceans and molluscs; bacterial species), and tertiary consumers (predatory fish, molluscs, birds and mammals, including man). The balance of these species and functions is critical to a well-functioning ecosystem. As mentioned above, man's impact on the functioning and carrying capacity of these systems has been significant and we are now at a point where we must consider human impacts in all of our approaches to resource management.

The United States National Oceanic and Atmospheric Administration (NOAA) is charged with the management of the nation's marine resources. The National Marine Fisheries Service (NMFS) manages marine fisheries and coordinates with several other NOAA agencies including Oceanic and Atmospheric Research and the National Ocean Service to do so. NOAA has a 5-year strategic plan that includes rebuilding marine fisheries as a primary objective. In the NOAA plan, rebuilding fisheries has three major components or considerations, including the management of fisheries, aquaculture, and the coastal communities that will depend on these industries. This view of a more holistic management system incorporates the use of geographic information systems, social sciences, environmental models based on hydrographic and nutrient profiles, and an interconnected understanding of the roles of the biotic factors in coastal ecosystems. The tools for such ecosystem management should be the biological functions available to us and the possibility of using aquaculture to put these tools into the correct temporal and spatial locations. Polyculture of selected organisms in chosen locations in the ecosystem can provide a better balance of ecosystem function than exists presently.

Microbial Role in a Balanced Ecosystem

Microbial communities play a significant role in reducing the negative impacts of nitrogen enrichment in coastal oceans. Certain bacteria are capable of converting ammonia to nitrite and others convert nitrite to the less toxic nitrate. Anaerobic microbial communities are capable of changing nitrate to nitrogen gas, which then escapes back to the atmosphere. The combination of these processes helps develop the balance between nitrogen input and outflow or loss to the ecosystem. Boynton *et al.* (1995) estimated that the natural microbial process of denitrification removes approximately 25% of the nitrogen inputs to Chesapeake Bay under present conditions.

Bacteria can be attached to substrates or associated with free-floating organic particles in an aquatic system. Shieh and Yang(1997) found that denitrifying bacteria were always greater in number in the root complexes of seagrasses than in control mud or sand substrates. Eighty-five strains of denitrifying bacteria were isolated from the plants. Michotey and Bonin (1997) found that there was a constant expression of bacterial nitrate dissimilation (nitrate converted to ammonium) processes associated with particles in the water column. Both denitrification and dissimilatory nitrate ammonification were associated with organic particles from 30 m down to 615 m in coastal waters. In the North Sea, Livingstone *et al.* (2000) found that denitrification decreased with depth in the sediments with the highest values in the 0–5 cm fraction. Also, the highest denitrification potential of 2100 μmol N m^{-2} h^{-1} was found in areas where there was a high anthropogenic input of nutrients. In addition, Gran and Pitkaenen (1999) found that in the nutrient-rich North Sea the highest denitrification rates occurred in the outer estuary and the open Gulf, where bioturbation fauna were present in high numbers. Highest nitrification also occurred in these areas.

The cited observations clearly show that there is a carrying capacity for nitrogen in aquatic systems and that higher nutrient levels lead to higher processing rates for nitrogen. In addition, other flora and fauna, such as plants and benthic burrowers, improve the biological functions of microbes and their ability to process nitrogen. Therefore, species diversity and balance are important to the functioning of microbes in these systems.

Eutrophication can cause hypoxia and anoxia as the result of the breakdown of organic material by the microbial community and the use of oxygen in these breakdown processes. Low oxygen conditions have resulted in significant losses of fish and shellfish resources. Eutrophication is also associated with loss of diversity both in the benthic community and among planktonic organisms, as manifested by the incidence of nuisance algal blooms in many estuaries. The Chesapeake Bay and the upper Gulf of Mexico have anoxic conditions yearly because of the breakdown of organic products by microbes and this results in loss of productivity and species diversity.

Marine Plants in a Balanced Ecosystem

Plants photosynthesize during daylight, producing oxygen and taking up nutrients. Cultivation of seaweeds and animals complement one another. Plants should be integrated with other species to develop a balanced ecosystem approach to responsible aquaculture (Chopin *et al.*, 2002). In China, which produces more than 4.8 million tonnes of brown and red algae annually, seaweeds are considered to be nutrient removers. Production of *Laminaria* sp. alone is estimated at 4 million tonnes, which is equivalent to 2 million tonnes dry weight or 60,000–100,000 tonnes of nitrogen removed each year (Fei, 1998).

The red alga *Porphyra yesoensis*, or nori, is a very valuable commodity. The value of nori was estimated at US$2 billion worldwide in 1992 (Jensen, 1993) and at nearly that amount in Japan alone in 1999 (Kito and Kawamura, 1999). Nori responds to higher levels of phosphorus and nitrogen in the environment by absorbing more into its tissues. In Maine, USA, phosphorus and nitrogen reached 7.9 mg P g^{-1} dry weight and 66.4 mg N g^{-1} dry weight, respectively, in nori plants when water phosphorus and nitrogen reached 0.93 μmol and 11.23 μmol, respectively. Lower levels of phosphorus and nitrogen in the water resulted in lower levels in the plant tissue. Nori culture in China is optimal when total ammonia levels are greater than 100 mg m^{-3}, but the quality and yields go down significantly below 50 mg m^{-3} nitrogen and fertilization becomes necessary (Fei, 1998).

Porphyra sp. can be considered an extremely efficient nutrient pump. The plants reach harvest size on nets in only 40 days and can be harvested thereafter every 9 to 15 days. Nori requires a constant supply of nutrients, particularly during summer when natural levels of nutrients are low. This corresponds to the time when fish culture operations are resulting in the highest levels of nutrient output.

Realizing that algae could provide a sparing of nutrient impact in waters around salmon farms, researchers in Maine have been experimenting with the polyculture of *Porphyra* sp. and Atlantic salmon. Approximately 72% of the nitrogen and 70% of the phosphorus in modern feeds is not retained by the fish. Earlier estimates of phosphorus and nitrogen output from salmon farms of 9.5 kg phosphorus and 78 kg nitrogen per tonne of fish have probably been reduced to 7 kg phosphorus and 49.3 kg nitrogen per tonne of fish because of improved feeds that support better assimilation rates. The new value for the number of nori nets needed to mitigate a tonne of fish per year is 27 standard nets because of the availability of improved fish feeds (Chopin and Yarish, 1999). It is not necessary to completely absorb all nutrients from a salmon farm. It is only necessary to keep below threshold limits for deleterious harmful algal blooms or levels that result in reductions in dissolved oxygen levels. Ongoing research is trying to determine the threshold limits for algal blooms and develop the management models for balancing aquaculture and nutrients in the coastal zone.

There is a gradual reduction in dissolved nutrient levels away from finfish aquaculture facilities. Placement of macroalgal farms close to marine fish farms would provide the optimal location for the plants and could help balance nitrogen levels in the ecosystem. In contrast, phytoplankton, which also depend upon dissolved organic and inorganic nutrients, would probably reach their greatest abundance at some distance from a fish farm, depending upon hydrographic conditions and the reproductive rates of the phytoplankton species.

Wear and Moore (1994) found that epiphytes in enriched seagrass beds were significantly greater than in control beds. Increased epiphytes led to coverage of blades and stems and loss of photosynthetic efficiency resulting in a loss of bottom coverage for the grass beds. Phytoplankton respond more rapidly than macroalgae or seagrasses to excess nutrients in coastal ecosystems because of their reproductive rate. The loss of water clarity in many estuaries, and the corresponding loss of seagrass beds, has been due to significant increases in phytoplankton levels.

Recirculating systems in aquaculture still have to contend with high levels of nutrients, and polyculture systems are being considered for mitigating increases in phosphorus and nitrogen in such systems. One recirculating aquaculture system company in the USA, which produces 8000 kg of summer flounder per year in recirculating systems, estimates that the fish generate 82 g phosphorus and 547 g nitrogen per day. The company has calculated that algal tanks put in line with flounder tanks would need to be 287 m^3 and 217 m^3 in volume to handle all the phosphorus and nitrogen (Chopin and Yarish, 1999). Even though the company can safely and responsibly dispose of nutrient-rich sludge in a municipal sewage plant, it is considering adding nori culture to the system to take advantage of the high value of the product and the natural cleansing of nutrients that would result. The fact that we can calculate the amount of phosphorus and nitrogen produced in aquaculture and the ability of plants like *Porphyra* sp. to take up those nutrients allows us to model and design systems, whether completely controlled by man or in nature, that are in balance.

The Role of Shellfish in a Balanced Ecosystem

Plants address the issue of inorganics produced by fish culture but they do not address that of organic matter. Suspension feeding organisms and filter feeders are more important for that function.

In the Chesapeake Bay, Newell (1988) estimated that the oyster population was once so numerous that it could filter the water in the bay in less than a week. Because of overfishing and disease, the oyster resource has been reduced to the point that it is now estimated to require over a year to filter the water volume of the bay. The ecological role of oysters in Chesapeake Bay is so important that the decline of water quality and fishery resources in the bay is considered to be linked to the collapse of the oyster populations. A multimillion US dollar, decade-long effort is focused on increasing the oyster biomass by tenfold in order to restore the ecological role of the oyster.

Individual bivalves have the capacity to filter from 1 to 4 litres of water per individual per hour. Communities of bivalves have the capacity to filter considerable volumes of water. Bivalves filter particles including silt and clay, phytoplankton and detritus (Jorgensen, 1966). This entrainment of organic material from the water column and deposition on the bottom in the form of faeces and pseudofaeces from bivalves is an integral and essential part of ecosystem function. Rice (2001) calculated that the population of quahog clams (*Mercenaria* sp.) in the Providence River is able to filter 21.3% of the tidal prism volume of 2.58×10^6 m^3 day^{-1} on each tidal cycle. Several studies have shown that filter-feeding bivalves can increase water clarity, thereby increasing light penetration. Cohen *et al.* (1984) studied the effects of *Corbicula*, an introduced freshwater clam from Asia, on light penetration in the Potomac River. Increased clarity in the river led to the re-establishment of submerged aquatic vegetation in the area where the clams were most plentiful. The impact of the zebra mussel on water clarity in Lake Erie is also well documented, with clarity increasing by an order of magnitude. In both cases this has resulted in increased macroalgal production and dramatic shifts in ecosystem function and the appearance of the water.

Mussel farms can remove sufficient phytoplankton so that they compete with zooplankton for the consumption of phytoplankton cells (Rodhouse and Roden, 1987). Mussels convert phytoplankton into rapidly falling organic particles, which can increase sedimentation rates threefold (Kaspar *et al.*, 1985). The hard clam, *Mercenaria mercenaria*, excretes about 9.35 mg NH_3 kg^{-1} of soft tissue per day and oysters produce about 4.76 mg NH_3 kg^{-1} of soft tissue per day. So it is important to understand the processing capabilities of benthic communities for additional organic material and the actual primary productivity of phytoplankton relative to the abundance of filter feeders, including zooplankton. We do not have sufficient understanding of these relationships to perfectly model their functions, but we do know enough to be vigilant with respect to both the positive and negative aspects of bivalve culture and to make rough estimates to be included in management models.

Rice (1999) stated that the dry weight of the soft tissues of most bivalves is typically around 30% protein. For each kilogram of shucked shellfish meats harvested there are 16.8 g of organic nitrogen removed from the estuary. Nutrient removal from estuaries can by maximized through management of shellfisheries for maximum biomass production and harvest, and development of aquaculture projects where growing shellfish are harvested regularly (see Chapter 14). An average person excretes 3.8 kg of nitrogen annually. Rice (1999) also calculated that it would take 5600 oysters (225 kg of meats) harvested from an estuary to counter the nitrogen deposition of a single human. It will take better management of human waste, increased populations of wild oyster stocks through the establishment of sanctuaries, better management of existing public beds, and the use of oyster aquaculture as a filtering mechanism and method of nitrogen removal by harvest to move towards better ecosystem function in Chesapeake Bay and other water bodies around the world.

The Role of Fish in a Balanced Ecosystem

Every species of fish has its own unique role within an aquatic ecosystem. The evolution of thousands of fish species has depended upon the ecological and environmental conditions that exist on this planet. All fish have evolved morphologically and behaviourally to the feeds and habitats that are available. Forage fish species, such as menhaden and mullet, are essential for healthy populations of more commercially important species, but menhaden are dependent on zooplankton, and mullet are more dependent on detrital materials rich in microbes and other small biota. Some species of fish have adapted to extremely cold temperatures by having blood proteins that are resistant to freezing and others have adapted to the warm conditions of tropical oceans and may be totally intolerant of winter water temperatures that are commonly experienced by temperate species.

Some coral reef fish species have become adapted to eat the skeletal material and polyps of hard corals. These fishes can process the protein for growth and eliminate the calcium carbonate that ends up as sand. Several coral reef species have developed elongated mouthparts to be able to access the many crevices and small holes in a coral reef where prey may be found. Many fish have evolved special grinder mechanisms that allow them to consume molluscs with their hard shells or crush plant material to release the nutrients from within the plant cells. Many fishes are equipped with fine gill rakers that are used to filter food from the water. Others have fleshy lobes on their heads that act as lures to attract prey. In the ocean depths, fish may be equipped with bioluminescent organs that can be used to attract prey (or mates). Fish have adapted morphologically to their feeding niche by having mouths that open downward, mid-line or up depending upon their feeding strategy. Many additional examples could be provided, but those related here give some idea of the diversity of feeding mechanisms and habits that exist.

All of this diversity and adaptation provides aquaculturists with an extensive tool box in terms of developing a balanced ecosystem approach. Fish species can be polycultured in the same containment system in such a way that one species can help graze down algae on the cage and another can reduce encrusting worms or barnacles. However, in an aquaculture context most fish will be receiving feeds based upon their ability to process animal or plant proteins and the result will be some form of nitrogen, phosphorus and other nutrient enrichment of the water mass. This enrichment can be either positive or negative depending upon the carrying capacity of the culture system for nutrients and its location within the hydrographic and ecological system. In coastal waters, heavily impacted by man's activities and nutrient inputs, any additional nutrients can lead to harmful algal blooms. On the other hand, in nutrient-poor waters, additional nutrients can lead to higher productivity and increased fishery resources. Inputs of nutrients from aquaculture into nutrient-poor waters can increase food-web interactions and careful placement of aquaculture facilities can contribute to ecosystem balance. Phytoplankton derived from such nutrient inputs can provide food for zooplankton species that are important to larvae and juveniles of commercially important species. Fish that consume zooplankton, such as alwives and menhaden, which are commonly preyed upon by commercially important species such as mackerel and cod, could benefit from properly placed nutrients resulting from aquacultural operations.

There have been a number of polyculture investigations in both marine and freshwater aquaculture systems in which secondary species were employed to utilize or recycle waste products from the primary species. Recent examples are production of the alga *Gracilaria parvispora* in a shrimp farm effluent in Hawaii (Nelson *et al.*, 2001) and production of *G. chilensis* in conjunction with salmon cages in Sweden (Troell *et al.*, 1997). Polyculture of such species as mussels (Stirling and Okumus, 1995) and sea urchins (Kelly *et al.*, 1998) with Atlantic salmon has also been evaluated.

Ahlgren (1998) stocked sea cucumbers in salmon netpens in Alaska to graze on fish faeces, excess feed and fouling organisms. A review of integrated polyculture systems designed to meet the balanced ecosystem approach was prepared by Brzeski and Newkirk (1997).

Enell and Ackefors (1991) estimated that 9.5 kg of phosphorus and 78 kg of nitrogen per tonne of fish per year are released into the water column in a typical salmon farm operation. These nutrient additions have to be considered in the context of overall nutrient processing and removal on an ecosystem scale. However, the nutrient processing abilities of algal and filter-feeding species, which we have already discussed, suggest that balance between nutrient inputs and utilization by other species, both in culture and in the wild, is possible. It is important to remember that the existing populations of microbes, plants, invertebrates and fish represent reservoirs of nutrient processing capability. The biological functions of this diverse biota serve as a buffer to nutrients and we have to understand these complex relationships as we begin to factor in human-induced processes.

The removal of nitrogen from the Chesapeake Bay by fisheries activities has been estimated at nearly 10% of nitrogen removal for the bay (Kemp, 1997). This would include harvest of bivalves, crustaceans (crabs) and fish. If we promote aquaculture of bivalves and enhancement of crabs and fish, the harvest of these resources would also remove nutrients from the bay. Human harvesting activity as well as nutrient generation through domestic waste, agriculture and industrial waste are driving forces in the balanced ecosystem equation.

Human Community Role in a Balanced Ecosystem

The profound impact of human communities on the natural environment has been described earlier in this chapter. Coastal waters have suffered the most from industrial wastes, agricultural runoff of pesticides and herbicides, as well as nutrients and domestic waste. In many cases the nutrients flowing into estuaries have overwhelmed the ability of the natural systems to process them and water quality has deteriorated. Many billions of dollars are now being spent to improve domestic-waste treatment, reduce atmospheric pollution, reduce toxic inputs, improve agricultural practices, treat existing toxic sites and correct water flow problems caused by dredging and filling.

We are at a transition in human use and dependence on the oceans of the world. The world human population has grown to the point where we can no longer expect to obtain additional protein from the sea without moving into the husbandry of the food species that are desired in the human marketplace. The capture fisheries have decimated many species of fish, crustaceans and molluscs leading to disruption of the natural balances in nature. Understanding these balances and managing the wild catch and the technology used to capture these resources is the responsibility of fishery resource managers around the world and new management procedures are being implemented for many of the fishing sectors.

We have also learned that unrestrained aquaculture can have negative environmental impacts and that it is essential to balance aquaculture production with ecosystem function and ability to handle additional nutrients. This we have described as the natural carrying capacity for nutrients in the ecosystem. But it is also becoming apparent that certain types of aquacultural production, e.g. filter-feeding species of oysters, clams, mussels and scallops, or commercial algal species, can be used to balance the nutrient additions that result from most finfish production systems. The approach of using these extractive types of aquaculture, coupled with an understanding of the natural carrying capacity of natural systems, can lead to sustainable aquaculture and the adding of desired fishery products to the human food-distribution system.

Proper placement of aquaculture facilities is very important in maintaining ecosystem function. Extractive aquaculture, such as bivalve and algae production, should occur in high-nutrient areas where aquaculture can serve to reduce nutrient levels. Finfish culture should be placed in areas that have assimilative capacity for nutrients. Appropriate areas should have high current-flow rates, be sited in offshore locations that have low nutrient levels, or be located on land, where nutrients can be processed or recaptured through filters or recirculating technologies.

Human populations have an obligation to use all natural resources in such a way that we do not overload the assimilation capacity of natural systems. There should be no such thing as fishery or aquaculture waste and we need to think more of recycling the waste produced in our agricultural and aquacultural industries. The food yield from processed fish is generally less than 50%, leaving the greatest amount of protein and bone tissue as waste. Proper treatment of this waste can provide the fish, crustacean and molluscan meals that can be utilized in the aquaculture industry (see Chapter 16). This is particularly important as fish meal supplies will eventually limit the growth of the aquaculture industry because of its value as feed for not only fish but also for cows, pigs and chickens. Integrating aquaculture and fishery industries with processors and meal production facilities is one way that human communities can reduce their impact on the natural environment.

In the future, fisheries resources will continue to be allocated among several different users. Recreational fishermen and commercial fishermen are already in conflict over the allocation of the most popular sport fish and the commercial fishermen are losing to the larger number of recreational fishermen (see Chapters 4 and 5). Many states, such as Florida, Texas and Louisiana, have enacted laws that prohibit commercial fishing for certain sport fish and this trend is expanding. The US consumer will be denied many of the most popular fish species unless they are cultured.

Other fish species and populations, such as cobia (*Rachycentron canadum*) in the South Atlantic and Gulf of Mexico, or groupers and snappers in coral communities, are not plentiful enough to withstand high levels of commercial exploitation. These top predators have in some cases been fished to near extinction, thus eliminating their important ecological function of keeping other fish species in balance. Yet, they are extremely popular foodfish for human populations. It would seem far better to culture these valuable species while maintaining the wild populations for their ecological function and contribution to the subsistence fisheries and carefully regulated recreational fisheries.

In the past, the random and piecemeal modifications of the natural environment by human populations has had the cumulative impact of upsetting the natural balance of both terrestrial and aquatic ecosystems. Human activities have been credited with the extinction of many terrestrial species. Agriculture evolved when human populations grew too large to maintain the hunter and gatherer cultures that predominated 10,000 years ago. The difference between the number of humans that existed then and now can primarily be attributed to agriculture technology development.

We have reached the same point in terms of the wild harvest of the seas. The wild fishery harvest has stabilized over the past decade (FAO, 1997). Many species are commercially extinct and the function of coastal and oceanic ecosystems compromised by commercial and recreational fisheries. Our response to these obvious changes in species abundance and balance is to impose quotas and restrictions on capture and harvest that reduce the amount of individuals captured.

New food for human consumption can only occur through aquaculture, just as it did for terrestrial systems through agriculture. In order to do that in an ecologically balanced way we must understand and utilize the natural functions of both cultured and wild species so that energy flow and distribution of nutrients is utilized through biological activity. Modelling these relationships in the context of the hydrographic and environmental conditions found in different regional contexts is our challenge.

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