CHAPTER 1

Sustainability of seafood production – challenges and the way forward

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Abstract

Sustainability of seafood supplies is a matter of growing concern at a time when demand is increasing and some of the factors constraining the development of aquaculture are challenging the efforts towards increasing production. Stabilization of harvest from fisheries has generated a great deal of interest in aquaculture. Besides directly enhancing production, aquaculture can reduce pressure on wild stocks and biodiversity, and contribute to enhancing depleted stocks. Aquaculture systems are diverse, requiring a comprehensive understanding of the different issues and knowledge-based solutions, and an enabling environment that favours application of innovative ideas to support development of this sector. Diversity in aquaculture often requires adopting more balanced and informed approaches that take into consideration the environmental, social and economic conditions. The future of aquaculture depends on management of key issues and application of appropriate strategies. This chapter discusses the trends that characterize the emergence of aquaculture as a major provider of high quality protein, the challenges it faces in a changing climate, the impact of adaptation measures on sustainability, the possible role of some forms of biotechnology, introducing ecosystem perspectives and the potential of forging synergies of this sector with other means of producing seafood.

Keywords: Seafood security, aquaculture, climate change, adaptation strategies, ecosystem approaches

1.1 Sustainability issues and concerns

The long-held world view of oceans as a limitless source of fish was a mistaken notion. In less than two centuries, during the age of industrialization, human impacts have pushed the oceans to the brink. We have not taken seriously signs

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of resource exhaustion, out of ignorance of the consequences or for convenience, and we still continue to do so for lack of cheap options.

Until a few decades ago we did not believe that the cost of inaction could be far greater than the cost of remedial action. Catching fish from the sea is, of course, cheaper than farming it but the situation in the twenty-first century tells us what used to be a free bounty has a cost. Oceans have been taken for granted for too long. We need to invest not just in saving what is left in the oceans but also in growing in farms what we used to harvest from the sea.

Most of the marine fish stocks are under great pressure: almost 30% are overexploited, 57% are fully exploited (at or close to their maximum sustainable production) and only about 13% are not fully exploited (FAO, 2012).

For a long time, we did not care about the environmental impacts of fish farming. We could have learned lessons from the green revolution but we chose not to. The green revolution increased agricultural production from land-based crops and saved a vast population from hunger and malnutrition. However, it created environmental problems. The blue revolution was launched with the aim of increasing animal protein supply. This was achieved but also at the cost of the environment.

When the green revolution was launched and progressed, oceans were still viewed as a major frontier for food production. However, this frontier is facing serious challenges that are pushing it to the tipping points. Oceans being the last frontier on Earth for food supply, we have nowhere else to go to produce food. The consequences of factors as powerful as ocean acidification, warming and oxygen deficit on capture fisheries are already becoming visible and are strong enough to undermine the seafood supply.

Sustainably managing what is left in the oceans and rapidly developing sustainable aquaculture are the very basis of seafood security.

The world's human population has exceeded seven billion and is projected to reach 9.3 billion by 2050 (UN, 2010). The maximum potential fish production from current marine fisheries is estimated to be about 80 million tonnes per year (FAO, 2010). If it declines while human population grows, aquaculture would be expected to meet the world demand. How much marine fisheries and aquaculture will be able to supply fish in the future will depend to a great extent on ecosystem productivity (Brander, 2007; Cheung *et al.*, 2009a, 2009b), the efficiency of fisheries management (Rice and Garcia, 2011) and on the capacity to expand environment-friendly aquaculture (Naylor *et al.*, 2009). The human welfare dimension of fisheries and aquaculture is more than just direct consumption of seafood. These sectors also provide means of livelihood and income.

In the course of this chapter, certain terms will be used and to avoid any confusion their technical definitions provided by the United Nations Food and Agriculture Organization (FAO) are explained here. Let us start with aquaculture and fisheries. Aquaculture denotes farming of aquatic organisms including fish, molluscs, crustaceans and aquatic plants, which implies some form of intervention in the rearing process to enhance production, such as regular stocking, feeding and protection from predators. Farming also implies individual or corporate ownership of the stock being cultivated. The aquatic organisms that are harvested by an individual or a corporate body that has owned them throughout their rearing period contribute to aquaculture, while aquatic organisms which are exploitable by the public as a common property resource, with or without appropriate licences, are the harvest of capture fisheries. Capture fisheries comprise the range of all activities related to harvesting fish and may refer to the location, the target resource, the technology used, the social characteristics (artisanal, industrial), the purpose (subsistence, commercial, recreational) as well as the season.

The primary sector of fish production engaged 55 million people in 2010 (FAO, 2012). Interestingly, due to stagnation in capture fisheries, the number of people engaged in fishing increased by only 0.8% per year compared to 5.5% in fish farming based on the pattern in the last five years (FAO, 2012). The FAO report further stated that, in addition to the primary production sector, numerous jobs are also provided by ancillary activities, such as: post-harvest processing; packaging; marketing; distribution; manufacture of fish-processing equipment, nets and gears; ice factories; feed mills; boat construction; maintenance of facilities; transport of product; administration; and research and professional services.

Overfishing should be viewed from the point of view of its adverse impact on fish production and its socioeconomic consequences. To increase the contribution of marine fisheries and aquaculture to food security, economies and human welfare, a thoroughly integrated and effective management of seafood production along the lines suggested above is absolutely necessary and time is not on our side. Our options are reducing and the cost of the remaining options is increasing. There are pathways explained in the FAO's Code of Conduct for Responsible Fisheries, Guidelines for Inland Fisheries and Aquaculture, Sustainable Livelihoods Approach, Ecosystem Approach to Fisheries Management, UN Fish Stocks Agreement and Manual of Good Aquaculture Practices. Provisions under these frameworks can be implemented according to local conditions. The UN Conference on Sustainable Development held in 2012, known as Rio+20, dealt with the governance of fisheries and aquaculture and countered the notion that sustainability and growth are mutually exclusive. At a time when pressures on land-based farming systems are increasing, the focus on the world's oceans is a logical development. In this context, the importance of improved management and sustainable growth in minimizing the use of natural resources and increasing food security cannot be overemphasized.

World supply of fish from capture fisheries and aquaculture reached 154 million tonnes (mt) in 2011. Capture fisheries contributed 90.4 mt and aquaculture 63.6 mt to this total fish production (Table 1.1). This figure suggests an increasing trend in production, which was demand driven.

Analysis of production and consumption data for the period 2006–2011 presented in Table 1.1 suggests that:

Table 1.1 World fisheries and aquaculture production and use (FAO, 2012).

	2006	2007	2008	2009	2010	2011
PRODUCTION (Million tonnes)						
Capture						
Inland	9.8	10.0	10.2	10.4	11.2	11.5
Marine	80.2	80.4	79.5	79.2	77.4	78.9
Total capture	90.0	90.3	89.7	89.6	88.6	90.4
Aquaculture						
Inland	31.3	33.4	36.0	38.1	41.7	44.3
Marine	16.0	16.6	16.9	17.6	18.1	19.3
Total aquaculture	47.3	49.9	52.9	55.7	59.9	63.6
TOTAL WORLD FISH PRODUCTION	137.3	140.2	142.6	145.3	148.5	154.0
USE						
Human consumption	114.3	117.3	119.7	123.6	128.3	130.8
Non-food uses	23.0	23.0	22.9	21.8	20.2	23.2
Population (billions)	6.6	6.7	6.7	6.8	6.9	7.0
Per capita food fish supply (kg)	17.4	17.6	17.8	18.1	18.6	18.8

- Global capture fisheries production remained stable at about 90 mt (inland = 10 mt; marine = 80 mt).
- Aquaculture production increased significantly from 47.3 mt (2006) to 63.6 mt (2011).
- Increase in aquaculture production occurred in both inland as well as marine sectors.
- Inland aquaculture production exceeded marine aquaculture output, with the former registering an increase from 31.3 mt to 44.3 mt steadily during 2006–2011 and the latter an increase from 16 mt to 19.3 mt in the same period.
- The per capita food fish consumption also increased from 17.4 kg (2006) to 18.8 kg (2011) – providing more than 4.3 billion people with about 15% of their animal protein intake.
- In the last three decades (1980–2010), world aquaculture production has grown by almost 12 times, at an average annual rate of 9%. The 2010 production figure of about 60 mt is valued at US$ 119 billion. It does not include farmed aquatic plants and non-food products. When these are included, the world aquaculture production amounts to 79 mt, worth US$ 125 billion in 2010.

1.2 The emergence of aquaculture

The trend of rapid growth of aquaculture seen in recent years is likely to continue and even intensify. It is driven by demand and the demand is growing. Aquaculture is a diverse activity. It is carried out in freshwater, brackish water and marine water. This classification of environment is based on the level of salinity. Measured in terms of salt concentration (grammes of salt per litre or as parts per thousand, ppt) the environment is considered saltwater, brackish water, saline (marine) and brine if the values are in the range <0.5, 0.5–30, 30–50 and >50 ppt, respectively.

Depending on the suitability of species and environment, aquaculture is mostly practiced in ponds, pens, cages, tanks, raceways and paddy fields. For species of molluscs, ropes, floating rafts and trays are used. The common form of aquaculture pond is an earthen unit created by earth levees, although other materials can be used. Ponds are of various sizes and depths, depending upon their purpose. Most ponds have an arrangement for interchanging water (regulated inflow and drainage). Tanks are artificial units of varying sizes capable of holding and renewing water. They can be constructed of cement, fibreglass, hard plastic or any other durable material. A raceway is basically a sort of tank culture facility capable of high rates of water exchange. Cage and pen are facilities for enclosure culture; they hold organisms captive whilst maintaining a free exchange of water. A cage has a rigid frame on all sides and can be enclosed on all four, or all but the top, sides by mesh or netting. In a pen, there is no mesh enclosure at the lower end, since the seabed where the pen is installed forms the bottom. There is some confusion concerning the terms ‘cage’ and ‘pen’ in certain countries, where both names are used interchangeably and marine cages are often referred to as net pens!

Rafts, ropes and stakes are used for culture of shellfish, notably mussels, and seaweeds. Ropes are suspended in deeper waters from rafts or buoys while stakes are impaled in the seabed in intertidal areas. Scallops and oysters are also raised in plastic trays suspended from rafts.

Recirculating aquaculture systems (RAS) are gaining popularity due to their environment-friendly operation. The water flow is controlled by pumps that return it to a storage tank, where wastes are extracted and the water is then pumped back into the tanks for recycling.

The design of the facilities, selection of site and quality of environment are important factors in the successful culture of any species. Of course, for all aquatic animals, water quality is a factor of fundamental importance. Sediment characteristics can significantly influence animals that are cultured in ponds. There is no dearth of information on design and operation of the culture facilities and readers can obtain details from numerous books and papers published to date.

Several considerations are, however, necessary for a profitable culture. Selection of suitable species, sites and design of the facilities in addition to adaptation to changing climate are of considerable importance, since these factors affect survival and growth of the fish, operational cost and durability of the culture unit.

1.2.1 Selecting culture sites

1.2.1.1 Physical conditions

The coastal culture site in the sea should be in a safe location that is sheltered and protected from strong winds and waves. Since climate change is increasing the severity of rough sea conditions, this factor has to be taken more seriously than ever before. Malaysia, being free from typhoons and cyclones, offers many suitable locations, but we still have to take into consideration the rough sea conditions and storm surges that can damage the cage culture facilities and put serious stress on captive stocks of fish.

The use of cages to culture marine finfish is the most popular and widespread method. In the last three decades, interest in inshore as well as offshore net cages has increased rapidly (Benetti *et al.*, 1995); this has resulted in many designs and sizes of cages. Fredrikson *et al.* (1999) have discussed three main considerations – biological, engineering and socioeconomic – that have characterized the directions in the development of cage systems. A basic requirement for all types of cages, no matter where they are installed, is the stability of their structures against the forces of currents, waves and winds while holding the fish stocks (Emmanuel and Olivares, 2003). Details of these physical forces on cage systems and suitable designs have been published in the past. Carson (1988) and Beveridge (1996) have discussed this topic with regard to currents. Structural engineering of cages has been elaborated by Cairns and Linfoot (1990). Milne (1972) and Beveridge (1996) have described the mechanics of wind and wave forces on a cage installed in the sea.

Basically, there are four types of cages (Beveridge, 1996): fixed (or stationary), floating, submersible and submerged. A fixed cage consists (Figure 1.1) of a net supported by posts (or poles) that are driven into the bottom. This is the simplest and cheapest type of cage; it is used in south-east Asia in places that are sheltered and shallow, and where the seabed has a substrate that is firm enough to ensure that the supporting poles are stable. The floating net cage has a buoyant frame that supports a net bag. The assembly keeps the net bag suspended in the water. The unit can be easily towed when required. This is the most widely used cage in Asia, including Malaysia. A submersible cage has a frame that maintains shape of the cage. The position of the cage can be changed according to prevailing environmental conditions. They are kept at the surface when the water is calm but submerged when the sea is rough. Such cages are mainly used in offshore aquaculture operations. Submerged cages are in the form of boxes, mostly wooden, with spaces between the wooden structural planks to allow the flow of water. They are anchored to the bed using rocks or posts, and are used in running water. The type of cage chosen, its size and design depend on several factors, such as the species selected for stocking, conditions at the site, environmental factors and investment capacity.

The advantages of culturing fish in cages are that they: come in various sizes and shapes, can be tailored according to the needs and convenience of farmers

Figure 1.1 Fixed net cage used for growing coral reef fish in Tuaran, Sabah, Malaysia. *(See insert for colour representation of the figure.)*

and can be fabricated locally using readily available materials. Moreover, they are cheap compared to other farming facilities, and the caged fish can be easily monitored compared to fish stocked in a pond.

The culture site should be away from navigation routes, so as to avoid conflict of interest and prevent exposure of the fish to turbulence that passing boats produce. If culture is carried out in cages, the desirable depth of the cages should be such as to ensure flushing to prevent accumulation of waste, decomposition of organic matter (that produces hydrogen sulphide [H_2S]) and oxygen depletion. Since the usual depth of floating net cages in coastal water is 2–3 metres, a ground clearance (vertical measure of water column between the seabed and bottom of the cage) of more than five metres but less than 20 metres is sufficient. For stationary cages, the suggested minimum depth is more than four metres but less than eight metres. The physical conditions that require consideration for a suitable net cage culture site are summarized in Table 1.2.

The characteristics of the sea bottom in the site selection also deserve attention. A firm substrate compising a suitable mix of gravel, sand and clay is better than a muddy bottom because the latter can impair the water quality and is not suitable for the stability of cage structures.

Besides these general physical features, the selection of a suitable culture site also requires consideration of several physical and chemical parameters. These are described in Table 1.3. Since water quality in coastal areas is dynamic, the range of variations needs to be examined before a final decision is taken.

Table 1.2 Criteria for selection of site for marine finfish net cage culture (NACA, 1989).

Physical conditions at the site	Type of net cage	
	Stationary cage	Floating cage
Wave height, m	<0.5	<1.0
Depth, m	Minimum >4 Maximum <8	Minimum >5 Maximum <10
Wind velocity, knots	<5	<10

Table 1.3 Physical and chemical factors suitable for sea cage culture (NACA, 1989).

Physical and chemical parameters	Quantities/ranges
Temperature, °C	27–31
Current velocity, cm/s	Minimum >10 Maximum <100
Suspended solids, mg/l	>10 mg/L
Dissolved oxygen, ppm	>4 (Pelagic fish) >3 (Demersal fish)
Salinity, ppt	15–30
Ammonia- nitrogen (NH_3-N), ppm	<0.5
pH	7–8.5
Nitrate (NO_3-N), mg/l	<200
Nitrite (NO_2-N), mg/l	<4
Phosphate, mg/l	<70
Chemical Oxygen Demand, mg/l	<3
Biochemical Oxygen Demand, mg/l	<5
Manganese (Mn), Iron (Fe), Chromium (Cr), Tin (Sn), ppm	<1.0 (each)
Lead (Pb), Nickel (Ni), Zinc (Zn), Aluminium (Al), ppm	<0.1 (each)
Copper (Cu), ppm	<0.01
Cadmium (Cd), ppm	<0.03
Mercury (Hg), ppm	<0.004

1.2.1.2 Biological factors

Fish selected for culture should be amenable to confinement. Some species, such as sardine and mackerel, which live in big shoals and swim over long distances as a part of their normal daily activity, do not take captivity easily. Certainly, species that can adapt to captivity and continue to grow are preferred for culture in these facilities. The selected species should also have high tolerance to environmental conditions and resistance to diseases. They should fetch high market value, have consumer acceptance and have seed that is easily available for stocking.

The problem of a sustainable supply of high quality and disease free seed is a major impediment to the growth of marine finfish culture in many countries. Farmers select predatory fish for culture because of their high market value and their ability to thrive on the supplied feed. Planktivorous fish are not cultured in cages because they require large grazing areas, which captivity does not provide.

The selected sites should be free from harmful algal blooms. Generally, marine areas with a high intensity of light and nutrient concentrations in warmer water and stagnant conditions are prone to red tides and oxygen depletion. Furthermore, if biological activity of an area is high on account of high pathogen load, it is also not suitable for culture. Places in the sea such as those near water villages that are known for an *E. Coli* concentration exceeding 3000/ml should be avoided for culture (NACA, 1989).

Together with high nutrient concentrations and phytoplankton blooms, high salinity, temperature and turbidity in areas with low hydrodynamic activity, which manifest in poor flushing and low current velocities, are prone to fouling. This creates unfavourable conditions for the survival and growth of the captive fish. As many as 200 species of marine organisms are known to cause fouling (Lovegrove, 1979). Cheah and Chua (1979) noticed more than 34 species of algae, coelenterates, polyzoans, annelids, arthropods, molluscs and lower chordates clinging to net cages after their immersion for only two months. Silt particles deposited on net cages facilitate the colonization of fouling organisms. Clogging of the net by fouling organisms reduces the water flow across the cage, which hampers waste removal and lowers the dissolved oxygen (NACA, 1989). Cages require regular maintenance to control fouling. Often, net replacement is recommended where there is excessive biofouling.

1.2.1.3 Other factors

Other matters that require attention in culture include the legal requirements and security. There are rules and regulations for organizing cage cultures in the sea that need to be complied with. There could be social problems as well, especially those pertaining to security of fish and farming facilities, and activities detrimental to the culture environment. These situations vary from place to place, and some knowledge of the challenges that cage culture might face related to such issues will be helpful in the planning stage.

1.2.2 Effects of climate change

Climate change is affecting the marine environment by warming water, depleting oxygen levels, causing acidification and increasing the toxicity of pollutants, frequency and severity of harmful algal blooms, and abundance of animals such as jellyfish.

The nature and degree to which aquaculture will be affected by climate change depend on the biological attributes of the species and systems used in the culture. Climate change is causing ocean acidification, warming of seawater, oxygen deficit and alteration in the physical conditions in the sea. Obviously, culture carried out in land-based facilities and that carried out in the sea will affect the stocked species differently. In cage and pen farming, there is little or no control over the aquatic environment in which the animals are held. Therefore, those systems that involve farming directly in the sea have to directly bear the brunt of the climate change effects in the sea. Adaptation to changing climate will minimize the risks and enable the aquaculture to continue to grow and achieve sustainability.

Most of the studies on the effects of climate change on marine life have, however, approached this topic from a physiological perspective (Jobling, 1997) and their focus has been on warming and acidification of seawater. Acidification interferes with the calcifying ability of many marine organisms that build skeletons and calcium carbonate shells (Feely *et al.*, 2009).

We need to examine the combined effects of acidification, warming and hypoxia (oxygen depletion) on marine life. The effect on fish will depend on the tolerance threshold of the species. If a species has a high sensitivity to pH decline, it will have a low ability for acid-base regulation (Portner, 2009). The author further explained that the disturbed extracellular acid-base equation will affect metabolic processes involved in growth, calcification, neuron function, blood gas transport and behaviour pattern.

Local factors can modulate the effects of climate change. A fish in captivity can live within the threshold of its tolerance, but beyond that it will succumb as it is not in a position to explore new grounds where it can minimize the effects of climate change.

Climate change will not produce similar effects in every region and in all habitats within a region. Thus, a culture site located in a freshwater environment will be affected by an increase in water temperature, decrease in dissolved oxygen and increase in toxicity of pollutants to fish (Ficke *et al.*, 2007), not by factors such as upwelling, and blooming of harmful algal blooms and jellyfish. Moreover, if as a result of human activities, eutrophication levels increase, that will affect the quality of the environment where the culture is located, resulting in a decline in growth and increase in mortality rate. Both eutrophication and rise in water temperature cause oxygen depletion, the former by increased microbial activity and the latter by reducing water's oxygen holding capacity. If oxygen depletion happens in culture areas, the fish will suffer. However, the degree to which they will be affected will depend on the type of species. Air-breathing fish will be in a better position to withstand oxygen deficiency, as they can adapt by increasing their dependence on air-breathing organs.

Because most of the marine organisms cultured are poikilothermic, increase in water temperature will influence their general metabolism, which will have implications for their growth, production, reproduction and susceptibility to diseases and pollutants (Ficke *et al.*, 2007). Changes in monsoon pattern, ocean circulation and organic production, and increase in extreme weather events linked to climate change will affect fish farmed in the sea. Most of the other impacts on aquaculture being discussed are potential scenarios that make sense based on the current state of our understanding. The implications of a decline in pH of seawater (acidification), increase in water temperature and expansion of the so-called 'dead zones' in the ocean on marine life have been discussed in detail in earlier publications (Hill and Mustafa, 2011; Mustafa and Hill, 2011).

In many Asian countries fish culture in rivers is not a widespread activity and does not contribute substantially to fish landings from inland water. However, it does provide subsistence to a small population living near the rivers. Culture in rivers involves growing wild-caught fry to a harvestable size. If climate change affects river populations, there could be shortage of fry and this will affect the cage culture unless hatcheries are in a position to supply the fry at low cost.

Climate change-induced severe weather conditions could cause damage to cage facilities, requiring additional reinforcements and more maintenance costs. Also, an increase in the frequency of red tides will affect fish. Transfer of fish from sea cages and pens to hatcheries during red tide outbreaks will increase the cost of producing fish and energy consumption, since land-based aquaculture requires aeration and other energy-consuming devices. Transfer of mussels and oysters from their culture sites in the sea poses more difficult problems. Despite these and other concerns, an economic analysis of the impact of climate change on aquaculture remains elusive. We know that even one factor as powerful as ocean acidification will produce economic impacts but calculation of its true cost is difficult at this stage (Hilmi, 2011).

The question whether or not climate change will provide any advantage to aquaculture has been addressed by some researchers. Simply put, warming of water will enhance growth rate and this might appear to support production. However, we should keep in mind that temperature increase is not the only consequence of climate change. Other factors, such as acidification and oxygen depletion, related to climate change will offset any increase in growth, and cause decline in production. Of course, rise in temperature is one of the most noticeable aspects of climate change (Baez *et al.*, 2011) because metabolic rates depend on this parameter (Clarke and Johnston, 1999) but the effect of temperature cannot be discussed in isolation of other factors in evaluating the total impact. Temperature increase can create a mismatch between oxygen demand and the capacity of the oxygen transport system to meet cell demand (Portner and Knust, 2007). Perhaps, for this reason mass mortalities of fish reported from many regions of the world are attributed to changing climate (Kangur *et al.*, 2007).

There is yet another scenario wherein increase in seawater temperature and eutrophication will lead to increase in plankton productivity, which will offer a feeding advantage to planktivorous species. However, since fish with this kind of feeding habit are not generally cultured in cages due to the vast grazing area that they require, which is not available in a cage, it is not a factor to reckon with in this discussion. Indeed, prey fish are mainly planktivorous and their populations might grow on abundant planktons, thereby improving the so-called 'trash fish' catch in the form of raw product, meal or oil, for caged fish. Again, it is unlikely that prey fish will be spared from the adverse effects of acidification and oxygen deficit. As far as the reported effect of climate change on breeding is concerned, the data published on Pacific oyster (*Crassostrea gigas*) (Parker *et al.*, 2009) suggest that this species will generate more recruits, which in turn will make the spat more easily available and at a lower price. However, due to chemically changing ocean conditions and mounting stress level on all marine species, including oysters, any optimism on the production scenario is unrealistic.

Ocean acidification linked to climate change is receiving increasing attention and is considered a major factor to reckon with. This deserves detailed explanation. Ocean acidification, a progressive increase in the acidity (or reduction of pH) of seawater over an extended period, typically decades or longer, caused primarily by uptake of excessive quantities of carbon dioxide (CO_2) from the atmosphere, is one of the most profound consequences of climate change (Caldeira and Wickett, 2003; Feely *et al.*, 2009; Orr *et al.*, 2005). Seawater is the medium of living for marine life. Obviously, any change in the chemical composition of water would influence the organisms that live in the sea and bring about change in the biological systems (Lovejoy and Hanna, 2005).

When CO_2 dissolves in seawater, it alters the carbonate chemistry which causes acidification. Rate of ocean acidification is increasing and is causing concern about its implications for the marine ecosystem. Oceans are known to absorb one-third (more than 33%) of CO_2 released into atmosphere by human activities (Sabine *et al.*, 2004) and, thus, account for the largest carbon sink on the planet. By removing so much CO_2 from the atmosphere, oceans help in reducing climate change. However, excessive quantities of this gas are disturbing the marine ecosystem.

In the ocean, CO_2 reacts with H_2O molecules to form carbonic acid (H_2CO_3). This is a weak acid that rapidly dissociates into hydrogen (H^+) and bicarbonate (HCO_3^-) ions. The latter split into H^+ and carbonate ion (CO_3^{2-}). As the concentration of H^+ increases due to these reactions, the water becomes acidic while at the same time the extra H^+ reacts with carbonate ions (CO_3^{2-}) to form bicarbonate, thereby reducing the abundance of carbonate and decreasing the saturation state of calcium carbonate ($CaCO_3$) minerals. The concentration of H^+ determines the acidity of water, which is measured by pH on a logarithmic scale: $pH = -\log [H^+]$. In this scale, a decrease of one pH unit corresponds to a 10-fold increase in acidity. The pH of the surface water of an ocean is 0.1 unit lower than the preindustrial value some 200 years ago (a decline from 8.2 to 8.1), representing a nearly 30% increase in H^+ concentration. This rate of acidification is estimated to be 10–100 times faster than any time in the past 50 million years

(UN-DESA, 2009). If the pH declines by further 0.3–0.4 pH units, as is expected to happen by 2100, this will amount to 100–150% increase in the concentration of H^+ (Orr *et al.*, 2005). With this sort of trend, even by mid-century, the rate of acidification will be 100 times faster than the changes that occurred in the past 20 million years. It needs to be clarified that the pH of the open-ocean surface layer is unlikely to ever become acidic (i.e., drop below 7.0) because seawater is buffered by dissolved salts. The term 'acidification' refers to a pH shift towards the acidic end of the pH scale (not amounting to decline below 7.0).

Changes in ocean chemistry as described above will be irreversible for many thousands of years and the biological consequences could last much longer (UN-DESA, 2009). The Intergovernmental Panel on Climate Change (IPCC) report puts into doubt if the biological impacts will be reversible at all.

According to the fact sheet developed to reflect the state of ocean acidification research and understanding for IPCC documentation, full recovery of the oceans will need tens to hundreds of millennia. The reason is that over a period of decades to centuries, neither the weathering of continental rocks, deep ocean mixing or dissolution of calcium carbonate minerals in marine sediment can occur fast enough to reverse the acidification that will occur over the next two centuries.

The net effect of CO_2 addition to seawater, therefore, takes the form of an increase in the concentrations of H_2CO_3, HCO_3 and H^+, and decrease in the concentration of CO_3^{2-}. Decline in pH decreases the saturation points of minerals such as calcium carbonate. Simply put, excess of CO_2 in seawater reduces the availability of the carbonate ions that are necessary for calcifying organisms, such as corals, molluscs, sea urchins, crustaceans and calcareous phytoplankton, which build $CaCO_3$ shells and skeletons. How much these organisms are affected mainly depends on $CaCO_3$ saturation state determined by the concentrations of Ca_2^+ and CO_3^{2-} (Fabry *et al.*, 2008).

Many shell-forming marine organisms including corals, bivalves (such as oysters, clams and mussels), pteropods (free-swimming snails) and certain phytoplankton species, are very sensitive to changes in pH and carbonate chemistry. Among these calcifying groups of organisms, phytoplanktons are at the base of the food chain and any disruption of their activities is bound to influence other levels in the complex food webs in the sea. Not only will the shelled organisms be affected, but the acidification will have general effects on marine life. In fish and other marine animals that do not possess shells, the lowered pH will cause acidosis in the body or accumulation of carbonic acid in body fluids. These processes can throw physiological homoeostasis in total disarray, with consequences as serious as immune suppression, decreased resistance against environmental variables, impaired oxygen transport, metabolic disorder, reproductive failure and increased vulnerability to pollutants. When the partial pressure of CO_2 increases and acidity prevails in the body, the ability of blood to transport oxygen declines and animals suffer from asphyxiation.

When exposed to change in pH and carbonate chemistry, marine organisms have to spend more energy in regulating the chemical process in their cells. This can put some animals in a situation where they are left with little energy for other physiological activities related to growth, breeding and dealing with stress.

Shells require a continuous supply of carbonate ions, failing which they become weak. Furthermore, the acidification of water tends to dissolve the calcium carbonate shells. Calcium carbonate ($CaCO_3$) shells are, therefore, not just difficult to form and maintain due to insufficient supply of carbonate but are also vulnerable to the eroding effect of acidity.

In those areas of the ocean where marine animal populations are high, the seawater gets saturated with $CaCO_3$. This provides adequate raw material for the shells. Ocean acidification that decreases this carbonate saturation interferes with the calcifying activity in the shelled organisms.

Currently, the atmospheric concentration of CO_2 as reported by the National Oceanographic and Atmospheric Administration (NOAA) is close to 400 ppm compared to its value of 250–275 ppm in 1850; this has happened in just over one century and a half (Pinet, 2009) and is evidently caused by release of 375 billion tonnes of carbon into the atmosphere since 1750. Half of this enormous quantity has been absorbed by carbon sinks in the form of oceans and forests. According to the Intergovernmental Panel on Climate Change (IPCC), the concentration of atmospheric CO_2 will be in the range of 450–550 ppm by middle of the twentyfirst century (2050). If that happens, many marine organisms will not be able to form $CaCO_3$ shells or exoskeletons (Pinet, 2009). Gattuso *et al.* (2009) have also determined that when CO_2 concentration reaches 500 ppm, it will significantly elevate the acidity of sea water and reduce the CO_3^{2-} ions, resulting in decline in the carbonate saturation of seawater (Raven *et al.*, 2005) to the extent of causing drop in calcification rates by 15–35% and, in some cases, even by 60%.

If ocean acidity more than doubles by 2050, this rate of acidification will be 100 times faster than the changes that occurred in the past 20 million years and will probably cross the ocean's capacity to restore pH and carbonate chemistry. It is unlikely that most of the marine species will be able to adapt to this rapid change. Since oceans have never undergone acidification at this rapid rate, there are no recorded effects of such a change in the chemistry of seawater on marine life but logical consequences can be understood and anticipated. It is a relatively new field of study and, therefore, more research is needed to examine the effects of ocean acidification on marine organisms and ecosystem dynamics, and socioeconomic implications for empirical data. Evidences gathered from different parts of the world indicate that the rising sea surface temperatures and bleaching coupled with acidification are affecting coral reefs. Even in the marine park area housing the Great Barrier Reefs, decline in coral calcification is raising concerns about the irreversible changes in the marine ecosystem (UN-DESA, 2009).

The biological effects of acidification of seawater will not be similar on all organisms because of differences in the range of their sensitivities to changes in seawater chemistry. The long-term decline in pH could go beyond the tolerance limits of marine species living in coastal waters despite the fact that they may have evolved adaptations or strategies to pH fluctuations on short timescales, which normally happen in coastal waters on a daily basis, and the range of fluctuations could be greater than in the open sea. However, these fluctuations are fast; the effect of pH decline with the acidification process is over an extended period of time and the marine animals are permanently exposed to low pH seawater.

Data have been published on the general effects of acidification, warming of seawater and hypoxia on marine organisms (Seibel and Walsh, 2001, 2003; Raven *et al.*, 2005; Kleypas *et al.*, 2006; Turley *et al.*, 2007; Portner and Farrel, 2008; Feely *et al.*, 2009; Fossa *et al.*, 2009; Gattuso *et al.*, 2009; Manzello and Kleypas, 2009; Parker *et al.*, 2009; Portner, 2009; Mustafa, 2010). The findings suggest several effects on marine life: disturbance of homoeostasis in the body such as by alteration in acid-base balance, impairment of growth, neural functions, blood gas transport, diminished calcification, dissolution of exoskeleton components (calcareous shells), coral bleaching, loss of Zooxanthellae from reef-associated organisms such as giant clams leading to their food deprivation and death, increased sensitivity of marine organisms to water pollutants and hence decline in their resilience, increase in frequency and duration of harmful algal blooms, mass mortalities of endemic and native species and their replacement with alien species, changes in seasonal succession, sex ratio, and feeding and spawning behaviour, alteration in the inter-species interactions, geographical shifts in some species and decline in organic production and fisheries. Mustafa *et al.* (2013) conducted a unique experiment wherein the authors simulated an ocean acidification scenario for exposing the pure stock of tiger grouper and tiger grouper x giant grouper hybrids. The CO_2 was exogenously introduced to bring about change in the carbonate chemistry and reduce the pH of the seawater. While this condition affected both the stocks in terms of their growth and condition, the hybrids exhibited a better resilience.

More specific data on the response of ocean acidification on marine fauna are summarized in Table 1.4.

1.2.3 Impact of aquaculture on climate change

Aquaculture produces 63.6 million tonnes of fish annually and certainly an activity of this scale will have an impact on the environment. Exploiting prey fish for feeding captive stocks and processing them into meal for feed pellets have an impact on the environment (Naylor *et al.*, 1998, 2000).

Clearing of mangroves for shrimp pond construction, for example, not only removes a carbon-sequestration source but the sediment where mangroves once stood emits greenhouse gases.

Table 1.4 Response of aquatic species to decline in pH.

Species	pH	Response	References
Mollusca			
Haliotisd laevigata (Greenlip abalone)	7.78, 7.39	5% and 50% growth reduction	Harris *et al.* (1999)
H. rubra (Blacklip abalone	7.93, 7.37	5% and 50% growth reduction	Harris *et al.* (1999)
Mytilus edulis (Mussel)	7.1	Dissolution of shell	Lindinger *et al.* (1984)
Mytilus gallprovincialis (Mediterranean mussel)	7.3	Reduction in metabolism and growth rate	Michaelidis *et al.* (2005)
Placopecten magellanicus (Giant scallop)	<8.0	Decrease in fertilization rate and embryonic development	Desrosiers *et al.* (1996)
Pinctada fucada (Japanese pearl oyster)	7.7	Dissolution of shell and reduction in growth	Knutzen (1981)
Arthropoda			
Euphausia pacifica (Krill)	<7.6	Mortality increased with increasing duration of exposure and declining pH	Yamada and Ikeda (1999)
Chaetognatha			
Sagitta elegans (Chetognath)	<7.6	Mortality increased with increasing the duration of exposure and decreasing pH	Yamada and Ikeda (1999)
Echinodermata			
Strongylocentrotus purpuratus and *Psammechinus miliaris* (Sea urchins)	6.2–7.3	Increase in sensitivity and dissolution of shell during immersion	Burnett *et al.* (2002)
Cystechinus sp. (Deep sea urchin)	7.8	80% mortality under simulated CO_2 sequestration	Barry *et al.* (2002)
Fish			
Scyliorhinus canicula (Dogfish)	7.7	Increase in ventilation rate	Truchot (1987)
Sparus auratus (Mediterranean seabream)	7.3	Reduction in metabolic capacity	Michaelidis *et al.* (2007)
Dicentrarchus labrax (Seabass)	7.25	Decline in food intake	Cecchini *et al.* (2001)
Epinephelus fuscoguttatus (Tiger grouper)	7.4	Decline in growth and 1% mortality in 2-week exposure	Mustafa *et al.* (2013)

Aquaculture has long been known to produce some environmental consequences mainly related to its effluents (Gowen and Bradbury, 1987). The magnitude of effect is variable, depending on the site; it is small in deep waters but measurable in shallow, confined and eutrophic areas (Muller-Haeckel, 1986; Iwama, 1991). Although water movement and flushing take place in the sea, in semi-enclosed coastal bays or shallow inshore areas the flushing is insufficient to remove organic waste (unused feed and faecal matter) from below the culture sites. These materials settle at the bottom, thereby affecting the benthic fauna (Wildish *et al*., 1993) by way of anoxic conditions (Holmer and Kristensen, 1996).

When the quantity of organic matter in the benthic sediment beneath the culture system increases, the outgassing of hydrogen sulfide, ammonia and methane that occurs due to decomposition of organic matter (Hargrave *et al*., 1993; Phillips, 2010) contributes to climate change. This problem can be addressed by organizing the culture in areas where adequate flushing occurs and which are not prone to eutrophication.

Selection of species is also important. Species which have low protein demand and high food conversion efficiency will be more compatible with the environment. Their uneaten food and waste will not be as much of a problem as those of carnivorous species.

Construction of culture facilities and manufacture of commercial feeds involve processes that contribute to the carbon footprint of aquaculture. Ways and means have to be found using environment-friendly products and processes for developing culture systems and for preparing feeds. Rossita *et al*. (2008a, 2008b, 2010) have developed some eco-friendly feed formulations for groupers to address this problem.

Aquaculture uses energy in its various operations which originate from sources which contribute to carbon footprint on the environment.

1.2.4 Adaptation to climate change

Because climate change cannot be reversed but can be slowed down, adaptation is the way forward to reduce its adverse effects. Methods of aquaculture are quite diversified and climate change is likely to affect them differently. Aquaculture carried out in land-based facilities and under more controlled conditions will be less affected compared to systems of farming, such as cage culture and pen culture, where grow-out is done in the sea. Whatever the farming systems, it is amply clear that there is a need for aquaculture to change course to help adapt to climate change effects. Adaptability of aquaculture is a key to its sustainability.

A plan of action for adaptation should give priority to the following suggestions:

- **Design of facilities and selection of areas.** Climate change is associated with rough sea conditions, which affect the facilities used for farming, such as cages. Cage design and strength that can better withstand these conditions offer solutions to this problem. Based on the expected forces of currents, winds and waves, the required strength of cage materials can be calculated following the criteria suggested by Milne (1972), Fridman (1986), Carson (1988) and Beveridge (1996). Also, selecting areas not likely to be subjected to extreme events linked to climate change, and avoiding zones of upwelling and those prone to harmful algal blooms and jellyfish aggregation, will be helpful.

- **Restoring connectivity of marine critical habitats and building resilience in the ecosystem.** For coastal aquaculture in tropical countries protection and restoration of marine critical habitats (mangroves, seagrasses and coral reefs) will create a better environment for culture. Oceans serve as the largest carbon sink on Earth. The absorption of CO_2 by oceans (coastal ecosystems such as mangroves and seagrasses) in the form of 'blue carbon' equals that stored by land resources (forests) in the form of 'green carbon' (Bender *et al.*, 2002). Although the mangroves and seagrasses make up only a small proportion of the vast ocean, their capacity to store carbon is remarkable. According to Conservation International (CI, 2009), mangroves and seagrasses can store blue carbon in quantities up to five times greater than the tropical forests. It is worth mentioning that the capacity of both these coastal ecosystems is measured not only in terms of the amount of carbon they sequester in their tissues but also in the sediment just beneath them. It makes sense to give attention to such biological resources where management actions can produce quick results.

  Degradation or destruction of mangroves and seagrasses not only eliminates a major carbon sequestration process but also turns these long-term natural sinks of greenhouse gases into a major source of these very gases.

  In addition to carbon sequestration the blue carbon resources also contribute to preserving marine biodiversity, ecological connectivity, survival and recruitment of many species of marine fauna, fisheries, food security of coastal communities and coastal protection from erosion. These habitats not only create better grow-out conditions for cage culture or other forms of marine aquaculture carried out in the sea but also for land-based aquaculture, including hatchery operations that require sea water intake or security from rough sea conditions.
- **Preserving biodiversity.** The culture site, if located in an area with intact biodiversity links, is likely to be more productive. It is still not known how the species diversity outside the cage will influence the fish inside the cage. Of course, mangroves and seagrasses create a better water quality by filtering the waste arising from land-based activities (Figure 1.2), and coral reefs break the impact of rough sea conditions, thereby minimizing the stress on captive stocks. It is not known if there are cues originating from marine life outside the cage that influence the fish inside the cage but it could be a possibility that needs investigation.

Figure 1.2 Cage culture near a mangrove forest in a sheltered coastal bay on the west coast of Sabah, Malaysia. *(See insert for colour representation of the figure.)*

- **Use of prey fish substitutes in feeding.** A major issue concerning the development of aquaculture is its reliance on fish meal and fish oil. Growth of aquaculture since the late 1970s has averaged 8% per year (FAO, 2010) and this has made increasing demands on prey fish. Even now, prey fish caught from the wild remain by far the most abundant aquafeed in the aquaculture industry (Figure 1.3). Carnivorous fish used in aquaculture consume more fish than their own biomass production. The 'Fish In Fish Out ratio' (FIFO), which Merino *et al.* (2012) defined as an indicator of the efficiency with which aquaculture converts a weight-equivalent unit of wild fish into a unit of cultured fish, appears to be an accurate measure of fish (prey) consumption by food fish and food fish production in aquaculture. It has been determined that aquaculture converts 65% of the wild fish reduced into fishmeal at a FIFO ratio of 0.66 (Jackson, 2009) and 0.7 (Tacon and Metian, 2008).

  Aquafeeds are widely used for feeding omnivorous species (for example, tilapia, catfish, common carp and milkfish), carnivorous fish (groupers, sea bass, snapper, sea bream and tuna) and crustaceans (shrimps, crabs and lobsters). In 2008, about 31.7 million tonnes (46.1% of total global aquaculture production) of fish and crustaceans were feed-dependent and this fed-aquaculture (that uses aquafeeds in contrast to the farming of filter-feeding invertebrates and aquatic plants, which relies entirely on natural productivity) contributed 81.2% of global

Figure 1.3 Prey fish widely used as feed in aquaculture.

farmed fish and crustacean of 38.8 million tonnes and 60.0 % of global farmed aquatic animal production (FAO, 2012). According to this report, in the same year (2008) aquafeeds formed 29.2 million tonnes (4.1% of all animal feeds) of 708 million tonnes of industrial compound animal feed globally.

The prey fish also support the natural predator populations in the sea that constitute the capture fisheries, and the increasing use of fish meal in aquaculture will affect the sustainability of commercial fishing (Merino *et al.*, 2012). This is bound to have adverse implications for aquaculture production. If aquaculture is to lessen pressure on wild fisheries, it should follow a strategy that does not deplete the prey fish and biodiversity links. If it fails to do that, the net result will be decline in landings from capture fisheries as well as aquaculture. Merino *et al.* (2012) have warned of a possible ‘Ecological Collapse’ scenario if corrective measures are not urgently put in practice. They have emphasized the need for alternative protein sources, use of low food chain species and review of fisheries management aimed at protecting the web of life in the sea that supports commercial fish populations with effective policies. In this connection, the suggested use of by-products or fish waste to produce fishmeal (FAO, 2007) and microalgae to produce aquafeed (Becker, 2007) is very relevant.

From the point of view of food security (when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life), producers in Asian countries, particularly China, India, Vietnam, Indonesia and Bangladesh, have benefitted from the culture of low trophic-level species (for example, carps, barbs, tilapia). Farming of these species eased our dependence on high-protein feeds and, because of this, reduced the vulnerability to externalities (FAO, 2012). An interesting case is that of grass carp, which consumes mostly aquatic vegetation that grows inside the farm or is supplied from outside, instead of depending on formulated feeds only.

Culture of carnivorous fish is criticized for ecological reasons because they feed in higher levels of the food chain and require prey fish. However, a novel method was developed for producing highly carnivorous Mandarin fish (*Siniperca chuatsi*) on low trophic-level carp fingerlings, which are grown with low protein feeds and pond fertilization (FAO, 2012).

Aquaculture offers enormous opportunities for innovation which are worth trying. If cost effective and economically viable prey fish substitutes evolve for coral reef fish widely used in farming, such as in the feeding system for Mandarin fish, it will help transform the image of aquaculture of high value finfish as ecologically responsible.

- **Developing integrated multitrophic aquaculture modules.** In such culture modules, fed organisms are combined with culture of organisms such as seaweeds that extract the dissolved inorganic nutrients or organisms such as shellfish that extract particulate organic matter (Choplin *et al.*, 2001). This sort of integration allows the basic biological and chemical processes to balance each other while ensuring growth of the desired organisms in the system.
- **Reducing stress by good aquaculture practices.** Captivity puts stress on the animals. While it is not possible to eliminate all sorts of factors that create stress, a farming system should try to reduce it to a minimum. Good aquaculture practices can achieve stress reduction. Maintaining quality of water, with temperature, salinity and pH within tolerance levels, suitable concentrations of dissolved gases and controlling pollution are important considerations. For culture directly into the sea, the physical and biological factors also need to be taken into account. Stress reduction strengthens the ability of animals to resist environmental variations, including the effects of climate change.
- **Selection of climate hardy species.** Selection of fish species for culture is based on their biological features, behaviour, amenability to a captive environment and market value. A confined environment does not provide enough grazing ground for planktivorous and filter-feeding fish, which are, therefore, not stocked in sea cages. Fish that live in shoals, move fast and swim over long distances are also not suitable for a life in captivity. Species that do not fetch a good price and do not grow to large size, and cost as much as a high value species in seed production and grow-out, do not make a profitable economic choice for culture. In a changing climate, we need to find new candidate species for trials. Those traditionally used in culture, because of demand and high value might not be adaptable enough to sustain production in a changing environment. Certain species, for

example cobia (*Rachycentron canadum*), that are environmentally resilient and economically important seem to be suitable for cage culture. Culture of grouper hybrids has already started but potential environmental effects need to be examined in case there is any release of the fish from the cages into the natural ecosystem.

To be able to face the challenges of the twenty-first century, aquaculture needs a fundamental transition from management that is based entirely on maximizing the production of target species to integrated management of natural resources and ecosystems (Pullin *et al*., 2007). The elements of sustainability should be deeply embedded in the objectives and practices. Integrated management is an important dimension in the sustainable development of aquaculture. If aquaculture is to contribute to seafood security, it has to be affordable, and thus economically feasible. Economic sustainability ultimately depends on how effectively we are able to blend the biological, ecological and intersectorial considerations (Pullin *et al*., 2007). Important biological considerations are growth, condition, feed and trophic levels. The ecological considerations comprise mainly the ecological footprint (the ecosystem area that is functionally required to support an aquaculture system), effluents, escape of captive stocks and interaction of hatchery stocks with their wild counterparts. The intersectorial considerations basically relate to sharing of water resources in aquaculture with other sectors, diversity of produce, services and livelihood opportunities, cycling of by-products among sectors, stability to cope with change and the capacity of the system to support product quality, services and environmental mitigation.

A forward-looking approach to aquaculture development is learning from the past while looking ahead with problem solving, innovative and progressive ideas and plans. This is the essence of sustainability of aquaculture in the twenty-first century. Comprehensive approaches that take into consideration scientific perspectives, environmental standards and socioeconomic needs will be more resilient and beneficial for growth of the aquaculture industry (Bert, 2007).

Use of technology without environmental or ecological considerations will not be able to achieve the aquaculture production targets. The future of aquaculture as a means of dependable, responsible and sustainable production of high quality animal protein lies in green technology and perspectives integrated with essential ecological processes. Learning from nature and creating, as far as possible, conditions resembling natural processes hold prospects for successful aquaculture development.

1.3 Biotechnology intervention

Due to rapidly growing interest in application of biotechnology, this topic needs to be addressed in this chapter. Undoubtedly, aquatic genetic resources are facing growing pressures of overexploitation, habitat degradation, alien species and the effects of climate change. As a result, the future scenario of capture fisheries is not promising and aquaculture is the way forward. Biotechnology is emerging as a tool to stimulate production. The term aquatic genetic resources includes DNA, genes, gametes, populations and species of natural as well as genetically altered forms (selectively bred stocks, hybrids, polyploids and transgenic forms). Biotechnology offers tools to achieve different outcomes, especially conservation of natural fish populations even without manipulating their genotypes or changing their biological attributes and increasing production in aquaculture. There is a growing variety of biotechnology tools that, according to their purpose and relevance, have been used in conserving wild stocks, increasing aquaculture production and improving yield from capture fisheries. Some of the tools have proved effective in enhancing growth, immunity, environmental resistance and health of captive stocks, artificial feed formulation, sex control, improving fertility, inducing breeding, gamete preservation, line crossing, stock improvement, implementing biodynamic and integrated production modules and bioremediation of water quality. Other biotechnology tools use knowledge of molecular biology and genetics, especially genomics, for genetic marking and marker-assisted selection, immunization, diagnostics of diseases and genetic engineering. Genetic biotechnology methods ranging from hybridization to gene transfer are applied to develop required qualities in economically important species of fish. Fish have received far more attention than invertebrates of commercial importance as far as genetic studies are concerned.

Application of genetic information deserves special importance for sustainable management of aquaculture. Populations and stocks of exploited species are subjected to pressures of different types and magnitudes. Management frameworks and methods have to be adapted to deal with the specific conditions of the exploited stocks. While factors such as overexploitation and habitat degradation are generally considered in fisheries, the problem of inbreeding depression, water quality impairment, nutritional imbalance and health are topics of core concern in aquaculture.

In tropical countries, fish landings are from typically mixed fisheries and attention is given to total catch and catch composition. Generally, the factors recorded at species level are sex and size in addition to seasonal pattern of abundance. Beyond the species level, topics such as stock composition or genetic diversity are pursued in research but the results are not used for legislative purposes. Also, fisheries statistics do not relate species diversity to ecosystem diversity in the official formats for data presentation. Nonetheless, analysis of fish diversity at gene level in certain aquatic species has received interest in recent years. A growing number of publications bear witness to increasing interest in bar coding, stock structure and gene flow in aquatic animals. Genetic information on some species used in aquaculture is also available, thanks to the familiarity of researchers with the molecular techniques and investment in the required infrastructure. Stocks of some species have been genetically characterized. Working on genetic variations using the mitochondrial cytochrome b gene in Asian sea bass (*Lates calcarifer*), Norfatimah *et al.* (2009) reported high intrapopulation relatedness for a few populations but considerable heterogeneity among others, indicating a low gene flow. This calls for specific methods for conservation of wild genotypes and fisheries management, and use of natural broodstock in hatchery production. Manjaji-Matsumoto and Rodrigues (2010) studied the DNA profile of 10 species from six families (Haemulidae, Labridae, Lethrinidae, Nemipteridae, Pseudochromidae and Serranidae) of coral reef fish from the Sulu Sea. The aim of their study was to develop molecular markers to characterize stocks of these species of fish for conservation purposes.

The air-breathing catfish, *Clarias macrocephalus*, which supports freshwater capture fisheries and is widely exploited in aquaculture, was the subject of study by Nazia *et al.* (2010). Mitochondrial DNA sequencing carried out by these authors revealed that no significant genetic differentiation existed in the geographically isolated populations. However, the presence of several private haplotypes suggested local adaptation that these populations have developed by independent evolution. The authors have recommended separate management of these population units and maintaining the genetic integrity of each of them, avoiding artificial admixture that often happens in the hatcheries. In an earlier investigation on genetic structure of grouper (*Epinephelus tauvina*), Ransangan *et al.* (1999) identified the northern part of Sabah where the South China Sea joins the Sulu Sea as the corridor for gene flow along the two coasts and discussed the exploitation pressure and habitat degradation as the two important factors that can disrupt this natural genotype mixing with consequent change in genetic structure of the population units. Broodstock sourced from the wild population for captive breeding in the hatchery is, therefore, not in the best genetic form. In *Channa striatus*, an intensively exploited freshwater species of murrel, the geographical separation by physical barriers to gene flow has resulted in establishment of distinct evolutionary units in the two separate regions that were the focus of a study by Jamaluddin *et al.* (2011). The authors were of the view that habitat degeneration and fragmentation with a potential of disrupting the population connectivity with the genetically segregated stocks will cause loss of genetic diversity and inbreeding depression. In aquaculture, the founder effect from a genetically eroded broodstock will lead to heavy mortality of fry, low resistance to disease and environmental variability, and poor growth.

As far as endangered fish species are concerned, the focus of research is on *Cheilinus undulatus*, commonly known as humphead wrasse, giant wrasse, Napoleon wrasse or Maori wrasse. It is the largest member of the wrasse family (Labridae, order Perciformes). The fish is classified as Endangered on the International Union for Conservation of Nature (IUCN) Red List and is included in the Appendix II of CITES (Convention on International Trade in Endangered Species of Wild Fauna and Flora). This fish is extremely vulnerable to overexploitation due to its large size, slow growth, late maturity, protogynous hermaphrodite condition, tendency to aggregate at spawning time in large numbers towards the outer side of reef, and high market value in the live reef fish trade. Recently, an attempt has been made to genetically characterize this fish. Manjaji-Matsumoto *et al.* (2011) analysed the cytochrome oxidase subunit 1 gene sequence in the mtDNA of the wrasse samples from northern and eastern coastal waters of Sabah. Results showed high (99.7–100%) nucleotide identity, suggesting that the stocks have originated from the same or closely related maternal spawners. The authors linked it to relatively short distance and physical interconnectivity of the two regions where numerous coral reef patches served as 'stop-over' points for this reef fish.

Despite growing interest and availability of published information on genetic composition of native fish fauna, these data are not widely used in management of wild fisheries. In the case of aquaculture, the application of biotechnology is limited to certain farming methods. Because fisheries and aquaculture are largely driven by the private sector, there is a gap between the perspectives of scholars who suggest scientific approaches to selective breeding and the farmers who work in the field and find scientific prescriptions difficult to apply. Generally, hatcheries continue to use the same broodstock of fish for seed production as long as they survive and remain fertile. While there is an interest in closing the breeding cycle in the hatchery and reducing the inbreeding, raising the hatchery-produced generation to the broodstock stage faces some problems, especially in species which take long time to mature. For marine fish such as groupers, which attain maturity in about five years or more, the time, cost and space constrain the rearing of a large stock of F1 generation to reach the maturity stage. Due to the short life span of shrimp, the wild caught stocks are induced to breed for no more than two years before intake of the new stock for seed production.

The sustainability of aquaculture industry is constrained by inadequate supply of high quality seed of the required species at the required time and poor rate of production. To overcome these problems and, especially, to address the needs for sustainable seed production, various tools of biotechnology are used. Recent developments in the area of genomics have provided means for identifying fish genetic resources not only for conservation of wild populations but also for sustainable and biosecure aquaculture production. Marker-assisted selection for genetic improvement of farmed fish, and diagnosis and prevention of fish diseases for production of specific pathogen-free fry, are examples of the application of biotechnology tools in aquaculture. A recent notable contribution to this area is that of Ransangan and Mustafa (2009). Interest in genomic information for aquaculture gained interest due to heavy mortality, even in fish stocks that were free of infection at the time of stocking. Since the 1980s, the genetic basis of poor performance has received more serious attention. Daud *et al.* (1989) noticed a lack of genetic variability in samples of different populations of catfish, *Clarias macrocephalus*, in Malaysia and linked it to founder effect and genetic drift. They also found low intraspecific genetic variability in the hatchery stock of *C. batrachus*. These findings pointed to the need for introducing genetic analysis in the broodstock management and captive breeding practices.

Hybridization of high value species of groupers is also carried out in the hope of getting some positive attributes of hybrid vigour (or heterosis), such as faster growth, lower food conversion ratio, higher resistance to environment and diseases, and greater tolerance to high density stocking, in addition to addressing the shortage of broodstock of individual species in the hatcheries. The groupers selected for crossing were: *Epinephelus lanceolatus* (giant grouper) x *E. fuscoguttatus* (tiger grouper), *E. coioides* (orange-spotted grouper) x *E. fuscoguttatus*, *E. coioides* (organge-spotted grouper) x *E. lanceolatus*, and *Cromileptes altevellis* (mouse grouper) x *E. fuscoguttatus* (Senoo, 2010). The F1 hybrids (Figure 1.4) of *E. fuscoguttatus* (Figure 1.5) and *E. lanceolatus* (Figure 1.6) were genetically characterized using nuclear and mtDNA markers (Zin *et al.*, 2011). This provided data for construction of a genomic DNA library, followed by sequencing of individual inserts and designing of locus-specific primers. The outcome of this study has

Figure 1.4 Tiger grouper x giant grouper hybrid.

Figure 1.5 Tiger grouper.

Figure 1.6 Giant grouper.

implications for determination of clonal identity and mapping of quantitative loci in the F1 hybrids. If F1 hybrids happen to be fertile, repeated back-crossing with the giant grouper will probably impart more desirable growth qualities. Since these species normally mature when about 5–6 years of age, the work requires patience to measure the outcomes of the breeding trials.

Gene transfer in fish and shellfish for commercial aquaculture is not currently practiced. However, with the successful production of genetically engineered salmon, interest might catch up in large-scale production of this species and also other species. Recently, Atlantic salmon eggs were engineered to contain a growth hormone gene from Chinook salmon, which provided the fish with the potential to reach market size in a much shorter time. The genetically modified specimens of the salmon are all female and sterile. They are allowed to be grown in physically contained systems at approved facilities for reasons of environmental protection. However, when application of genetic engineering becomes widespread, it is unlikely that the enforcement will be adequate enough to prevent escape of transgenic fish to the wild environment. The implications for marine ecosystem, especially biodiversity and wild populations could be serious. World opinion is divided when it comes to farming of genetically modified organisms. Undoubtedly, building resilience in aquatic ecosystems is crucial to deal with climate change effects and this should remain a pillar of our adaptation measures. Widespread production and use of genetically modified organisms will definitely lead to their escape to the natural habitats and that will pose a threat to biodiversity, even though we benefit from higher production through their culture in controlled systems. It might also impede progress towards efforts aimed at fortifying natural systems because the quick production benefits from genetic manipulation might make this an attractive tool for the industry. Those in favour believe that climate change is a game changer, as evident from the dramatic challenges originating from climate variability that might confront the farmers. Transgenic animals are new potential candidates, unlike genetically modified plants, which are commercially farmed for the reasons that they are high yielding, resistant to pests and diseases and have the ability to tolerate extreme variations in environmental conditions such as heat and drought. I suggest that instead of letting biotechnology and genetically modified organisms address all sorts of challenges facing aquaculture for meeting the production targets, serious attention should be given to environmentally safe and sustainable means of increasing production. This is not to suggest banning the use of biotechnology in aquaculture, but a comprehensive study of its feasibility while promoting research and development in methods of aquaculture that also hold immense potential and are free from controversies. Worth mentioning in this connection are culture conditions that reduce stress on fish, yield multiple species harvests and require little or no material inputs. This opens up the opportunities for developing ecological aquaculture.

Given the growing interest in aquaculture by the industry and the fact that the environmental situation is worsening, I believe we need to keep our doors open to biotechnology intervention. Having said that, I must emphasize that gene transfer is one of many biotechnological procedures. There are biotechnologies that are environmentally compatible and with innovative efforts there could be good results attained which match those likely to be produced by farming of transgenic fish and yet are free from the controversies and risks that are thought to be associated with genetically modified organisms. Funding agencies, research institutions and industry have to prioritize this sort of research to be able to achieve a breakthrough in ecological aquaculture. As far as research on genome manipulation is concerned, it is continuing and probably will continue. However, better safeguard mechanisms and risk management methods should be given serious attention in case aquatic genetically modified organism farming starts and environmental stability comes under threat as a consequence of it.

Observations made by Senoo (2010) suggested that hybrids of giant grouper and tiger grouper could be more resistant to environmental variations compared to parent stock, apparently due to heterosis. Culture of grouper hybrids has gained popularity in south-east Asia. Using such hybrids would then be an adaptive strategy of aquaculture for dealing with climate change but questions that have to be addressed pertain to the risk they will pose to the environment in case of release, especially biodiversity and impact on the native species which have been part of the ecosystem, and the ecological links that sustain organic productivity. The hybrids are not transgenic. They contain genomes of the parent stocks selected for cross-breeding without any alteration. Even in such cases, there are concerns that require scientific attention.

Of all the factors, selection of species is crucially important. Species that are environmentally resilient, fast growing, have high food conversion efficiency, low protein and fat requirements, high fecundity and have high larval survival stand a better chance of coping with the effects of climate change. Given their biological attributes, species which feed in lower levels of the food chain, such as sea cucumbers, will be able to face the climate change better than those species of predatory fish whose nutritional preferences involve complex ecological links to produce food that they consume. With decline in prey fish populations, it makes sense to select species for culture that can consume and make best use of pellet feed formulated to contain ingredients from sustainable sources and which are a good replacement for fish meal and oil.

1.4 Ecological fisheries–ecological aquaculture synergy

Recent years have witnessed the emergence of models of aquaculture ecosystems which combine many species of fish, shellfish and seaweeds or other plants with nitrifying bacteria playing a synergistic role in bioremediation of water quality. The complexity of this type of aquaculture system, unlike monoculture, resembles the natural ecosystem to some extent. In fact, it is a newly emerging topic referred to as 'Integrated Multitrophic Aquaculture' (IMTA). In this system, as explained by Choplin *et al.* (2001), the waste from one aquatic species serves as inputs (fertilizer, food) for another species (Figure 1.7). Through proper planning, the system combines fed aquaculture (for fish, shrimp) with seaweed or other plants that act as inorganic extractives as well as shellfish, which are organic extractives, to achieve a balanced system for bioremediation, economic

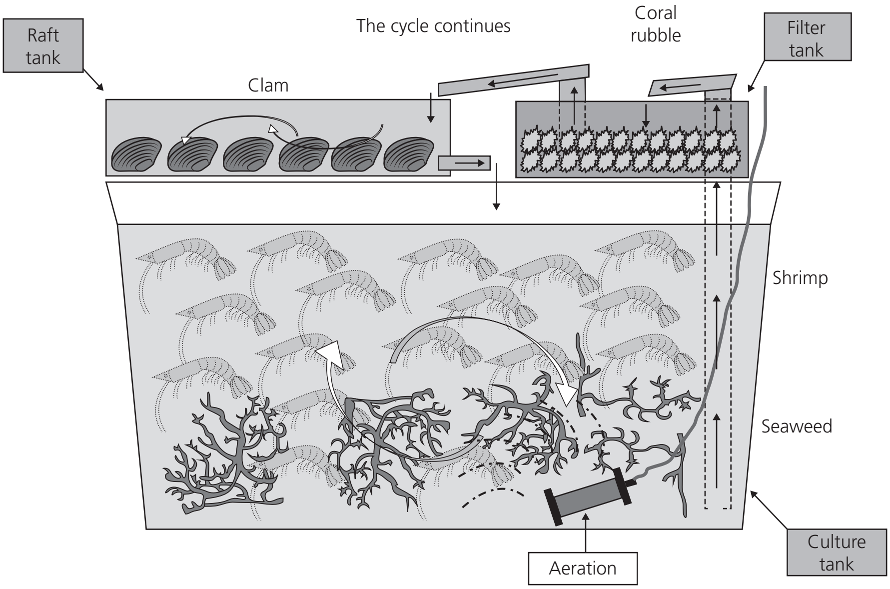

Figure 1.7 A conceptualized model of multitrophic aquaculture system. *(See insert for colour representation of the figure.)*

feasibility (lower cost, product diversification, risk reduction, improved output) and social acceptability (good management practices, quality control).

Introducing ecological perspectives to aquaculture and combining them with the social and biophysical dimensions can be appropriately termed: Ecosystem Approach to Aquaculture Management (EAAM). It is a strategy for the integration of the activity within the wider ecosystem such that it promotes sustainable development, equity and resilience of interlinked social-ecological systems (FAO, 2010). The FAO (2010) has suggested a policy framework under which the most appropriate strategy could develop through the following steps:

- Scoping and definition of ecosystem boundaries and stakeholder identification.
- Identification of the main issues.
- Prioritization of the issues.
- Definition of operational objectives.
- Elaboration of an implementation plan.
- Corresponding implementation process, which includes reinforcing, monitoring and evaluation.
- A long-term policy review.

I agree with Costa-Pierce (2002) that ecological aquaculture is an integral part of our common planetary wisdom and should be considered as an essential element for our harmonious living with the complex ecosystems of the Earth.

Although, in some ways, it amounts to going back to basics, it is not a retrogressive approach. It is a progressive step that combines the time-tested and traditional practices with modern developments in green technology to attain the aims that neither the traditional methods nor technology alone could achieve. It is a knowledge-based development that will progress with intensive and highly focused research on topics that are important to it,, such as: efficiency of water recirculation, nutrient dynamics, reducing the residence time of ammonia and nitrite, rapid nitrate assimilation, innovative surfaces for concentrating nitrifying bacteria, low or zero carbon footprint and compatible species combinations and their stocking biomass. In a multispecies pond culture, it is not difficult to find species that differ in their nutritional and space requirements but which can be stocked together for a more efficient production from a water body.

Aquaculture has an inherent environment-friendly attribute due to the metabolic systems of aquatic animals which, unlike ruminant livestock (cattle, buffalo, sheet and goat), do not produce methane in the course of digestion. It is the decomposition of organic matter below the cage that causes emissions of greenhouse gases. Suitable culture systems can address this problem.

With the environmental situation worsening, pressure on bioresources mounting due to rise in demand and new approaches to managing fisheries, such as the Ecosystem Approach to Fisheries Management (EAFM), still remaining in the discussion or planning stages, rather than in widespread implementation, ecological aquaculture must progress rapidly and be counted as a major, responsible and socially acceptable supplier of high quality seafood.

The purpose of EAFM as explained by the FAO (2003) is ‘to plan, develop and manage fisheries in a manner that addresses the multiplicity of societal needs and desires, without jeopardizing the options for future generations to benefit from a full range of goods and services provided by marine ecosystems’. A further elaboration that flows from the definition explains that EAFM strives to balance diverse societal objectives by taking into account the knowledge and uncertainties about biotic, abiotic and human components of ecosystems and their interactions, and applying an integrated approach to fisheries within ecologically meaningful boundaries.

Introducing ecological perspectives to fisheries and aquaculture also serves to bring unity in these two subjects. The interdependence of capture fisheries and aquaculture needs to be comprehensively examined in the interest of promoting sustainability in both these sectors of seafood production.

Ecological fisheries and ecological aquaculture should no longer be planned and managed as independent entities. They share common concerns, such as genetic diversity in hatchery-produced fish, sustainability of fish meal and oil (originating from capture fisheries but used in aquaculture), a common distribution system and the same marketplace and sustainability of marine ecosystem services (Figure 1.8). Of course, innovative approaches are needed to evolve new seafood production systems that do not segregate capture fisheries and aquaculture. Such production systems have to be adaptable to be able to respond to inevitable change in response to conditions linked to changing climate.

In conclusion, the aquaculture of the twenty-first century should change course. There is a need for it to embrace ecosystem perspectives while making full use of knowledge that has been generated over several decades of hard work in the area. Fisheries and aquaculture share many common concerns and it

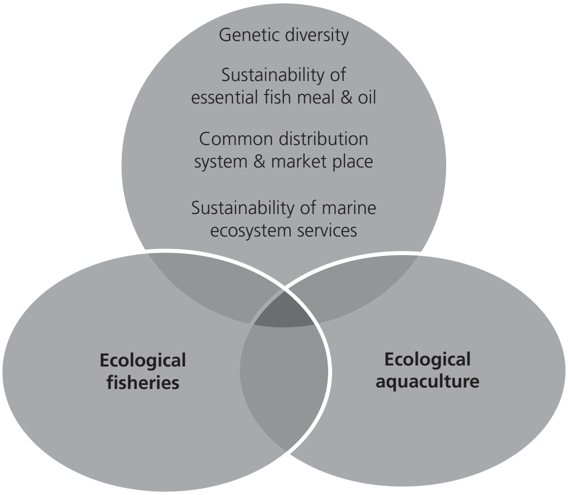

Figure 1.8 Issues of common concern to ecological fisheries and ecological aquaculture.

makes sense to foster synergy between the two in the interest of sustainable seafood supply. Climate change is a powerful factor that will affect seafood production. We need to develop strategies to manage its impact.

As a matter of fact, fisheries and coastal marine management regimes should incorporate aquaculture for sustainably managing fisheries of the future, either by increasing market supply of farmed seafood to lessen pressure on wild stocks or by stock enhancement or ranching. The disciplinary boundaries between capture fisheries and aquaculture are blurred by culture-based fisheries and stock enhanced fisheries. The former is supported by stocking of post-larvae, fry or fingerlings originating from aquaculture facilities (hatcheries and nurseries) while the latter requires supplementing the depleted wild stock by juveniles produced by aquaculture. FAO has defined culture-based fisheries as all activities aimed at supplementing or sustaining the recruitment of one or more aquatic species and raising the total production or the production of certain elements of a fishery beyond a level which is sustainable through natural processes. In this sense, culture-based fisheries include measures that may take the form of: introducing new species, stocking of natural and artificial water bodies, fertilization, environmental engineering (including habitat improvements and modification of water bodies), altering species composition (including elimination of undesirable species, or constitution of artificial fauna of selected species, and genetic modification of introduced species).

Culture-based fisheries consist of two phases – a farmed phase (hatchery, nursery) for the provision of stocking material, and a wild phase where the onward growth of the stocked fish depends on natural processes.

In sea ranching, a fishery can be supported by large-scale release of hatchery-produced stocks. The stocking (release of fish, usually as fry or juveniles) into a water body can continue in a harvest-type of sea ranching or be discontinued in a recruit-type of ranching when the released stocks have developed a breeding population that sustains the impact of fishing. Generally, the stocking material is obtained from aquaculture (hatchery produced) but, in some places, seed collected from the wild is stocked in different areas for improving the catch.

An interesting case is when wild specimens are transferred to the hatchery, developed into broodstock and at breeding time transferred back to the sea but maintained in sea cages, pens or enclosures to release their gametes directly into the sea, where they fertilize and grow to commercial size and support fishing operations. The broodstock can remain in captivity in these sea-based facilities (cages or pens) for subsequent spawning or transferred back to hatchery tanks for monitoring of health, nutritional status and fertility or to keep them safe from red tides, pollutants and other adverse environmental conditions in the sea. Although held captive and not enjoying the liberty of free movement over long distances, they can still get some ‘feel’ of the sea and this can be further enhanced for good outcomes from aquaculture. While in captivity, some natural ecosystem conditions can be simulated to meet the requirements of ecological aquaculture.

Culture-based fisheries do not require external inputs of feed or other supplies and infrastructure. This reduces the cost of production and market value of the produce. A problem could be that culture-based fishery is influenced by weather and climate change. They could be adversely affected by upwelling, rough hydrodynamic conditions and variations taking place in the sea as a result of climate change. Aquaculture in land-based facilities, compared to capture fisheries, is managed under somewhat controlled conditions, wherein stocked animals are not exposed as much to the vagaries of nature as fish in the ocean. Enhanced fisheries, unlike aquaculture, suffer from uncertainty in terms of returns; this, therefore, creates market volatility. This is unlike culture in ponds, pens and cages where the entire stock can be harvested.

Differences in technical definition between aquaculture and culture-based and enhanced fisheries fade when community-based arrangements or legal frameworks provide ownership rights to individuals or groups to monitor grow-out of the released stocks until harvesting. This is possible in limited areas but unlikely to happen on a vast scale in the sea, which provides open access to fishing operations.

A unique type of synergy between aquaculture and fisheries that holds great potential is restoration of endangered fish species. A typical case could be that of humphead (Napoleon) wrasse, *Cheilinus undulates* (Figure 1.9), which as a result of excessive exploitation has become locally extinct in many places where its populations once thrived. Due to biological attributes such as late maturity, visible presence that helps targeted hunting, its tendency to associate with coral reefs and the high market price, the excessive fishing pressure has depleted the population of this species to the extent that it had to be listed by the World Conservation Union (IUCN) in 1994 under Appendix II of CITES (Convention on International Trade in Endangered Species of Wild Fauna and Flora). Efforts are underway to grow the immature specimens of this species in the hatchery and if the captive breeding is successful, the juveniles will be tested for health and genetic diversity, and released into their natural habitats for replenishing the population. If population in the wild grows to the extent that it can absorb the fishing pressure, there will be justification to decide on regulated fishing. Should captive breeding and aquaculture grow to the extent of meeting the market demand that will lessen the pressure on wild stock.

Aquaculture and fisheries should not be viewed as having any sort of conflict with each other. Rather, they can complement each other if carried out in responsible ways. Ecological aquaculture benefits local economies by generating employment, providing business opportunities through marketing of seafood, feeds and seeds, and jobs in harvesting and downstream activities.

There is a convergence of the ultimate goal of fisheries and aquaculture, which is sustainable seafood production, despite their being diversified activities. They serve the same customers of seafood. I do not think any separate niche market exists for the two on a big scale. Differences in prices of the products

Figure 1.9 Humphead wrasse (Photo courtesy S. Senoo).

originating from capture fisheries and aquaculture could, however, be a factor that will matter in consumer choices. Soto *et al.* (2012) have also sought to explain a number of divergent as well as overlapping relationships between capture fisheries and aquaculture and also suggested the relevance of viewing a synergy between the two for sustainable food fish production.

Aquaculture has originated from fisheries. Fisheries continue to provide most of the broodstock used in hatcheries for captive breeding. Some hatcheries have closed cycle aquaculture, which does not require regular intake of wild broodstock. Aquaculture, by way of its hatchery technology, can reciprocate the contribution of fisheries by providing a healing touch to stressed wild populations by reseeding for stock restoration.

Fishing alone cannot meet the demand and aquaculture alone cannot meet the demand either, but the two together can serve as a more sustainable way of producing seafood (Bastien, 2003). The author considers fishing and aquaculture as part of a continuum, starting with capture fisheries and progressing to culture-based fisheries (stock enhancement), fisheries-based culture (catch and grow-out) and ending with full-cycle aquaculture.

Some possible developments which will have an impact on fish supply include the rate of climate change, biodiversity status, expansion of marine parks, efforts made toward building resilience in marine ecosystem, transformation of many of the contemporary aquaculture practices into good aquaculture practices and the extent to which the industry embraces ecological aquaculture. With focus on aquaculture and the dire situation facing seafood supply, we expect real efforts to be made towards transformation of aquaculture. This could happen in approach and technology, and institutionalization of major initiatives that act synergistically to improve production despite constraints.

The two recent approaches, namely EAFM and EAAM, have a common aim of moving away from management systems that focus only on harvest of target species to broader ecosystem benefits. The EAFM also considers the major components in an ecosystem, and the social and economic benefits that can be derived from their use. The EAAM seeks integration of the activity within the wider ecosystem, such that it promotes sustainable development, equity and resilience of interlinked social-ecological systems (FAO, 2010). At this stage, it is appropriate to explain the focus of Rio+20 on 'Green economy in a blue world'. The evolution of ecological aquaculture and ecological fisheries seems to have given a new meaning to what has been termed as the 'blue revolution'. It should be able to define the environmental compatibility, sustainability and ecological synergism, not just be limited to increasing yield while ignoring the factors that sustain it. It is obviously a departure from the past and received a good deal of attention at Rio+20 in the context of green economy in a blue world. The IUCN refers to the green economy as a resilient ecosystem that provides a better quality of life for all within the ecological limits of our planet. Ecological fisheries and ecological aquaculture fit pretty well into this environmentally-oriented economic perspective. Due to vastness of oceans and the unprecedented interest that they received at Rio+20, the term 'blue economy' came into prominence. It was an acknowledgement of the vastness of oceans and what they do for our planet. Humans depend on the oceans and on resources and services they provide, namely climate regulation, food, medicines, recreation, transport and economy. Specifically, the concept of the blue economy is guided by certain principles, the main ones, as explained by the IUCN, being:

- Substitute something with nothing.
- Natural systems cascade nutrients, matter and energy – waste does not exist and any by-product is the source for a new product.
- Nature provides room for entrepreneurs who do more with less.

The dependence of fisheries and aquaculture sectors on marine ecosystem services in sustainable development of seafood (through fishing or farming) is obvious. Viewed from ecological (and hence sustainable development) perspectives, which are at the core of the EAFM and EAAM, the justification for a wider ecosystem stewardship can be accepted as a voice of logic and reason. The earlier these two sectors transition to ecological standards, the better it will be for turning resource users into resource stewards (FAO, 2012). Greening of fisheries and aquaculture through this change in the mindset and practice will be a leap forward towards a blue economy and will be a catalyst for evolution of comprehensive governance structures. Analysis of the unfolding scenario suggests, beyond any iota of doubt, the emergence of seafood security and the blue economy as the global flagship programmes of this century.

The ecosystem approach is a strategy for integrated management of natural resources that promotes conservation and sustainable use in an equitable way (Shephered, 2004). Five steps have been identified towards its implementation: (i) determining the main stakeholders, defining the ecosystem area and developing the relationship between them; (ii) characterizing the structure and function of the ecosystem and setting in place mechanisms to manage and monitor it; (iii) identifying the important economic issues that will affect the ecosystem and its inhabitants; (iv) determining the likely impact of the ecosystem on adjacent ecosystems; and (v) deciding on long-term goals and flexible ways of achieving them.