Climate change and aquaculture: potential impacts, adaptation and mitigation

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Summary

This document addresses the potential impacts of climatic change on the aquaculture sector and to a lesser extent the contribution of aquaculture to climate change. In order to achieve these objectives, the status of this subsector in relation to the total food fish supply, recent changes therein and other related aspects are analysed with a view to addressing potential adaptations and mitigation.

Currently, the proportionate contribution of aquaculture to food fish consumption approximates 45 percent; this is also reflected in the increasing contribution of aquaculture to total fisheries figures recorded in the gross domestic product (GDP) of some of the main producing countries. Considering human population growth and stagnation in the growth of capture fisheries, it is expected that the supply of food fish from aquaculture will be required to increase even further to meet future demand for fish.

Aquaculture is not practised evenly across the globe and to evaluate the potential impacts of climate change, the document analyses current aquaculture practices in relation to: three climatic regimes, *vis-à-vis* tropical, subtropical and temperate; in relation to environmental types *vis-à-vis* marine, fresh and brackish waters; and in relation to geographic divisions by continents. It is seen that aquaculture is predominant in tropical and subtropical climatic regions and geographically in the Asian region. Furthermore, the most cultured commodities are finfish, molluscs, crustaceans and sea weeds, but species that feed low down in the food chain predominate. The geographic and climatic concentration of aquaculture necessitates, for the time being, a focus on the development of adaptive strategies for addressing or mitigating climate change impacts in these regions, especially if the predicted gap between supply and demand for food fish is to be realised through aquaculture. However, we cannot disregard the potential for aquaculture growth in other regions.

The main elements of climate change that could potentially impact on aquaculture production - such as sea level and temperature rise, change in monsoonal rain patterns and extreme climatic events and water stress - are highlighted and the reasons for such impacts evaluated. By virtue of the fact that the different elements of climate change are likely to be manifested or experienced to varying degrees in different climatic zones, the direct impacts on aquaculture in the different zones are considered. For example, it is predicted that global warming and a consequent increase in water temperature could impact significantly and negatively on aquaculture in temperate zones because such increases could exceed the optimal temperature range of organisms currently cultured. Such impacts may be balanced with positive impacts that might occur as a result of climate change, such as enhanced growth and production in tropical and subtropical zones. However, positive impacts are unlikely to occur without some potential negative impacts arising from other climatic change elements (e.g. increased eutrophication in inland waters). In both instances possible adaptive measures for reducing or maximizing the impacts are considered. An attempt is also made to deal with the climatic change impacts on different culture systems, for example, inland and marine systems and different forms of culture practices such as cage culture. Furthermore, it is likely that diseases affecting aquaculture will increase both in incidence and impact.

Nearly 65 percent of aquaculture production is inland and concentrated mostly in the tropical and subtropical regions of Asia. Climate change impacts as a result of global warming are likely to be small on aquaculture practises taking place in such systems and if at all positive, brought about by enhanced growth rates of cultured stocks. On the other hand, climate change will impact on water availability, weather patterns such as extreme rain events, and exacerbate eutrophication and stratification in static (lentic)

waters. The influence of the former on aquaculture is difficult to project. Some adaptive measures related to the location of farms are discussed here. However, based on current practices, particularly with regard to inland finfish aquaculture that is predominantly based on species feeding low in the food chain, the greater availability of phytoplankton and zooplankton through eutrophication could possibly enhance production. On the other hand, in marine cage culture, adaptive measures will revolve around the introduction of improved technologies to withstand extreme weather events.

Sea level rise and consequent increased salt water intrusion in the deltaic areas of the tropics where there is considerable aquaculture production is likely to occur. Adaptations to related impacts will involve the movement inland of some operations that culture species with limited saline tolerance. Equally, aquaculture is seen as an adaptive measure to provide alternative livelihood means for terrestrial farming activities that may be no longer possible and or cost effective due to sea water intrusion and frequent coastal flooding. One of the most important, though indirect, impacts of climate change on aquaculture is considered to be brought about by limitations on fish meal and fish oil availability (for fish feeds) as a result of a reduction in raw material supplies. Other types of raw materials might also be affected. The negative impacts are likely to be felt mostly in the temperate regions where the finfish aquaculture is based entirely on carnivorous species. Adaptive measures to counteract these impacts are suggested.

The ecological cost of different aquaculture species and systems, as opposed to other sources of animal protein production, is presented and the indirect contribution to carbon emissions is considered. As a mitigation measure to curtail the contribution of aquaculture to carbon emissions, it is suggested that the consumer is made aware of the carbon emissions associated with various products, in the same way that traceability is indicated. In this context, it is demonstrated that on the whole aquaculture is less energy costly and could contribute to carbon sequestration more than other terrestrial farming systems.

The document concludes by reviewing more general policy oriented adaptation measures that can be implemented regionally, nationally or could be site specific.

1. Introduction

World population is predicted to reach nine billion by 2050, resulting in increased global food needs in the first half of this century (McMichael, 2001). The capacity to maintain food supplies for an increasing and expectant population will depend on maximizing the efficiency and sustainability of the production methods in the wake of global climatic changes that are expected to adversely impact the former. A recent analysis of global food production within the Special Report on Emission Scenarios (SRES) of the Inter Governmental Panel on Climate Change (IPCC), when linked to the food trade system model indicates that the world will be able to feed itself well into the next century, a heartening conclusion. However, the model that demonstrated this outcome was based on the production of developed countries, which are expected to benefit mostly from climate change. This compensated for the declines projected in the terrestrial food crops of developing countries, suggesting that regional differences in crop production are likely to grow stronger with time (Parry *et al*., 2004). Perhaps aquaculture, an industry of the developing world, may provide a different scenario in relation to its contribution to our future food needs.

Humans and fish have been inextricably linked for millennia, not only because fish is an important source of animal protein, providing many millions of livelihood means and food security, but also from an evolutionary view point. Indeed, one school of thought has suggested that the development of the human brain and hence what humans are today, is linked to food sources rich in n- 3 (DHA, EPA) and n- 6 (AA) PUFAs - literally fish constituting a major part of the diet of our ancestors. In this regard, a large quantum of evidence has been brought forward to show that *Homo sapiens* evolved not in a savannah habitat but in a habitat that was rich in fish and shellfish resources (Crawford *et al*., 1999). More and more medical studies are emerging on the positive aspects of fish in a healthy diet, physical growth and general well-being. Currently, it is well documented that deficiencies of some of these PUFAs are associated with major health risks (Stansby, 1990; Ulbricht and Southgate, 1991; de Deckere *et al*., 1998) and some diseases and clinical conditions can be alleviated by supplementing with PUFAs (Hunter and Roberts, 2000). As a result of this increasing awareness of the importance of fatty acids in the human diet, there has been a general growth in fish consumption in most societies, particularly in the developed world. On the other hand, fish provide an affordable and often fresh and unique source of animal protein to many rural communities in developing countries.

Of all current animal protein food sources for humans, only fish is predominantly harvested from wild origins as opposed to others which are of farmed origin. Overall, there have been significant changes in global fish production and consumption patterns (Delgado *et al*., 2003) with a major shift in dominance over a 25-year period towards developing countries and China. This changing scenario is accompanied by one in which supplies from capture fisheries are gradually being superseded by farmed and/or cultured supplies, accounting for close to 50 percent of present global fish food consumption (Figure 1, FAO, 2008b).

Over the last decade or so, especially among the public, climate change, its impacts and consequences have been used rather indiscriminately and loosely. Climate change, defined and interpreted variously, but supported by rigorous and robust scientific data and analyses, is accepted as a reality even though it is still refuted by a few (e.g. Lomborg, 2001). As a result, it is commonly agreed that our lives will be impacted in many ways by climate change and one of the primary ways will be food production and the associated environments (IPCC, 2007). In the present synthesis the definition[1] provided by the IPCC is adopted (IPCC, 2007). Equally, how the global community collectively mitigates the causative factors of climate change and adapts measures to confront it, will determine the degree of impact on the various sectors in the ensuing decades and perhaps centuries. However, this synthesis deals mainly with adaptation measures to confront climate change.

It is also important to point out that considerations on climate change and food fish production, apart from a few dedicated studies on the subject (see Section 4), has thus far received only scant attention, especially in comparison to all other primary production sectors. Fisheries *per se* have been referred to only once in the Synthesis Report of the IPCC (2007), which suggests that in relation to the meridional overturning circulation in the Atlantic Ocean there are likely to be changes in ecosystem productivity and fisheries.

The most notable and significant changes associated with climate change are the gradual rise of global mean temperatures (e.g. Zwiers and Weaver, 2000) and a gradual increase in atmospheric green house gases (Brook *et al*., 1996), both of which have been aptly synthesized and documented (IPCC, 2007). Our planet has experienced more floods (in 1960 approximately $7x10^6$ persons were affected but today the figure is 150×10^6, annually), more hurricanes and irregular monsoons than in previous decades. The debate and controversies, however, lie with the degree of change of the main elements such as global temperature, sea level rise and the extent of precipitation that result in the changes we experience. Global warming and sea level rise will occur but to what degree will these changes take place in the coming decades? There is agreement that our planet will heat up by 1.1 °C this century and if green house gases continue rising at the current rate, it will result in a 3 °C rise in temperature. Earth's average temperature is around 15 °C, and whether we allow it to rise by a single degree or 3 °C will decide the fate of thousands of species and perhaps billions of people (Flannery, 2005; Kerr, 2006).

Food fish production, as is the case in all other primary production sectors, is expected to be influenced and or impacted to varying degrees by climate change and the manifestations thereof are expected to occur in varying forms and to varying degrees in different parts of the world. However, unlike other animal food production sectors, food fish production is divisible into two subsectors: capture fisheries which overly depend on naturally recruited and occurring wild populations, the great bulk (approximately 85 to 90 percent) of which are in the oceans; and the cultured or farmed food fish subsector, that is growing in relative importance and is popularly referred to as "aquaculture".

This synthesis attempts to deal with the potential impacts of climatic change on aquaculture only. In order to achieve this objective, the status of this subsector in relation to the total food fish supply, the recent changes therein and other related aspects are analysed with a view to addressing issues and potential adaptations and mitigation. As very limited primary data were available to the authors, modelling of any suggested changes and or impacts were not attempted in this synthesis.

[1] "climate change refers to a change in the state of climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity"

2. Food fish production and needs

A synthesis on climate change and its impacts on fish production has to consider the potential needs of food fish for human consumption and the amounts available for reduction processes such as fish meal and fish oil. These products are used in the manufacture of feeds for domesticated animals and form the basis of a significant proportion of feeds for cultured aquatic organisms, in particular shrimp and carnivorous finfish and to a lesser extent the intensive culture of omnivorous species such as tilapias and carps, especially in relation to the production volumes of these commodities.

2.1 FOOD FISH NEEDS

Cultured food fish supplies currently account for nearly 50 percent of that consumed globally (FAO, 2008) and are targeted to increase to 60 percent by 2020 (FAO, 2007; Figure 1).

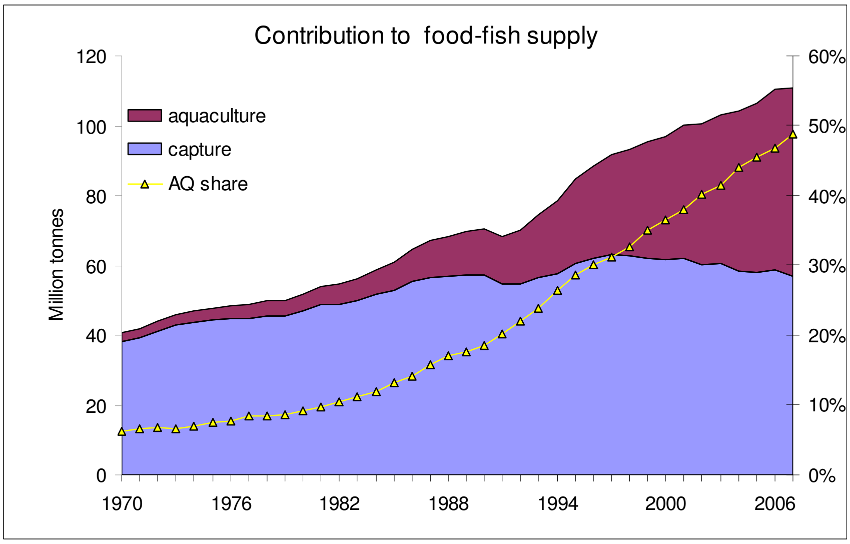


Figure 1. Food fish contribution from aquaculture and capture fisheries and percentage contribution from aquaculture (FAO Fishstat 2008 and FAO Food Outlook 2008).

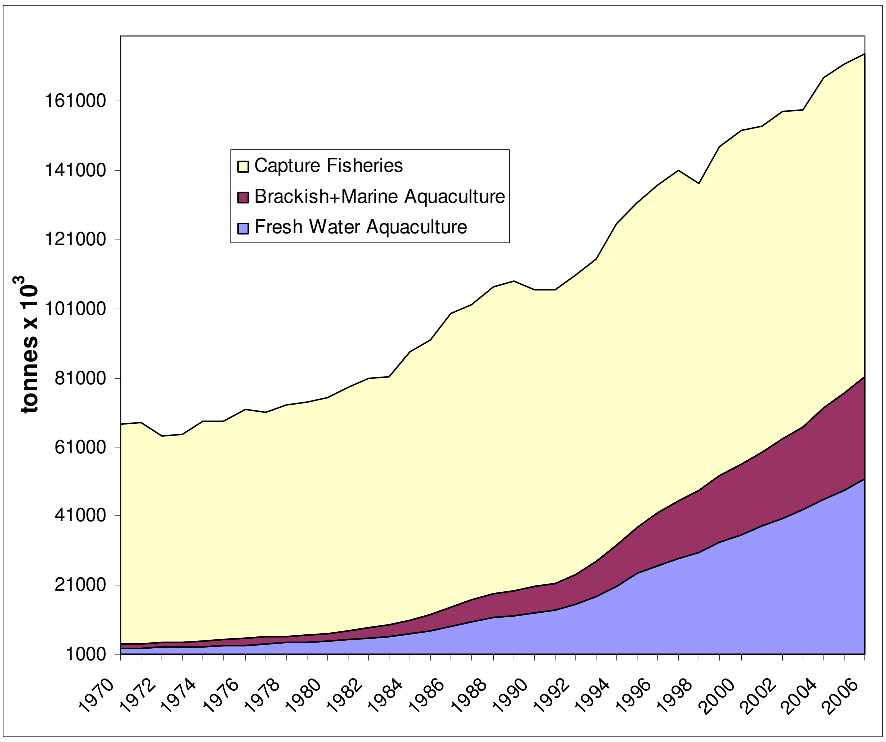


Figure 2. The total global fish production and the contribution from capture fisheries and aquaculture (Freshwater and Brackish + Marine), years 1975 to 2006 (FAO Fishstat, 2008).

Table 1. Projections on food fish demands in relation to population growth predictions (modified after Siriwardene, P.P.G.S, personal communication)

Continent	**Population (x 10^3)**		**Fish supply (2001)**		**Demand by 2020 (t)[d]**
	2005[a]	2020[a]	Total (t)[b]	Per capita (kg)[c]	
Africa	905 936	1 228 276	7 066 301	7.8	9 580 553
Asia	2 589 571	3 129 852	36 512 951	14.1	44 130 913
China	1 315 844	1 423 939	33 685 606	25.6	36 452 606
Europe	728 389	714 959	14 422 102	19.8	14 156 838
L. America & Caribbean	561 346	666 955	4 939 845	18.8	5 869 204
N. America	330 608	375 000	5 719 518	17.3	6 487 500
Oceania	33 056	38 909	760 288	23.0	894 907
World	6 464 750	7 577 889	105 375 425	16.3	123 519 591

a- UN; b- 2005 population x 2001 per capita supply; c- FAO; d- 2020 population x 2001 per capita supply

The contribution of cultured components to the global fish supply has increased significantly over the last ten year period to reach 47 percent in 2006 (Figure 2). Within that, freshwater production reached 30 percent.

Considering that the capture fisheries component of fish supply has almost reached a saturation level of approximately 100 million tonnes per year, and that nearly 25 percent of this is channelled to reduction processing industries and is therefore unavailable for direct human consumption, (Jackson, 2006; Hassan *et al.*, 2007), it is unlikely that there will be any further increases to the human food basket from capture fisheries, perhaps with the exception of potential developments in the inland fisheries sector in the tropics which appears to be gaining some momentum. This means that growing food fish needs for human consumption, as a consequence of population increase and increasing per capita consumption among certain sectors (driven by the health benefits of consuming fish) will have to be provided primarily through aquaculture.

Numerous predictions have been made about food fish supplies for the future and these have been aptly summarized (Siriwardene, 2007, personal communication) in Tables 1 and 2. In all instances it is clear that there has been a significant increase in the demand for food fish in the ensuing years, this demand being variable between continents and related to population growth predictions.

Table 2. Projected global food fish demands (modified after Brugére and Ridler, 2004).

Forecasts	Needs		Estimated needs from aquaculture ($x10^6$ tonnes)	
	Per capita consumption (kg/yr)	Total demand ($x10^6$ t)	Considering fisheries as:	
			Growing (0.7%)	Stagnating
Baseline[a] Lowest Highest	17.1 14.2 19.0	130 108 145	53.6 (1.8%) 41.2 (0.4%) 69.5 (3.2%)	68.6 (3.5%) 48.6 (1.4%) 83.6 (4.6%)
2010[b] 2050	17.8 30.4	121 271	51.1 (3.4%) 177.9 (3.2)	59.7 (5.3%) 209.5 (3.6%)
1999[c] 2030	15.6 22.5	127 183	45.5 (0.6%) 102.0 (3.5%)	65.1 (2.0%) 121.6 (4.2%)
a- Delgado *et al.* (2003), to 2020; b- Wijkstrom, 2003; c- Ye, 1999				

Table 3. Projected demand for aquaculture production, 2020 (modified after Siriwardene, P.P.G.S, personal communication)

Continent	Food fish demand- 2020 (t)	Aquaculture production 2003 (t)[a]	Aquaculture demand- 2020 (t)[b]	Needed change (%)
Africa	9 580 553	520 806	3 035 058	482.8
Asia	44 130 913	8 686 136	16 304 098	87.8
China	36 452 838	28 892 005	31 659 237	9.6
Europe	14 156 188	2 203 747	1 937 833	-12.1
L. America & Caribbean	5 869 204	1 001 588	1 930 947	92.8
North America	6 487 500	874 618	1 642 600	87.8
Oceania	894 907	125 241	259 860	107.5
World	123 519 591	42 304 141	60 448 307	42.9
a- FAO Stats; b- 2020 fish demand minus estimated current fisheries production				

The demand for aquaculture to provide increasing food fish needs is estimated to be around 60 million tonnes, a nearly 43 percent increase on production in 2003. The projected breakdown, continent by continent, is presented in Table 3. If food fish demands are to be satisfied by 2020 an increase in aquaculture production needs to occur on all continents with the exception of Europe, to varying degrees. The above is one scenario that has to be considered in evaluating the impacts of climate change on aquaculture.

2.2 FOOD FISH PRODUCTION: CHANGING SCENARIOS

Figure 3 illustrates the major changes that have occurred in global food fish supplies and availability and consumption patters over the past three decades.
The gradual increase in the role of aquaculture in the global food fish supply (Figure 1) and particularly the inland sector (Figure 2), contrasts with capture fisheries stagnation, where nearly 85 to 90 percent of supply comes from marine stocks. However, these are gross details and do not essentially reflect those that are required to investigate and or evaluate the major impacts of climate change on human food supplies and/or aquaculture.

2.3 FOOD SECURITY AND FISH

The accepted definition of food security is, “food security exists 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” (FAO, 2003). Food security, according to Sen (1981) may be achieved directly and or indirectly through:

- production-based entitlements – producing food for self;
- trade-based entitlements – selling/bartering goods or other assets;
- labour-based entitlements – selling own labour;
- transfer-based entitlements – receiving gifts or transfers of food.

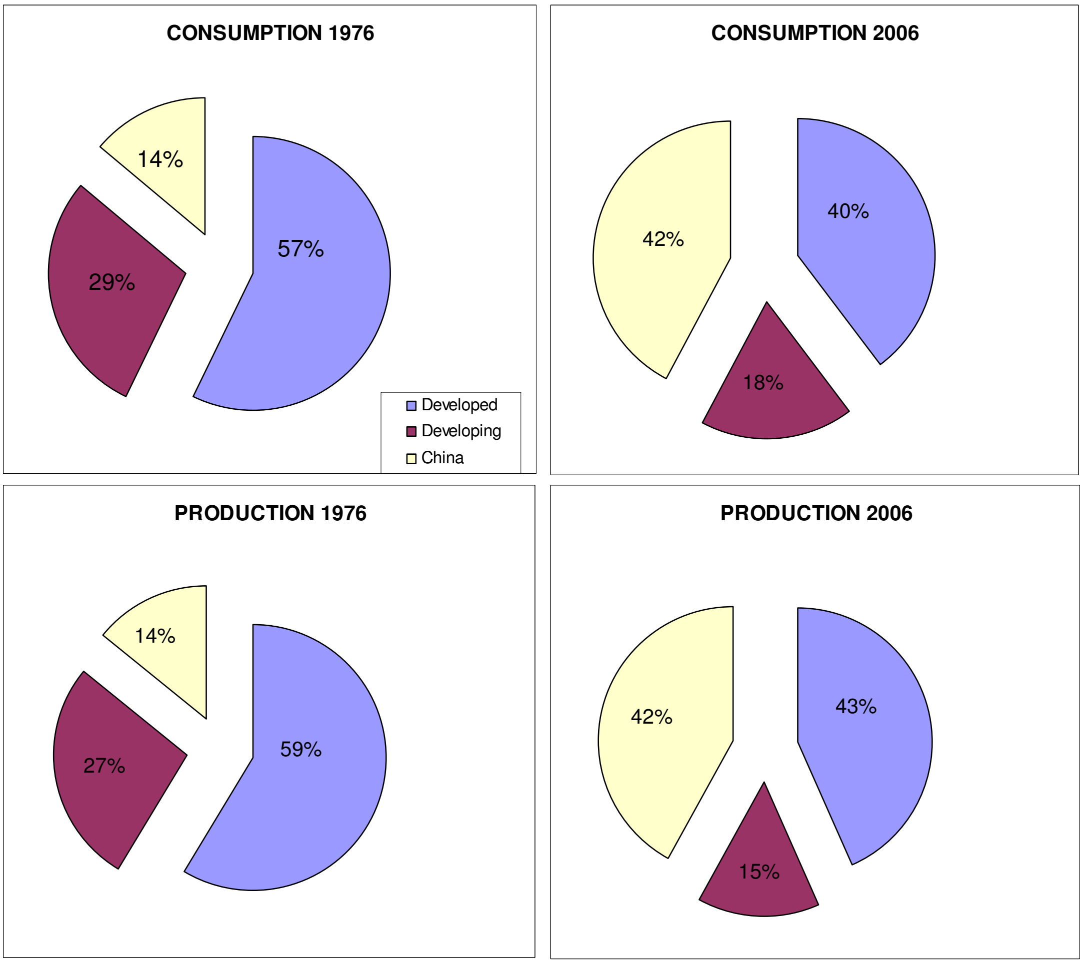


Figure 3. Changes in the global food fish production and consumption patterns for developed countries, developing countries excluding China and China. Source for consumption values; Laurenti (2007) and production values; FAO Fishstat 2008).

Food security is a universal human right. Issues related to food security have been the subject of much debate and resulting in acceptance of general principles by the world at large. These were aptly summarized by Kurien (2005).

The accepted recommended minimal daily calorie intake for a healthy life is 1 800 which has been increased to 2 100 per day by the United States Department of Agriculture (USDA), Economic Research Service[2]. Worldwide, it is estimated that there are one billion undernourished people in 70 lower income countries. It is also important to note that the great majority of such people live in rural areas. Over the last two decades the number of hungry people in Asia has recorded a decline. Fish food does not necessarily significantly contribute to daily calorie intake but at present it contributes an estimated 20 percent to animal protein intake and significantly more than that in the developing world. Fish food also provides essential micro nutrients in the form of vitamins, minerals (e.g. best sources of iodine and selenium) and some co-enzymes (Q 10), among others.

In general, consumption of fish does not directly account for food security *per se*, primarily because of its low calorie content. However, fish production, capture fisheries

[2] (www.ers.usda.gov/Briefing/GlobvalFoodSecurity/questions.hrm)

and aquaculture contribute significantly to food security through livelihoods and by ensuing income generation. It is estimated that 35 million people are directly employed in the fisheries sector, approximately 80 percent in fishing and 20 percent in aquaculture (FAO, 2003b). The greater proportions of livelihoods dependent on fisheries are concentrated in developing countries, particularly in Asia. It is also important to note that the sector supports several times the number of those directly employed through households and ancillary support sectors (Williams, 2004). Overall, fish and fish trade are considered to be important sources of direct and indirect food security, although until recently most concerns with regard to fish and food security have tended to focus on the direct dimension of fish on consumption (Kurien, 2005). This author further emphasized that in 10 out of 11 developing countries the top foreign exchange earner was fish, indicating its importance in ensuring food security at the aggregate level. It is also becoming increasingly apparent that aquaculture is bypassing the capture fisheries sector in production, currently contributing nearly 45 percent to total fisheries in Asia and nearing 70 percent in countries such as the Peoples Republic of China (De Silva *et al*., 2007). This gain in the relative importance of the aquaculture sector will be indirectly reflected in the associated trade and therefore its relative importance in contributing to food security.

"Fish workers" is a common term used to categorize workers who perform post harvest services in any fishery economy and essentially include those involved in sorting, packing and transporting fish; those involved in various processing activities that enhance the shelf life of fish and in value adding; and those engaged in the supply of fish to exporters, processors, wholesale and retail markets or directly to consumers. It appears that those involved in the reduction and feed manufacture industries are excluded, traditionally. However, it is known that this sector also provides a considerable number of jobs that contribute to overall food security. In this context, some of the emerging aquaculture commodities that aim for export are reported to provide significant employment opportunities to relatively impoverished rural communities. Examples are catfish (*Pangasianodon hypophthalamus*) and rohu (*Labeo rohita*) aquaculture in Viet Nam and Myanmar, respectively. In Myanmar, in order to service the growing export market of rohu (Aye *et al*., 2007) which currently amounts to about US$70 million (equivalent to 60 000 tonnes of 1 to 2 kg rohu), 80 processing plants have been established. On average, eight labour units are required for processing one tonne of rohu, thereby equating to year round employment for nearly 1 300 to 1 400 people in this processing sector. Vinh Hoan Corporation, one of the largest processors of catfish in the Mekong Delta employs 2 500 people, 80 percent of whom are women, [3] working in three shifts, to enable the processing of 200 tonnes per day, yielding approximately 80 tonnes of processed product for export (Vinh Hoa Corporation, undated). On the above basis, the catfish sector in the Mekong Delta that produced 1.2 million tonnes in 2007, almost all of which were processed and exported, would have provided year round employment for 40 000 to 45 000 people, which is very significant direct employment from the subsector within a geographical area. Undoubtedly, such a high degree of employment would have a significant impact on food security in that region.

[3] www.vinhoan.com.vn

Box 1. In most Asian aquaculture (and in Latin America) the processing sector is dominated by female employees. This empowers women in rural households and in addition to contributing to food security may contribute to household harmony and wellbeing, a factor that has that has hardly been taken into account in traditional analyses of aquaculture. Photos depict women in the aquaculture processing sector in Viet Nam (shrimp) and Myanmar (rohu).

In the case of high valued cultured commodities such as salmon and shrimp (and increasingly tilapia), the bulk of production is processed for export. As such, even though the overall energy cost is significantly higher, high value products provide a considerable number of livelihood opportunities and thereby contribute to overall food security. For example, in Thailand, the leading global cultured shrimp producing nation (375 320 tonnes valued at US$1.196 billion in 2005), only 30 percent is consumed as fresh, the rest being processed fresh chilled and frozen (37 percent) and/or canned (29 percent) (Fishery Information Technology Centre, 2006). Here again, the aquaculture sector provides considerable livelihood opportunities and contributes to food security. Another example is that of salmon farming in Chile. Salmon was the third largest export commodity in Chile with a value of US$2.2 billion in 2007. That year the industry provided employment to approximately 53 000, thereby impacting very strongly on the growth of local economies in the rural salmon farming areas. Participation of women, particularly concentrated in the processing plants, is also high in the salmon industry, accounting for approximately 50 percent of the total in the sector.

Poverty is linked to food security and malnourishment; the poor have a lesser probability of ensuring food security. Malnutrition often leads to disease. The status of malnourishment, by region, is summarized in Table 4.

Table 4. Total world population in millions (2000 to 2002), the numbers of undernourished people and the latter expressed as a percent of the total population (extracted from WFP, undated).			
Region/sub region	Total population	Undernourished	
		Total	*Percent*
Developing world	4 796.7	814.6	17
Asia-Pacific	3 256.1	519	16
East Asia	1 364.5	151.7	11
SE Asia	522.8	65.5	13
S Asia	1 363.3	301.1	22
Latin America and the Caribbean	521.2	52.9	10
Near East & N. Africa	399.4	39.2	10
Sub Saharan Africa	620.0	203.5	33
Countries in transition	409.8	28.3	7

The level of malnourishment is evident within the Asia-Pacific region, illustrating that poverty in south Asia is considerable. What appears to hold in most of the Asia-Pacific region is the relatively high dependence on fish as the main animal protein source. While malnourishment is highest in sub Saharan Africa, dependence on fish in that region is lower and aquaculture has barely started there. If the aquaculture sector ever develops in a sustainable way, it could provide significant benefits to the region through direct nutrition and social and economic development.

Aquaculture has been growing relatively rapidly over the last 15 years or so in Latin American and Caribbean countries, notably, Brazil, Chile, Ecuador, Honduras and Mexico (Morales and Morales, 2005). Two continents that have the highest growth potential in aquaculture are South America and Africa, whereas in Asia, the growth rate of aquaculture is decreasing (De Silva, 2001). It is probable that developments in aquaculture in the coming decades in South America and Africa will contribute even further to global food security and poverty alleviation. In countries such as Chile, Ecuador and Honduras the cultured commodities require processing and transport (as well as several other associated services) and therefore will indirectly contribute to food security.

3. Aquaculture production

In order to assess potential changes in aquaculture under different climate change scenarios it is important to base the evaluations on the past trends of aquaculture production on the basis of approximate climate regimes *vis-à-vis* tropical, subtropical and temperate regions.

3.1 CLIMATIC DISTRIBUTION OF PRODUCTION

To date most analysis of aquaculture production (see for example FAO, 2007, among others) has been based on nations/territories/continents and regions. From a climate change impact point of view, such analyses will be of relatively limited use unless those of individual nations/territories are considered. Accordingly, in this synthesis the trends in aquaculture production, at five year intervals (1980 to 2005), for each of the cultured commodities (vis-à-vis finfish, molluscs, crustaceans, and seaweeds), based on FAO Statistics (FAO, 2008) for three climatic regimes viz. tropical (23ºN to 23ºS), subtropical (24-40ºN and 24-40ºS) and temperate (>40ºN and >40ºS) are considered (Figure 4). Admittedly, this approach is not perfect. For example, aquaculture

production in China (roughly 20 to 42 ºN and 75 to 130 ºE) occurs across many degrees of latitude. In this analysis, the assumption was made that 60 percent of aquaculture production in China is considered to be subtropical and the remainder tropical.
It is evident from the analysis, that all of the major cultured commodity groups are primarily confined to the tropical and subtropical regions of the globe (Figure 4). For three of the four major cultured commodity groups, production in the tropics accounted for more than 50 percent, the highest being for crustaceans which approximated 70 percent. It is also important to note the trend over the last 25 years for molluscs and seaweed culture in temperate regions. The culture of these two groups was dominant in this climatic region until about a decade ago and since then has sunk below the other two regions and currently contributes around 10 percent to the total. This is largely as a result of the high growth rate of aquaculture in tropical and subtropical regions, rather than a reduction in absolute production in the temperate region *per se*.

3.2 ENVIRONMENTAL-CLIMATIC DISTRIBUTION OF AQUACULTURE

Aquaculture is an activity that occurs in three basic environments; freshwater, marine and brackish waters, each of the se environments being distributed throughout the three climatic regimes under consideration. In Figure 5, production of each of the major aquaculture commodities (at five yearly intervals from 1980 to 2005 in 10^6 t) in relation to the climate regime and freshwater, marine and brackish water environments are presented.
It is evident that, apart from molluscs, the culture of all other major commodities occurs predominantly in the tropics, followed by that in the subtropics, and significantly less in the temperate regions. In essence, over the last 25 years, cultured production of all four major commodities in temperate regions, except perhaps finfish, has declined its percent contribution because of the substantial increases in production in the other regions (Figure 5). Also, in all the regions, the total production of finfish far exceeds that of other commodities and this trend is consistent through the years. Finfish culture occurs predominantly in freshwater while crustaceans and mollusc culture occurs in brackish and in marine waters, respectively (Figure 5). Here again the production trends are rather consistent over the 25 year period. It is therefore important to notice that climate change impacts, if any, are likely to produce more significant net effects on the freshwater aquaculture subsector in tropical and subtropical regions than elsewhere because production is concentrated there.

3.3 CLIMATIC-NATIONAL-REGIONAL DISTRIBUTION OF AQUACULTURE

In order to obtain a view of the importance of the distribution of aquaculture production in relation to climatic regimes (tropical, subtropical, and temperate) by continents, the production of the four major commodities in 2005 in accordance with these two factors was analysed (Figure 6). This clearly shows that production of all four major cultured commodities in the three climatic regimes under consideration occurs predominantly in Asia. The differences in production between Asia and the other continents are extremely large, in excess of 90 percent in all instances. Therefore, adaptive strategies needed to prevent and counteract the potential impacts of climatic change on aquaculture should be initially be targeted at Asian aquaculture.

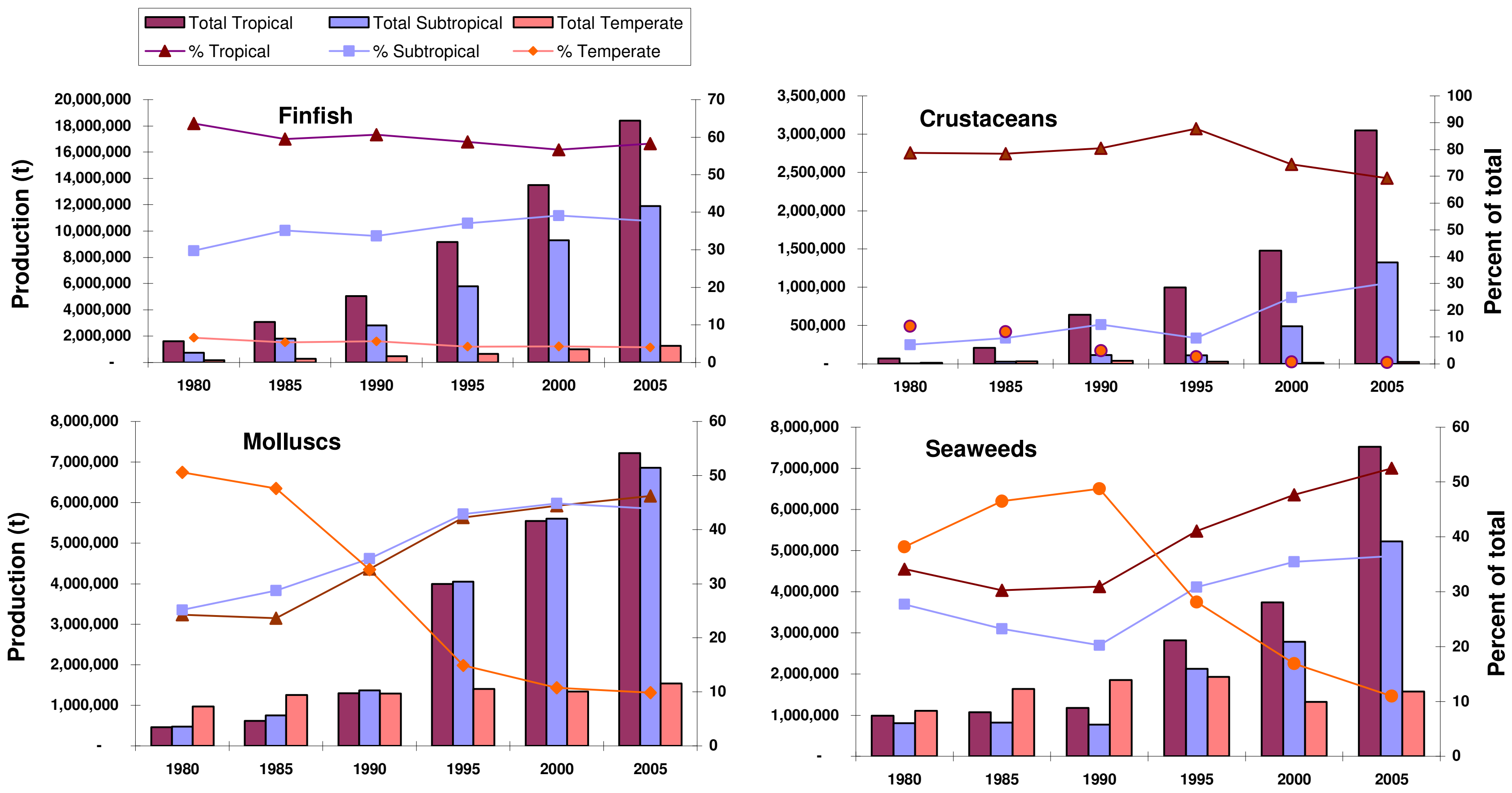


Figure 4. Aquaculture production of the four major commodities, at five yearly intervals from 1980 to 2005, distributed by climatic zones and the percent contribution from each zone to the total (based on FAO Statistics, 2008).

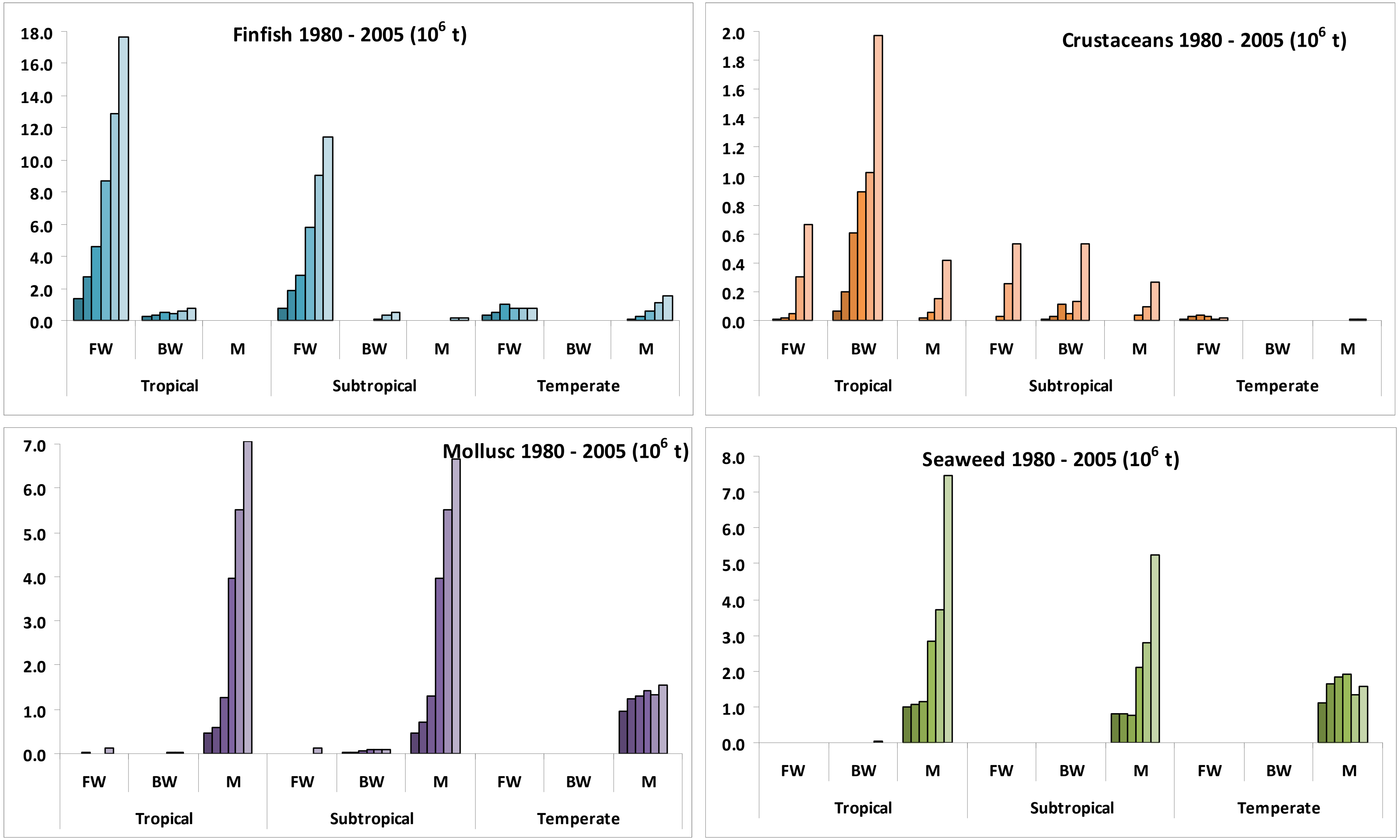


Figure 5. Production of each of the major aquaculture commodities ($x10^6$ t) in relation to climate zone and habitats (at five yearly intervals from 1980 to 2005).

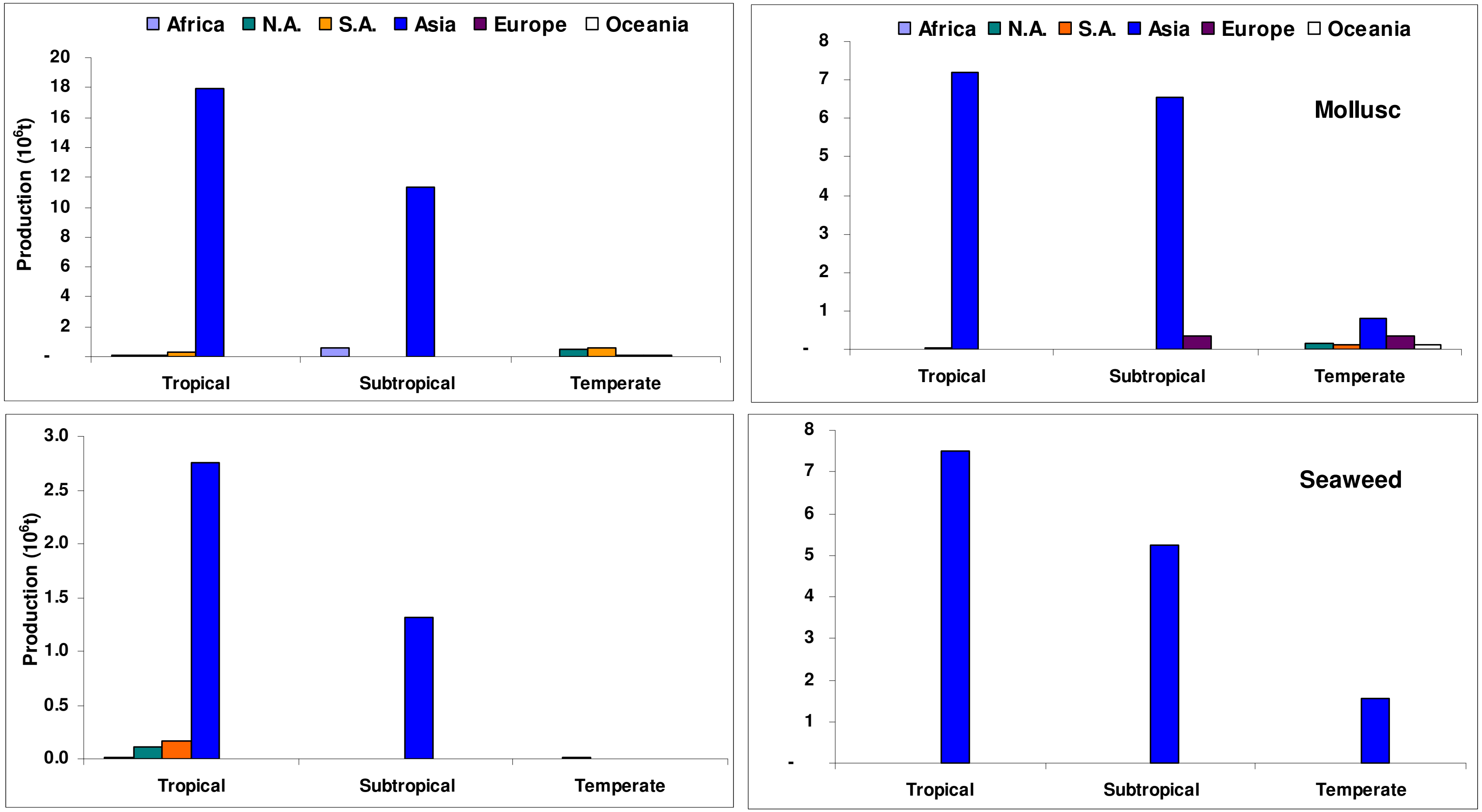


Figure 6. Production (2005) of the four major commodities by climatic zone and region.

3.4 VALUE OF AQUACULTURE PRODUCTS

The value of aquaculture commodities produced in the different climatic zones followed a similar trend to that of the overall production of each. The trend in values depicted in Figure 7, shows that in 2005, the value of products from the tropical region was highest, followed by the subtropics and lastly the temperate zone. In the case of the value of cultured molluscs and seaweeds, the differences between the climatic zones were much smaller than for finfish and crustaceans where the value of the respective produce exceeded 50 percent of the total (Figure 7). On the other hand, although in the temperate region finfish accounts for only about four percent of global production, it is worth nearly 11 percent of global total value of finfish production, indicating the predominance of higher valued finfish produced in this climatic region. Therefore, in the temperate zone, changes in production may have a greater potential impact on livelihoods per tonne of fish.

3.5 GROWTH TRENDS IN AQUACULTURE

Aquaculture is often referred as the fastest growing primary production sector in the last three decades, having witnessed an annual rate of growth of nearly 10 percent. However, trends data indicate that the rate of growth is decreasing (Figure 8) and it is generally accepted that aquaculture growth cannot proceed at the same rate in most regions (De Silva, 2000; FAO, 2007). However, it is important to bear these growth trends in mind when considering the impacts that climate change might have on aquaculture and its potential for growth.

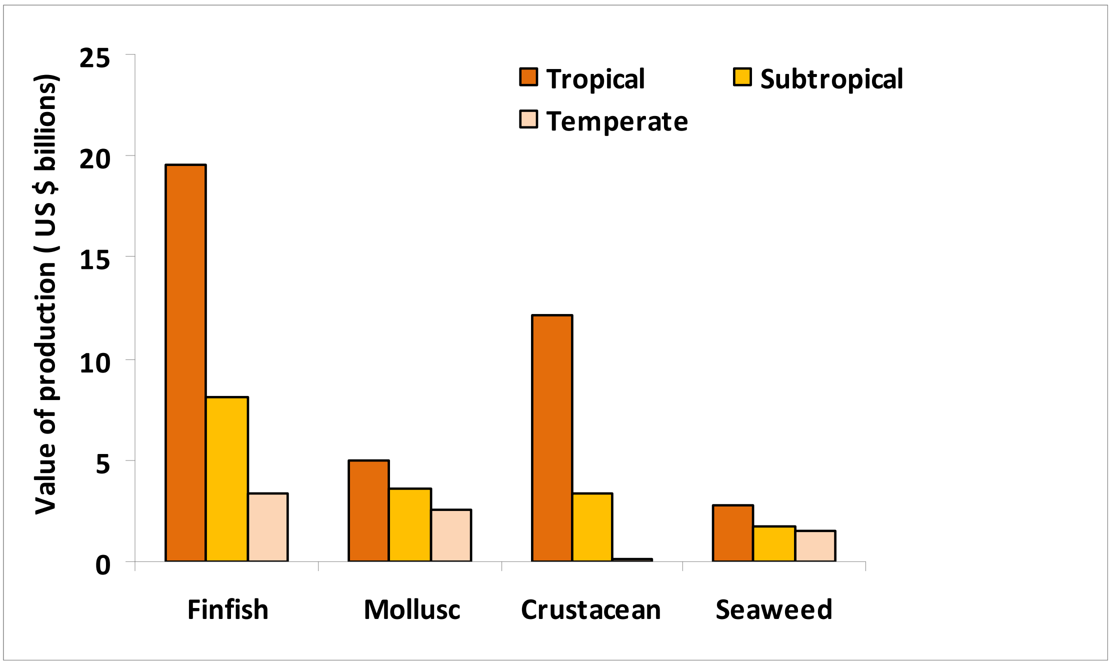


Figure 7. Value (in US$ thousands) of aquaculture produce in 2005 for each of the climatic regions.

3.6 *AQUACULTURE AND GDP*

Kurien (2005) highlighted the increasing relevance of the global fisheries trade, and showed that the contribution of fisheries to the GDP of many developing countries has bypassed that of traditional commodities such as coffee and tea. In 10 out of 11 developing countries fish was the top foreign exchanger earner and very important for ensuring food security at the aggregate level. In Asia, irrespective of climate regimes (Figure 6), the contribution of aquaculture to total fish production has been increasing over the last two decades (Figure 1), a trend that has been observed in many of the current major aquaculture producing countries on that continent (De Silva, 2007).

This trend is being reflected in the GDPs of some of the major aquaculture producing countries in the region and elsewhere, where aquaculture is becoming an increasingly important food fish production sector (Table 5).with positive impacts on food security.

Table 5. Estimated relative contribution from capture fisheries and aquaculture to the GDP in some selected Asian countries and Chile, South America (2004-2006)

Country	Capture	Aquaculture
Bangladesh#	1.884	2.688
PR China#	1.132	2.618
Indonesia#	2.350	1.662
Lao PDR#	1.432	5.775
Malaysia#	1.128	0.366
Philippines#	2.184	2.633
Thailand#	2.044	2.071
Viet Nam*	3.702	4.00
Chile**	2.17	2.63

From # Sugiyama, Staples, and Funge-Smith, 2004; * Viet NamNet Bridge
** www.subpesca.cl

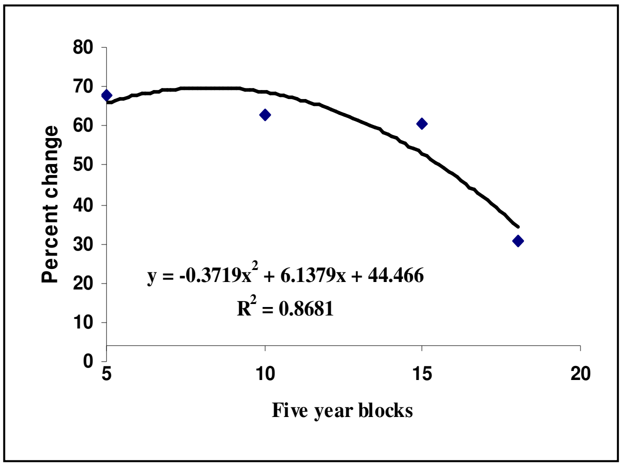


Figure 8. Line of best fit indicating the average percent change in average percent aquaculture production in five year blocks commencing from 1980 (from De Silva and Hasan, 2007).

4. Brief synthesis of previous studies on climate change effects on aquaculture and fisheries

Apart from a few dedicated studies, fisheries and aquaculture have thus far received only scant attention in the major considerations of climate change induced impacts on food fish production. This is especially so in comparison to all other primary production sectors as well as in relation to other pertinent and important issues such as climatic change influences on biodiversity (IPCC, 2002). However, it is important to note that the first notable attention to climate change issues in relation to fisheries was made almost a decade ago (Wood and McDonald, 1997). In this treatise, climate change influences on fisheries were dealt more from a physiological view point, with treatments on effects of temperature on growth (Jobling, 1997), larval development (Rombough, 1997) and reproductive performance (Van der Kraak and Pankhurst, 1997).

Two policy briefs pertaining to the threat to fisheries and aquaculture dealt with the significance of fisheries and aquaculture to communities depending on these sectors for livelihoods and the need for strategies to adapt to climate change induced effects on these sectors were considered briefly (WFC, 2006). This was followed by a brief in which it was stated that the two sectors could provide opportunities to adapt to climate change through, for example, integrating aquaculture and agriculture and suggested that fisheries management should move away from seeking to maximize yield but to increasing adaptive research (WFC, 2007). Furthermore, the brief called for further research to find innovative ways to improve existing adaptability of fishers and aquaculturists.

Sharp (2003) considered future climate change effects on regional fisheries by examining historical climate changes and evaluating the consequences of climate related dynamics on evolution of species, society and fisheries variability. The author ranked the impacts of climatic changes on regional fisheries and recognized the following fisheries as most responsive to climatic variables (in descending order of sensitivity):

- freshwater fisheries in small rivers and lakes, in regions with larger temperature and precipitation change; fisheries within exclusive economic zones (EEZ), where access–regulation mechanisms artificially reduce the mobility of fishing groups and fleets and their abilities to adjust to fluctuations in stock distribution and abundance;
- fisheries in large lakes and rivers;
- fisheries in estuaries, particularly where there are species *sans* migration or spawn dispersal paths or in estuaries impacted by sea-level rise or decreased river flow, and
- high seas fisheries. Furthermore, it was pointed out that large scale production sea fisheries are not under immediate imparted impacts by climate change and those that are most impacted are the ones affected by human interventions such as dams, diminished access to up- or down-river migrations and other issues related to human population growth and habitat manipulation (Sharp, 2003).

Perhaps the most comprehensive study dedicated to aquaculture and climate change was that of Handisyde *et al*. (undated). In that synthesis, the authors dealt with the influence of predicted climate changes such as temperature, precipitation, sea level rise, extreme events, climate variability and ocean currents on global aquaculture. Impacts on aquaculture production, aquaculture dependent livelihoods and indirect influences on it through fish meal and fish oil availability were also dealt with. An extensive modelling exercise was included and a series of sub models developed that covered exposure to extreme climatic events, adaptive capacity and vulnerability. The study was complemented with a case study on Bangladesh, a country with one of the most extensive deltaic areas in the world and one of the most sensitive ones to sea level rise and to severe weather damage.

A very comprehensive treatise on the influence of climatic change on Canadian aquaculture is also available (2WE Associate Consulting, 2000).

In their review of the physical and ecological impacts of climate change on fisheries and aquaculture, Barange and Perry indicate that considerable uncertainties and research gaps remain (see chapter 1, this volume). Of particular concern are the effects of synergistic interactions between current stressors, including fishing and ecosystem resilience and the abilities of marine and aquatic organisms to adapt and evolve according to climatic changes.

Roessig *et al*. (2004) called for increased research on the physiology and ecology of marine and estuarine fishes, particularly in the tropics. Regarding freshwater fisheries, Ficke *et al*. (2007) suggested that the general effects of climate change on freshwater systems will occur through increased water temperature, decreased oxygen levels and the increased toxicity of pollutants. In addition, it was concluded that altered hydrological regimes and increased groundwater temperatures would impact on fish communities in lotic systems. In lentic systems eutrophication could be exacerbated and stratification become more pronounced with a consequent impact on food webs and habitat availability and quality. A more specific case study on the recruitment success of cyprinid fish in low lying rivers, in relation to the potential changes induced on the Gulf Stream by climatic change, was dealt with by Nunn *et al.* (2007).

There have been a number of studies on climate change and its impacts on fisheries that could indirectly affect aquaculture, such as a decline in ocean productivity (Schmittner, 2005). At this stage no attempt is made to be exhaustive in reviewing these studies as the most relevant ones are dealt with in Section 5.4. However, here attention is drawn to a few selected examples. Atkinson *et al*. (2004) described a decrease in Antarctic krill density (*Euphausia superba*) and a corresponding increase in salps (mainly *Salpa thompsonii*), one of the main grazers of krill. It is supposed that this trend is likely to be exacerbated by climatic changes, sea temperature increases and a decrease in polar ice. The use of krill as a major protein source for replacement of fish meal in aquaculture feeds has been advocated (Olsen *et al*., 2006; Suontama *et al*., 2007) but the current trend appears to indicate that this would not be a possibility (De Silva *et al*., 2008). This situation is complicated by the fact that krill is the major food item of baleen whales and many wild fish species.

5. Impacts of climate change on aquaculture

Impacts of climate change on aquaculture could occur directly and or indirectly and not all facets of climate change will impact on aquaculture. Aquaculture practices, as in any farming practice, are defined in space, time and size and have a fair degree of manoeuvrability. Furthermore, aquaculture production concentrates in certain climatic regions and continents (See Sections 3.1, 3.2, 3.3) with a well defined concentration of the sectoral practices. It may be that these developments, at least in the early stages of the sector's recent history, were driven by cultural attributes, such as of "living with water" and the associated historical trends to farm fish by certain ethnic groups. Yet it must be recognized that aquaculture growth in different regions may in fact change as a result of climatic change particularly in areas and regions where aquaculture in itself can provide adaptation possibilities for other sectors (e.g. coastal agriculture).

5.1 MAJOR CLIMATIC CHANGES THAT WOULD POTENTIALLY IMPACT ON AQUACULTURE

Not all climatic changes are likely to equally impact fisheries and aquaculture, either directly and or indirectly. Also, it is difficult to discern the causative effect of different elements of impacts of climate change on aquaculture and fisheries. Furthermore, the potential impacts on farming activities cannot be attributed to one single factor of climatic change. In most instances it is a chain of confounded effects that become causative and not a single recognizable factor. Those elements of climatic change that are likely to impact on aquaculture, based on the IPCC forecast (2007) can be summarized as follows:

- Global warming: There is agreement that our planet will heat by 1.1 °C this century and the increase could be up to 3 ^{o}C.

- Sea level rise: rise in sea level will be associated with global warming. The IPCC has estimated that oceans will rise ten cm to 100 cm over this century; thermal expansion contributing 10 to 43 cm to the rise and melting glaciers contributing 23 cm. Sea level increases will profoundly influence deltaic regions, increase saline water intrusion and bring about major biotic changes.

- Ocean productivity and changes in circulation patterns: major changes in ocean productivity and circulation patterns are predicted; the most impacted being the North Atlantic (Schmittner, 2003) and Indian oceans (Gianni *et al*., 2003; Goswami *et al.*, 2006). These changes will impact on individual fisheries and other planktonic plant and animal group biomasses and result in changes in food webs.

- Changes in monsoons and occurrence of extreme climatic events: frequency of occurrence of extreme climatic events such as floods, changes in monsoonal rain patterns (Goswami *et al.*, 2006) and storminess in general.

- Water stress: IPCC (2007) estimates that by 2020 between 75 and 250 million people in Africa are expected to be under water stress and freshwater availability in Central, South, East and South East Asia, particularly in larger river basins is projected to decrease. South America and Europe are better placed.

- Changes in hydrological regimes in inland waters: atmospheric warming is likely to bring about changes that could impact on aquaculture activities in both lentic and lotic waters. For example, eutrophication could be exacerbated and stratification more pronounced and consequently could impact on food webs and habitat availability and quality (Ficke *et al*., 2007), both aspects in turn could have a bearing on aquaculture activities, in particular inland cage and pen aquaculture.

5.2 FACETS OF AQUACULTURE VULNERABILITY TO CLIMATE CHANGES

Unlike other farmed animals, all cultured aquatic animal species for human consumption are poikilothermic. Consequently, any increase and/or decrease of the temperature of the habitats would have a significant influence on general metabolism and hence the rate of growth and therefore total production; reproduction; seasonality and even possibly reproductive efficacy (e.g. relative fecundity, number of spawnings (see Wood and McDonald, 1997); increased susceptibility to diseases and even to toxicants (Ficke *et al.*, 2007). The lower and upper lethal temperature and the optimal temperature range for fish species differ widely (Table 6). Therefore, climate change induced temperature variations are bound to have an impact on spatial distribution of species specific aquaculture activities.

Furthermore, aquaculture occurs in three widely different environments viz fresh water, marine and brackish water, each suited to particular groups of aquatic species with particular physiological traits. Climate change is likely to bring about significant changes particularly with respect to salinity and temperatures in brackish water habitats and will therefore influence aquaculture production in such environments. In this context, current aquaculture activities could respond to the degree of sea level rise and the influx of brackish water inland by relocating farms or alternately farming more saline tolerant strains. There are interactive effects between temperature and salinity; one influencing the other. Such influences vary widely between cultured aquatic organisms and have to be taken into consideration in developing adaptive measures.

5.3 DIRECT IMPACTS

The impacts on aquaculture from climate change, as in the fisheries sector, will likely to be both positive and negative arising from direct and indirect impacts on natural resources required for aquaculture; the major issues being water, land, seed, feed and energy.

5.3.1 Known direct impacts to date

To date, there has been only one reported direct impact from human induced climatic change on aquaculture. This relates to a smog cloud generated over Southeast Asia during the 2002 El Niño. Although the phenomenon was not attributed to human activities *per se*, it cut sunlight and heat to the lower atmosphere and the ocean by 10 percent and, some authors suggest, contributed to dinoflagellate blooms that impacted aquaculture in coastal areas, from Indonesia to S. Korea, causing millions of US dollars worth of damage to aquaculture (Swing, 2003).

Major recent climatic disasters with relevant impacts on coastal communities, such as the 2008 cyclone in Myanmar or the repetitive hurricanes in the Caribbean have been connected to climate change but there is no scientific consensus on this.

5.3.2 Potential impacts

In the following sections we attempt to evaluate climate change impacts on different aquaculture practices in different environments and in certain instances in relation to commodities. Whenever possible we also address the most immediate adaptation measures.

Table 6. Temperature tolerances of selected, cultured species of different climatic distribution. Modified after Ficke *et al.* (2007).			
Climatic/temperature guild/ Species	**Incipient lethal temp. (ºC)**		**Optimal range (ºC)**
	Lower	**Higher**	
Tropical			
Redbelly tilapia (*Tilapia zillii*)	7	42	28.8-31.4
Guinean tilapia (*Tilapia guineensis*)	14	34	18-32
Warm water (sub tropical)			
European eel (*Anguilla anguilla*)	0	39	22-23
Channel catfish (*Ictalurus punctatus*)	0	40	20-25
Temperate/polar			
Arctic charr (*Salvelinus alpinus*)	0	19.7	6-15
Rainbow trout (*Oncorhynchus mykiss*)	0	27	9-14
Atlantic salmon (*Salmo salar*)	-0.5	25	13-17

5.3.2.1 Global warming and temperature increase associated impacts

Global warming is a major impact of climate change. Increased temperature brings about associated changes in the hydrology and hydrography of water bodies, exacerbates the occurrence of algal blooms and red tides etc., all factors that could have important impacts on aquaculture.

In order to assess this impact on aquaculture and consider appropriate adaptive measures It is thought best to deal with different major culture systems *vis-à-vis* freshwater and marine environments as separate entities.

Inland aquaculture

- **Pond aquaculture**:

The great bulk of aquaculture in the tropical and subtropical regions is finfish culture (Figure 9). The dominant form of inland finfish aquaculture is in ponds, the size of which range from a few hundred square meters to a few hectares. Often the ponds are shallow; the deepest aquaculture ponds in operation being catfish ponds in Viet Nam with an average water depth of 4 to 4.5 m. The main factors that contribute to determining pond water temperature are solar radiation, air temperature, wind velocity, humidity, water turbidity and pond morphometry. The predicted increase in air temperature will cause an increase in vaporization and cloud cover (IPCC, 2007) and thereby reduce solar radiation reaching the ponds. Overall therefore, an increase in global air temperature may not directly be reflected in corresponding increases in inland aquaculture ponds. This suggests there may be no need to plan species changes or the *modus operandi* of the current aquaculture practices, particularly in the tropics and sub tropics.

However, the scenario may be slightly different in pond aquaculture in temperate regions; such activity on a global scale is small and confined primarily to the salmonid species and to a lesser extent, carps. The most popularly cultured salmonids in freshwater are rainbow (*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*); these have a very narrow optimal range of temperature and a relatively low upper lethal limit (Table 6). These species are also cultured in tropical highland areas, albeit to a smaller extent, but provide livelihood means for poor farming communities. The air temperature increase could be reflected in temperature increases in aquaculture ponds impacting productivity and in extreme cases, causing mortality (see following section on cage culture for more details). In most cases the culture practices for trout and salmonids occur in high water exchange ponds or in raceways with a free flow of water, literally 24 hours a day through the culture cycle (see Section 5.3.2.4 for details). Such water exchange may soften the potential impact on increased temperatures. However, the availability of water becomes an issue for these systems when climate-change-driven droughts take place, as is already happening where glaciers are retreating in some areas on the Andes in South America.

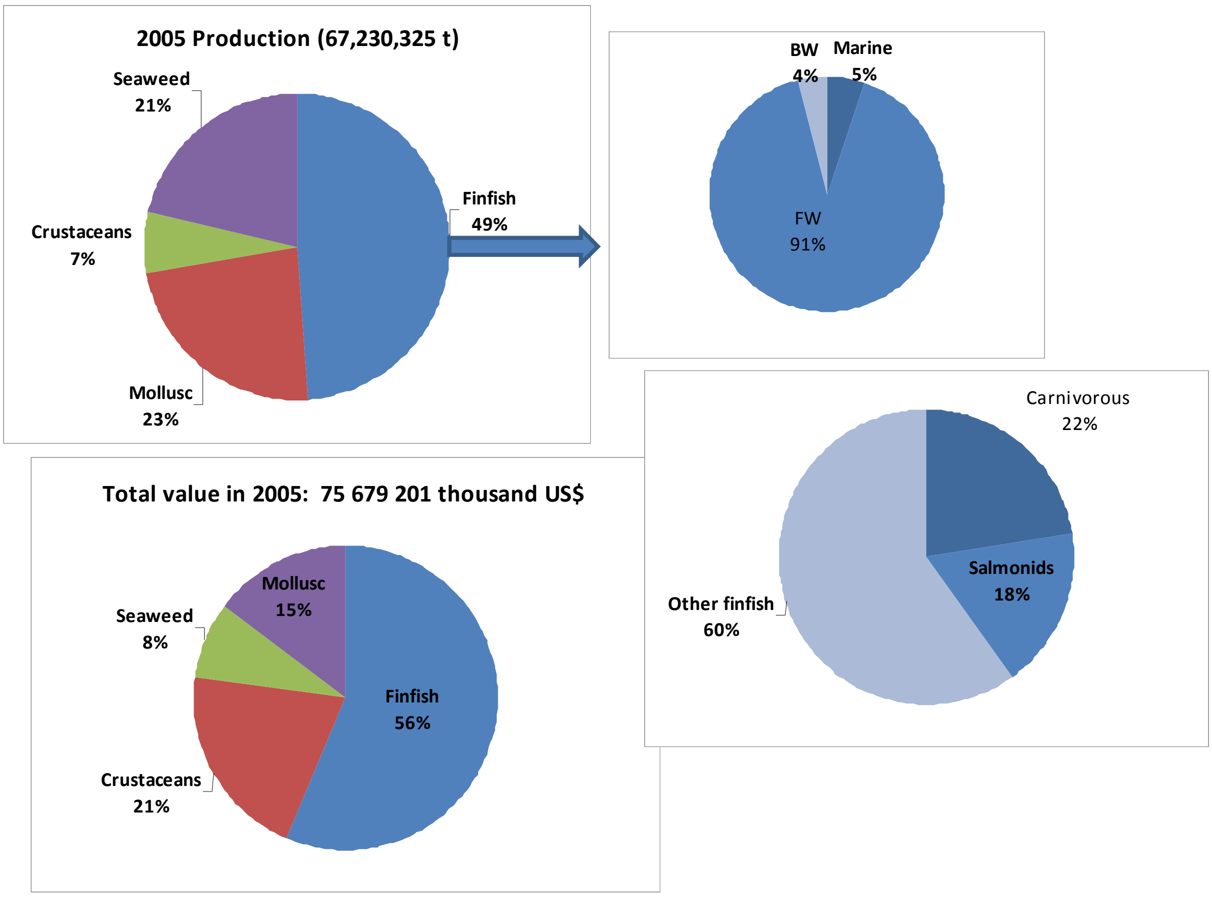


Figure 9. Percent contribution to global aquaculture production and value in 2005 commodity wise, together with the finfish production in relation to environment (FW - freshwater, BW - brackish water; M - marine) and habitat type. Based on FAO statistics (FAO, 2008).

- ## Integrated aquaculture

Integrated aquaculture is a very old practice that may take many forms: rice *cum* fish culture and/or aquaculture integration with animal husbandry. All these forms are very traditional practices, conducted on small-scale, often single unit family operations.

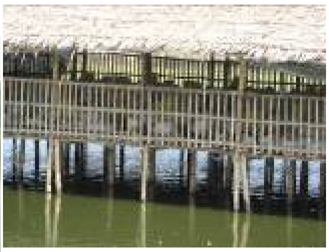
Integrated aquaculture is still relatively popular in rural China and is also practiced in other tropical Asian countries and a few temperate regions in eastern Europe. The exact production level of fish and other commodities from such practices is not accurately known, but suffice to say they are important to rural communities where aquaculture is practiced often as the sole livelihood (Miao, in press).

In general, the fish species cultured are those feeding low in the trophic chain and more often than not external feeds are not provided; stock fending for itself on the natural production of phyto- and zoo-plankton and the benthos. Consequently, these practices essentially act as carbon sinks. Feare (2006) suggested that integrated poultry/duck aquaculture could spread the avian influenza virus, especially in view of the fact that integrated aquaculture falls within sectors 3 and 4[4] of the FAO (2004) farm management guidelines for biosecurity. There are increasing concerns that these practices may imperil certification of the aquaculture produce and marketability and there is a need to adopt further precautionary approaches.

Highly pathogenic avian influenza, commonly known as bird flu, is mostly caused by the H5N1 strain of type A virus from the Orthomyxoviridae virus family. It is highly pathogenic i.e., easily spread among both domestic fowl and wild birds. The question is: would climate change impact on integrated fish farming in relation to the spread of the avian influenza virus, with increased risks to human health?

It turns out that the opposite may be true. The potential climatic change impact lies in the fact that an increase in water temperature could occur, albeit to less significant levels than in temperate climates. However, it has been shown that the persistence of H5 and H7 avian influenza viruses are inversely proportional to temperature and salinity of water and that significant interactive affects between the latter parameters exist (Brown *et al*., 2006). Overall therefore, climatic change influences on integrated aquaculture could be minimal, if the fears of these practices impacting on the spread of avian flu viruses disappear or minimize. Perhaps as an adaptive measure these practices, which help carbon sequestration (see Section 6.1.2), should be further popularized and encouraged and developed to meet the food safety standards.

Box 2. Integrated fish farming is a popular activity which originated in China and has been adopted by many Asian countries as an effective rural food production system. These farming practices are an efficient and effective means of recycling biological wastes, but are encountering important questions about food quality.. Photos: integrated fish and poultry and pig farming.



[4] Sector 3 - commercial production systems with low to minimum biosecurity and birds/products usually entering live bird markets; birds are in open sheds and may spend time outside the shed; and sector 4 - village or backyard production systems with minimal biosecurity and birds/products consumed locally)

- **Cage culture**

Globally cage aquaculture is becoming an increasingly important facet of aquaculture development and will continue to do so for the foreseeable future (Halwart, Soto and Arthur, 2007). This trend is possibly being driven by:

- a realization, in the wake of limitations on land and water availability, of the need to utilise existing inland waters for food fish production, (De Silva and Phillips, 2007) and

- in the marine environment to fulfil the increasing demands for higher quality/high valued food fish;

- inland cage culture is also considered an important means of providing alternative livelihoods for people displaced from reservoir impoundment (Abery et al., 2005), a situation occurring at the highest rate in Asia (Nguyen and De Silva, 2006).

Inland cage culture practices are very variable in intensity and mode of operation and in the species cultured. However, a large proportion of inland cage culture occurs in tropical regions, primarily in reservoirs and lakes, with more traditional and less commercial practices occurring in rivers. Almost as a rule, inland cage culture is confined to low- to mid-value food fish production (De Silva and Phillips, 2007). Unregulated proliferation of cage culture practices in many water bodies in the tropical region has resulted in the regular occurrence of fish kills, disease transmission and consequently lower profits mostly as a result of a high density of cages in a single water body without any consideration of the carrying capacity of the ecosystem (Abery *et al.*, 2005).

Ficke *et al*., (2007) suggested that climatic changes could exacerbate eutrophication and produce more pronounced stratification in lentic systems. Increased eutrophication could result in oxygen depletion in the dawn hours; sudden changes in wind patterns and rainfall could result in upwelling bringing deep/bottom oxygen depleted waters to the surface, with adverse effects on cultured stocks and naturally recruited fish stocks in the water body. Currently in some water bodies, deoxygenation problems caused by upwelling have resulted in restricting cage culture to one crop per year as opposed to two crops per year previously. In the presence of climatic changes it may be that in the tropics cage culture activities would have to be better planned to avoid such effects, otherwise those culture systems will no longer be possible. In this regard, adaptive measures would need to consider an ecosystem perspective with a high degree of conformity between the extent of cage culture practices and the carrying capacity of each water body. The siting of cages should also avoid very shallow areas and limited water circulation zones.

Traditional, river based cage culture occurs in most tropical regions in Asia. Although from a production point of view, the contribution from such practices is thought to be relatively minor; they provide a means of subsistence farming for many of those living in the vicinity of rivers. Often these farms tend to culture relatively low-valued fish for local markets and most of them rely on natural seed supplies (De Silva and Phillips, 2007). Although most aquaculture practices are now independent of wild caught seed resources (a major exception being eels and a few marine carnivorous species), there are still a few artisanal practices in rural areas, particularly by communities living in the vicinity of rivers, where some degree of subsistence cage culture is based on wild caught seed stocks (De Silva and Phillips, 2007). Climatic change could affect breeding patterns of natural populations and could impact on such seed supplies; also reduced water availability in the rivers could indirectly impact on this subsistence aquaculture. Improved farming practices, including more efficient feeding, could be an adaptation required to face the mentioned potential changes.

Mariculture

Mariculture practices involving sand and bottom culture and raft and cage culture, occur inshore and offshore areas in all three climatic regimes viz tropical, subtropical and temperate. The main aquaculture activity in temperate regions is the mariculture of salmonids in cages (Halwart, Soto and Arthur, 2007). Mariculture in tropical and subtropical regions consists of relatively high priced finfish varieties such as groupers (e.g. *Epinephalus spp*., snappers, *Sparus* spp., cobia, *Rachycentron canadum*, etc.). In addition, there are mariculture operations for molluscs such as *Ruditapes* sp., *Mytilus* sp., and seaweeds such as *Gracilaria* sp. (see Figures 4, 5, 6). Seaweeds, oysters and clams constitute the largest proportion of mariculture production worldwide. The culture of these latter groups implies minimal energy consumption and they are essentially carbon sequestering. The main energy costs associated with the culture of these organisms are in the transportation of the product to the consumer. These cultures are carbon friendly to a very high degree and in general, providing they are appropriately located, cause only minor environmental perturbation if any at all. Essentially, recorded perturbations have been associated with changes to the hydrographical conditions in the culture area and with sedimentation of faeces and pseudo-faeces on the bottom.

Climate changes and in particular global warming, could both directly and indirectly impact on mariculture in temperate regions. Species cultured in those regions, predominantly salmonids (e.g. *Salmo salar*) and emerging culture of cod, *Gadus morhua*, have a relatively narrow range of temperature optima (See Table 6). The salmon farming sector has already witnessed an increase in water temperature over the recent past and it is acknowledged that temperatures over 17 ºC would be detrimental, when feed intake drops and feed utilization efficacy is reduced. In order to develop possible adaptive measures, research has been initiated on the influence of temperature on feed utilization efficacy and protein and lipid usage for growth as opposed to maintaining bodily functions at elevated temperatures, e.g. 19 ºC.

Box 3 Cage culture in inland waters take many forms, often traditional, more subsistence, cage culture practices occur in tropical rivers and more commercial developments in lakes and reservoirs. The latter is often carried out intensively, often exceeding the carrying capacity of the water body and over the years in some instances, fish kills have begun to occur on a regular basis. Climate changes could perhaps exacerbate this situation unless mitigating measures are set in place. The photos show an array of cage culture activities in tropical Asia.

Some authors have shown that low fat feeds result in better performance at higher temperatures (Bendiksen *et al*., 2002); therefore there is some room for improvement and adaptation through feeding. Equally, there is the potential for increasing the culture of marine fish species such as cobia (*Rachycentron canadum*),one of the fastest growing species with high food conversion efficiency and requiring relatively less protein in its diet than many other cultured marine finfish species. Unlike many other cultured marine species, it is highly fecund and the hatchery production of seed is routinely achieved with a high survival rate of larvae (Benetti *et al.*, 2008).

Sea temperature rise in tropical and subtropical regions would result in increased rate of growth and hence in overall production. The predicted temperature rise itself will be within the optimal ranges for most species cultured in such waters (marine, brackish and/or freshwater) and therefore global warming could impact positively on the bulk of aquaculture production, provided the feed inputs required for compensating the enhanced metabolism are met and that other associated factors, such as disease, do not become more detrimental.

In 2006 the production of marine and brackish water fish reached 4 385 179 tonnes, of which 39 percent were salmonids. Most of that production was based on feed, the major ingredients of which were fishmeal and fish oil. Feed management in salmonid culture is probably the most efficient of all aquaculture practices, however, the high degree of dependence on fish meal and fish oil becomes a very pertinent issue under most climate change scenarios. The potential impacts of climate change on future availability of these commodities for aquafeeds are dealt with in detail later (see Section 5.4). Feed developments for salmon over the last two decades and more have resulted in a significant reduction of feed conversion factors and in the use of less fish meal in diets, primarily through the adoption of high energy diets utilising the protein-sparing capabilities of salmonids. In general other marine fish farming operations lag behind in these replacement trends as they do in reducing food conversion rates (FCRs) partly because their industries are relatively younger. The challenge that confronts the sector is to ensure that high energy density feeds are equally effective in an increased temperature *milieu*.

Climate change is predicted to increase global acidification (Hughes *et al.*, 2003; IPCC, 2007). Apart from its impact on coral formation, there is the possibility that increased acidification could impede calcareous shell formation, particularly in molluscs, an effect perhaps exacerbated by increased water temperature and thereby to have an impact on mollusc culture. This has received little attention and warrants urgent research. Currently, mollusc culture accounts for nearly 25 percent of all aquaculture (approximately 15 million tonnes in 2005) and therefore any negative impacts on shell formation could significantly impact on total aquaculture production. There is practically no information on the potential impact of increased water temperature on the physiology of the most relevant aquaculture bivalves. Nevertheless, if coastal plankton productivity is enhanced by higher temperatures and provided that nutrients are available, there may be a positive effect on the farming of filter feeders. However, increased temperatures associated with eutrophication and harmful algal blooms (Peperzak, 2003) could enhance the occurrence of toxic tides and consequently impact production, and also increase the possibilities of human health risks through the consumption of molluscs cultured in such areas. Clearly more research is needed to provide better forecasts of expected net effects.

5.3.2.2 Saline water intrusion

In addition to estuarine shrimp farming activities in Asia, South America and the Caribbean, in tropical regions of Asia significant aquaculture activities occur in deltaic areas of major rivers in areas at the middle to upper levels of the tidal ranges. Most notable among these are the relatively-recently-emerged catfish culture (*Pangasianodon hypophthalamus*) and rohu (*Labeo rohita*) in the Mekong, Vietnam (Nguyen, 2006) and the Irrawaddy in Myanmar (Aye *et al.*, 2007), respectively.

Box 4. Catfish and rohu culture of the Mekong Delta and Irrawaddy region in Viet Nam and Myanmar respectively are aquaculture practices that have witnessed the highest growth ever. The regions in which these activities occur can be impacted by saline water intrusion from predicted sea level rise. The species intensively cultured at very high stocking densities and with high levels of feeding, are freshwater species with relatively low salinity tolerance. As such culture areas must be shifted further upstream to mitigate climatic change effects. On the other hand, climate impacts could make extra pond space available for shrimp farming, providing adequate links in the supply chains. The pictures depict catfish farming activities in the Mekong Delta.


The former two aquaculture operations have exploded in the last decade, accounting for production of 1.2 and 100 million tonnes respectively, generating considerable foreign exchange earnings and providing additional livelihoods to rural communities. The brackish water of most deltaic areas in tropical regions in Asia are also major shrimp culture areas.

More importantly, both fish and shrimp culture practices are still in a growth phase and almost all the produce is processed and exported. The consequence of this is that a large number of additional employment opportunities are created with a profound impact on the socio-economic status of the community at large.

Sea level rise over the next decades will increase salinity intrusion further upstream of rivers and consequently impact on freshwater culture practices. Adaptive measures would involve moving aquaculture practices further upstream, developing or shifting to more salinity tolerant strains of these species and/or to farming a saline tolerant species. Such shifts are going to be costly and will also impact on the socio-economic status of the communities involved. Most significantly, adaptive measures could result in a large number of abandoned ponds, reflecting what happened with shrimp farms a decade ago. On the positive side for aquaculture, salinity intrusions that render areas unsuitable for agriculture, particularly for traditional rice farming, could provide additional areas for shrimp farming. Shrimp is a much more highly valued commodity than many agriculture products and has greater market potential but it also has higher management risks. If these shifts are to be made, major changes in the supply chains have to be adopted and nations should build these needs into their planning and forecasting. Sea level rise and saline water intrusion will also impose ecological and habitat changes, including mangroves that act as nursery grounds for many euryhaline species. Although in general terms, most aquaculture practices presently rely only to a small extent on naturally available seed supplies (a notable exception being freshwater eel (*Anguilla* spp.), the need for continued monitoring of such changes is paramount to developing adaptive measures.

Specific predictions from sea level rise are available for the Mekong Delta, Viet Nam. The Mekong Delta is literally Viet Nam's food basket, accounting for 46 percent of the nation's agricultural production and 80 percent of rice exports (How, 2008). A one metre sea level rise is predicted to inundate 15 to 20 000 km^2, with a loss of 76 percent of arable land. The Mekong Delta is already the home of a thriving aquaculture development and the loss of arable land may present a clear instance where alternative livelihoods through aquaculture should be explored.

5.3.2.3 Changes in monsoonal patterns and occurrence of extreme climatic events

The frequency of extreme weather events such as typhoons, hurricanes and unusual floods has increased dramatically over the last five decades. The number of such events increased from 13 between 1950 and 1960 to 72 from 1990 to 2000 (IPCC, 2005). These extreme events result in huge economic losses. For the above two decades the average economic losses have been estimated at between US$4 and US$38 billion (fixed dollars) and in some individual years as high as US$58 billion (IPCC, 2005). Extreme climatic events are predicted to occur mostly in the tropical and subtropical regions. In past events the damages to aquaculture were not estimated.

El Niño and La Niña events also produce extreme weather in temperate regions. For example, during El Niño 1994 to 95 very large storms in southern Chile damaged the salmon industry significantly and resulted in a large number of escapes from sea cages (Soto *et al*., 2001). El Niño is also known to induce ecological effects on terrestrial ecosystems with consequent effects on land and sea vegetation and fauna (Jaksic, 2001). An El Niño event also increases the severity of winter storms in North America which may hamper development of offshore aquaculture. With the prediction that climatic change is likely to increase, the frequency of these phenomena could have a significant impact on coastal and offshore aquaculture in temperate regions, in addition to those impacts that are related to fish meal and fish oil supplies (see Section 5.4.1).

Extreme weather has the potential to impact aquaculture activities in tropical and subtropical regions in Asia and elsewhere. Potential impacts could range from physical destruction of aquaculture facilities, loss of stock and spread of disease. Recent extreme climatic events, unusually cold temperatures and snow storms that occurred in southern China, provide an example of the extent of impacts on aquaculture of such climate induced changes (it is not suggested that the recent events are a cause of global climatic change, however). Similarly, central Vietnam experienced the worst flood in 50 years in 2007 and the damage to aquaculture is yet to be estimated (Nguyen, 2008).

Preliminary estimates suggest that in central China there was a loss of nearly 0.5 million tonnes of cultured finfish stocks, mostly warm water species and mostly alien species, e.g. tilapia, of which a considerable proportion was broodstock (W. Miao, personal communication). The possible environmental perturbations that escapees, in particular cultured exotic/alien species would cause are yet to be determined.

Asian inland aquaculture is dependent on alien species to a significant extent (De Silva *et al*., 2005). Although escape from aquaculture installations is almost unavoidable under normal circumstances and remains a persistent problem (Anonymous, 2007), the possibilities of large numbers of cultured stock entering natural waterways, because of the destructive effects of extreme climatic events, are far greater. Such large scale unintentional releases have a greater probability of causing environmental disturbances and the potential for impacting biodiversity becomes considerably higher. In addition, there are direct financial losses and damage to infrastructure of the aquaculture facilities.

It is, however, almost impossible to take adaptive measures to avoid such potential events, except perhaps a reduction on the dependence on alien species that would thereby limit damage to immediate financial losses only (lost stock). Yet this is not a perfect solution because escapes of native species can be a problem when they affect the genetic diversity of native stocks, as has been well documented for Atlantic salmon (Thorstad *et al.*, 2008); extreme weather events are cited as the most frequent causative factor for such escapes. However, the effect of escapes of other native farmed species has been largely neglected worldwide.

Climate change in some regions of the world is likely to bring about severe weather (storms), water quality changes (e.g. from plankton blooms) and possibly increased pollutants and other damaging run off from land based sources caused by flooding, impacting on coastal areas. Such weather conditions will increase the vulnerability of sea based aquaculture, particularly cage aquaculture, the predominant form of marine aquaculture of finfish and seaweed farming in coastal bays in Asia, which is gradually becoming the major contributor to cultured seaweed production globally (see Figure 7). There is an increased vulnerability of near-shore land based coastal aquaculture, of all forms, to severe weather, erosion and storm surges, leading to structural damage, escapes and loss of livelihoods of aquaculture farmers. Some of the most sensitive areas will be the large coastal deltas of Asia which contain many thousands of aquaculture farms and farmers, primarily culturing shrimp and finfish. Downstream delta ecosystems are also likely to be some of the most sensitive because of upstream changes in water availability and discharge, leading to shifts in water quality and ecosystems in the delta areas. Few adaptive measures are available for such impacts although they are perhaps similar to those suggested for inland aquaculture.

Hurricane seasons in Central America have had impacts on coastal rural aquaculture; such was the case in Nicaragua where shrimp farming flourished from early 1990 until 1998 when Hurricane Mitch devastated many farms and small farmers did not have the capacity to replace production. Other storms which caused heavy damage have been hurricanes Dennis and Emily in Jamaica, hurricane Stan in El Salvador and Guatemala and more recently hurricane Felix which wiped out many rural areas in Nicaragua, some of them with incipient aquaculture activities. In general, most relevant adaptive measures involve evaluation of weather related risks in the location of farms and this is highlighted under "aquaculture zoning" in section 7.2.4.

5.3.2.4 Water stress

Projected water stresses brought about by climate change could have major impacts on aquaculture in tropical regions, particularly in Asia. The predicted stress is thought to result in decreasing water availability in major rivers in Central, South, East and Southeast Asia and in Africa (IPCC, 2007), areas where there are major aquaculture activities. For example, the deltaic areas of some of the major rivers such as the Mekong, the Meghna-Brahamaputra and Irrawardy, are regions of intense aquaculture activity, contributing to export incomes and providing many thousands of livelihoods. Apart from this, prudent use of this primary resource is becoming an increasing concern for sustaining aquaculture.

The amount of water used in food production varies enormously between different sectors. Zimmer and Renault (2003) suggested the need to differentiate between food production sectors, such as, for example, in the main:

- primary products (e.g. cereals, fruits etc.);
- processed products (e.g. food items produced from primary products);
- transformed products (e.g. animal products because these are produced using primary vegetable products); and
- low- or non-water consumptive products (e.g. seafood).

A comparison of specific water needs for unit production for selected commodities of the animal husbandry sector are given in Table 7. However, apart from pond aquaculture, other practices such as cage culture are almost totally non water consuming, directly, except for the need for feeds. In general, reduction of aquaculture water use could be achieved through (a) selection of feed ingredients that need little water to be produced, (b) enhancement of within-aquaculture-system feed production through periphyton based technologies and (c) integration of water with agriculture (Verdegem *et al.,* 2006). Some of the above measures are already being used in Asian aquaculture based on finfish species feeding low in the food chain, such as for example, increasing naturally available food sources through appropriate periphyton production in carp polyculture systems (Wahab *et al*., 1999; Van Dam *et al*., 2002).

The predicted reduced water availability in major river systems in the deltaic regions of Asia, where major aquaculture activities exist, has to be considered in conjunction with saline water intrusion arising from sea level rise (Hughes *et al*., 2003) and the expected changes in precipitation or monsoon patterns (Goswami *et al*., 2005).

Along major river systems in tropical Asia there is extensive water extraction and discharge into rivers, particularly from very intensive aquaculture practices such as shrimp and catfish farming. As such, a major modelling attempt incorporating these variables for deltaic regions such as the Mekong, Meghna-Brahamputra in Bangladesh and Irrawardy in Myanmar, amongst others, will enable to determine more accurately:

- the degree of sea water intrusion in the river and into the adjoining wetlands;
- assessment of agricultural activity that is likely to be lost as a result of sea water intrusion;
- gross changes in habitats (also see Section 5.3.2.1.b). The potential impacts on spawning migrations and therefore the changes in seed availability for subsistence cage farming;
- overall socio-economic impacts of the resulting events.

Table 7. Specific water demand (m^3/t) for different animal food products (data from Zimmer and Renault, 2003) and comparison with needs for aquaculture.	
Product	**Water demand**
Beef, mutton, goat meat	13 500
Pig meat	4 600
Poultry	4 100
Milk	790
Butter + fat	18 000
Common carp (intensive/ponds)[a]	21 000
Tilapia (extensive/ponds) [a]	11 500
Pellet fed ponds [b]	30 100
a- Muir,1995: b- Verdegem *et al*., 2006	

Such information will allow adaptive actions; for example it would answer the question: would the loss in agricultural activity in these deltaic areas be compensated for by providing alternative livelihoods through aquaculture (mariculture)? This possibility can be considered as a potential non-detrimental impact of climate change on poor rural communities where a more lucrative livelihood could be found. If such an adaptive measure is to be undertaken there is a need for speedy capacity building in aquaculture amongst the agricultural communities and provision of suitable government support to facilitate the shift from agriculture to aquaculture, including perhaps financial support for infrastructure e.g. ponds, hatcheries and development.

Increasingly, inland culture of salmonids in temperate regions and in highlands, low temperature areas of subtropics and tropics, is tending to adopt a raceway culture, in which the demand for water is extremely high. The likelihood is that water stress will impact on these forms of aquaculture and consequently there needs to be a change in the practices if salmonid aquaculture in raceways is to survive. In upstream areas, because of increased melting of the snow cover, new areas for aquaculture of cold and temperate species may become a possibility.

Non consumptive uses of water in aquaculture, such as cage culture (apart from inputs into feed production) and the use of small lentic waters for culture-based fisheries (CBF) (De Silva, 2003; De Silva *et al*., 2006) based on naturally produced feed within the water system, are being encouraged. CBF is a community based activity that utilises a common property water resource, is less capital intensive and is known to be most effective in non perennial water bodies that retain water for six to eight months (De Silva *et al*., 2006). Climate change in some regions, particularly in Asia and Africa, is predicted to increase drought periods (Goswami *et al*., 2005; IPCC, 2007), resulting in less water retention time in non perennial water bodies. This will make such water bodies relatively unsuitable for aquaculture purposes because a minimum period of six months of water retention is needed for most fish to attain marketable size.

To relieve major constraints or the impacts of potential water stresses dedicated efforts are needed to conserve this primary resource in land based aquaculture, still the most predominant form of inland aquaculture. In this regard recirculation technology is considered a plausible solution. However, the capital outlay and maintenance costs for recirculation technology that is currently available are rather high, so are the required skill levels for routine management (De Ionno *et al.,* 2006). In order to be profitable, the

accepted norm is that species cultured in recirculation systems, should command a relatively high market price. This entails the culture of species feeding high in the food chain, which means problems of feed need to be addressed. One of the main goals of adaptive measures to minimize climate change impacts is that they revolve around "energy savings". Energy costs of maintaining recirculation systems are rather high (De Ionno *et al*., 2006) and even if the operations are financially rewarding, they would contribute to green house gas emissions, the primary causative factor for climate change, far more than other traditional aquaculture activities.
Over the last two decades, more often than not, development of offshore mariculture has been advocated as a plausible means of increasing food fish production and doing so with minimal immediate environmental perturbations. Such developments have been impeded by technical and logistical challenges and the capital outlays required (Grøttum and Beveridge, 2007). Needless to say, such developments will also have to encounter the inevitable problem facing most aquaculture that of supplying adequate levels of fish meal and fish oil in the feeds.

5.4 INDIRECT IMPACTS OF CLIMATE CHANGE ON AQUACULTURE

Indirect impacts on a phenomenon and or a production sector can be subtle, complex and difficult to unravel and the challenges in developing adaptation measures to combat or overcome them may be formidable.
Because fisheries are a major source of inputs for aquaculture, providing feed in particular and seed to some degree, changes in fisheries caused by global climate change will flow through into aquaculture systems. The suitability of different areas for aquaculture species will be particularly important and the availability and prices of resources such as fish protein for fish feed will also be pertinent factors. Handisyde *et al*. (undated) considered two indirect impacts that climate change may have on aquaculture *vis-à-vis* possible influences on price fluctuations of capture fishery produce and impacts on the availability of fish meal and fish oil. The report dealt with production changes in fish meal and fish oil and the need to change the extent to which fish meal and fish oil are utilized in aquaculture but did not elaborate further.
It is also important to point out that a relatively unpredictable scenario is likely to come about with respect to the production of aquafeed. This might be caused by the increasing diversion of some raw plant materials to produce biofuels. This competition could create impacts such as a limited availability and high cost of ingredients for aquafeed. As the production of biofuels and the diversion of raw materials for this purpose are in a somewhat transient stage, with opposing viewpoints being expressed by different stakeholders, it is premature for us to dwell on this in any detail, let alone to predict its impacts on future availability of aquafeed.

5.4.1 Fish meal and fish oil supplies

The most obvious and most commonly discussed indirect impact of climate change on aquaculture is related to fish meal and fish oil supplies and their concurrent usage in aquaculture. Tacon *et al*. (2006) estimated that in 2003, the aquaculture sector consumed 2.94 million tonnes of fish meal globally (53.2 percent of global fish meal production), considered to be equivalent to the consumption of 14.95 to 18.69 million tonnes of forage fish/trash fish/low valued fish, primarily small pelagics. Globally there has been a significant research effort to combat this burgeoning problem. Studies have been conducted on almost every cultured species to test fish meal replacement with other readily available and cheaper sources of protein, primarily agricultural by-products. The literature in this regard is voluminous and exhaustive. Unfortunately, however, the transfer of the findings into practice remains relatively narrow and negligible, the only notable exception being the relatively high amounts of soybean and corn meal being used in aquatic feeds. The problems encountered in this transfer, as well as other related issues have been dealt with in detail previously (e.g. Tacon *et al*., 2006; Hasan *et al*., 2007; De Silva *et al*., 2008).

Industrial fish meal and fish oil production is typically based on a few, fast growing, short lived, productive stocks of small pelagic fish in the subtropical and temperate regions. The major stocks that contribute to the reduction industry are the Peruvian anchovy, capelin, sandeel, and sardines. It has been predicted that the biological productivity of the North Atlantic will decrease by 50 percent and ocean productivity worldwide by 20 percent (Schmittner, 2003). Apart from the general loss in productivity and consequently its impact on capture fisheries and hence the raw material available for reduction processes, there are other predicted impacts of climate change on fisheries. It is a possibility that predicted changes in ocean circulation patterns will, result in the occurrence of El Niño type influences being more frequent. The latter, in turn, will influence the stocks of small pelagics (e.g. Peruvian anchovy, *Engraulis rigens),* as has occurred in the past. The influence of El Niño on the Peruvian sardine and anchovy landings and consequently on global fish meal and fish oil supplies and prices are well documented (Pike and Barlow, 2002). Similarly, the changes in the North Atlantic oscillation winter index (Schmittner, 2003), resulting in higher winter temperatures, could influence sandeel (*Ammodytes* spp.) recruitment. Such changes in productivity of fisheries that cater to the reduction industry will limit the raw material available for reduction and particularly the main fisheries on which fish meal and fish oil production is based.

Bearing in mind that aquaculture is not evenly spread across the globe, essentially predominating in tropical and subtropical regions, it is appropriate to consider which practices would be impacted most, and how. It is evident from Figure 10 that, although fish meal usage in aquafeeds is considerably higher in Asia, fish oil usage is higher in Europe. More importantly, the production per unit of fish meal and fish oil usage is considerably higher on those continents where aquaculture is mostly based on omnivorous fish species which are provided with external feeds containing much less fish meal and very little fish oil. The latter fact is highlighted when cultured species groups are considered in relation to the return per unit use of fish oil and fish meal in the feeds (Figure 11). This analysis is based on the amount of fish meal and fish oil used in the feeds for each group of finfish and crustaceans, the average food conversion rate (FCR) for each and the extent of use of such feeds for each group. The analysis presented indicates that, in the wake of possible climate changes and consequent negative impacts on wild fish populations that cater to the reduction industries, the way forward is to make a concerted effort to increase and further develop omnivorous and filter feeding finfish aquaculture in the tropics and subtropics.

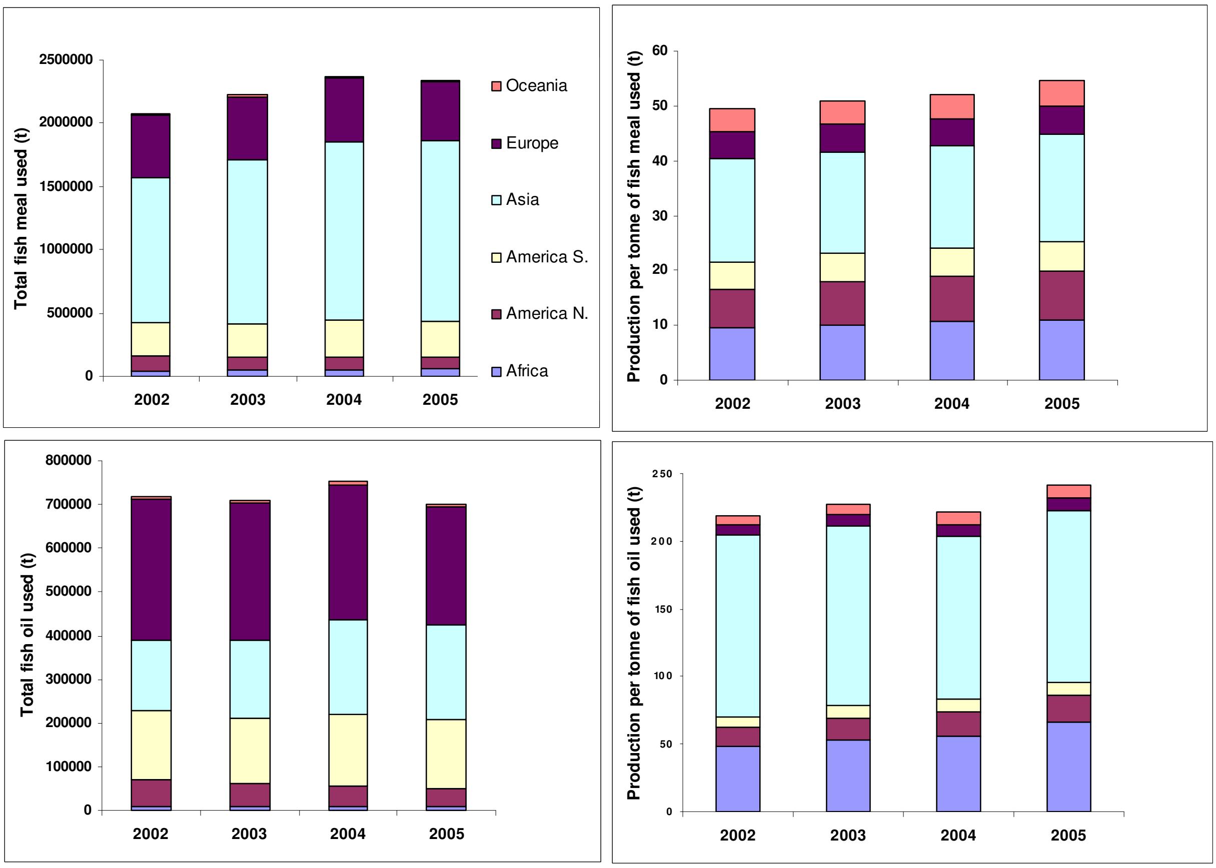


Figure 10. Estimates fish meal and fish oil used in aquaculture in the different continents and the aquaculture production per unit use of fish meal and fish oil (calculated from data from the IFMFO).

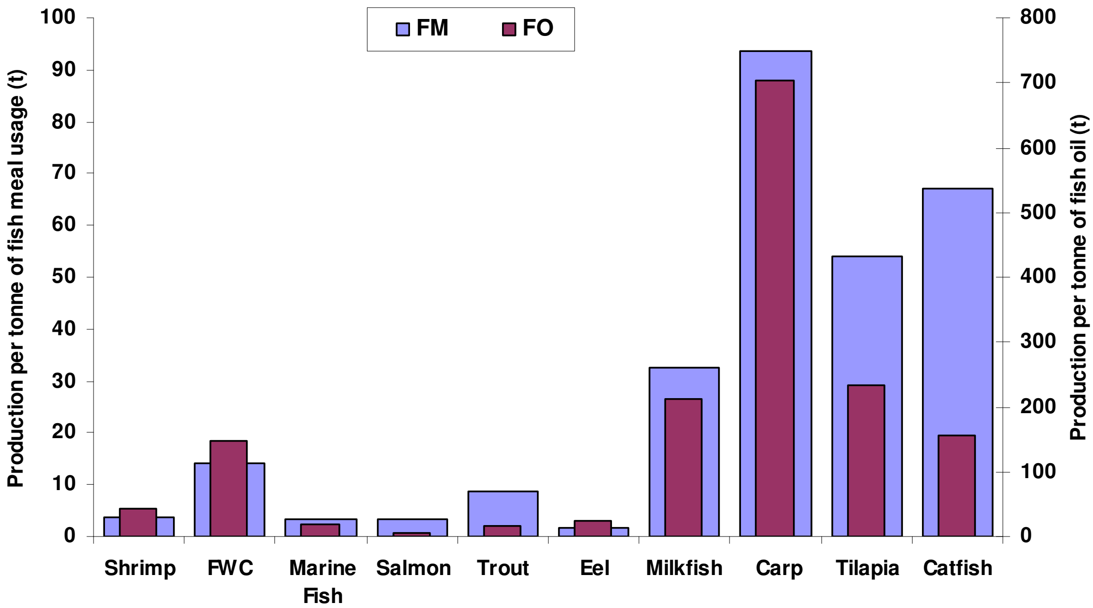


Figure 11. Aquaculture production per tonne of fish meal and fish oil used in the different cultured groups that are provided with aquafeeds containing these commodities.

This suggestion has been made many times, by several authors (Naylor *et al*., 1998; 2000, amongst others). Such an adaptation would require profound changes in consumer and market demands. Bringing the attention of the public to this issue transforms it into an ethical debate. Bearing in mind that many groups are, purely on ethical grounds, already advocating the channelling of the primary resources used in the reduction industries towards the poor as a direct food source (Aldhous, 2004; Allsopp *et al*., 2008), changes in public opinion could occur with time. Indeed, as further evidence becomes available on the channelling of fish resources for purposes other than the production of human food (De Silva and Turchini, 2008) there is a high probability that public demand would move slowly towards omnivorous and filter feeding finfish aquaculture.

5.4.2 Other feed ingredients used in aquaculture

Although the emphasis has been on how to reduce fish meal and fish oil usage in feeds for cultured aquatic organisms, over the last few years new problems are surfacing. For example soybean meal and corn meal are often used in feeds for cultured aquatic organisms and rice bran in tropical semi-intensive aquaculture. With the global quest to find suitable alternatives for fossil fuels, the current primary alternative is thought to be the production of biofuels. The use of some of the above ingredients for production of biofuels has resulted in many economic and social challenges resulting in a ripple effect (Naylor *et al*., 2006) and the ultimate impact of this on the aquaculture sector is difficult, if not impossible, to predict at this stage.

Apart from the above, the rising food price and the diminishing returns for the farmers (Anonymous, 2008a), also termed a “silent tsunami” (Anonymous, 2008b) are matters of concern for the aquaculture sector in that the availability of feed ingredients and the corresponding increased prices could impact on feed costs. In aquaculture, irrespective of the commodity and place of culture, farm gate prices have not increased significantly over the years; in fact for commodities such as shrimp (Kongkeo, in press) and salmon (Grøttum and Beveridge, 2008) it has declined in real terms. Profit margins in aquaculture are extremely narrow and such increases could impact them to the extent that at least some aquaculture activities become economically unviable. An important positive consideration is that in aquaculture feeds the agricultural ingredients used are almost always by-products. For example, soy bean meal used in aquafeeds is a by-product from the extraction of soy oil. Similarly, in semi-intensive aquaculture of carp species, for example in India mustard and peanut oilcakes, by-products after the extraction of oils, are used extensively in feeds (De Silva and Hasan, 2008).

Climate change impacts on terrestrial agriculture are beginning to be quantified and it is generally known that tropical terrestrial agriculture will be negatively impacted, more so than temperate regions (McMichael, 2001). A great majority of the agricultural by-products used in aquafeeds are of tropical origin. Unfortunately studies on price fluctuations of by-products are not readily accessible. There is an urgent need to evaluate the changes in availability, accessibility and price structure for agricultural by-products used in aquafeeds and to develop adaptive strategies to ensure that aquafeed supplies at reasonable prices could be retained well into the foreseeable future, so that aquaculture could remain economically viable.

5.4.3 Trash fish/low valued fish/forage fish supplies

There are other possible indirect impacts of climate change on specific aquaculture practices that are relatively large and, in a socio-economic context of great importance to certain developing countries. Again, these indirect impacts are related to aquafeed supplies and the ingredients thereof; in particular trash fish, low valued fish and forage fish (see Box 5).

It has been estimated that in the Asia-Pacific region the aquaculture sector currently uses 1 603 000 to 2 770 000 tonnes of trash fish or low valued fish as a direct feed source. The low and high predictions for year 2010 are 2 166 280 to 3 862 490 tonnes of trash fish or low valued fish as direct feed inputs (De Silva e*t al*., 2008). Sugiyama *et al*. (2004) estimated that in China 72.3 percent of five million tonnes (3 615 000 tonnes) of trash fish or low valued fish and 144 638 tonnes in the Philippines are used as feed for cultured stocks. Edwards *et al*. (2004) estimated that in Viet Nam 323 440 tonnes are used in aquaculture, the bulk of it to make farm-made feeds for pangasiid catfish cultured in the Mekong Delta. The summary of the different estimates of use of trash fish or low valued fish in Asia-Pacific aquaculture is given in Table 8 and it is evident that the quantities used are relatively large. It is important to note that the great bulk of this trash fish or low valued fish is produced by coastal artisanal fisheries in the region that provide thousands of livelihoods to fisher communities.

Apart from the general predicted reduction in ocean productivity it has been suggested that the Indian Ocean is the most rapidly warming ocean and consequently climate change would bring about major changes in it and on land, primarily on productivity and changes in current patterns (Gianni *et al*., 2003). The situation could be further exacerbated by extreme climatic events such as changes in monsoonal rain patterns (Goswami *et al.*, 2006) that influence inshore fish productivity and overall impact on the supplies of trash fish or low valued fish. Although issues related to reducing the dependence on trash fish or low valued fish of the growing mariculture sector in tropical Asia are being addressed, the impacts of the coming decade or so on this aquaculture sector cannot be ignored and needs to be addressed urgently. This is more so as subsistence and other small-scale fishers who lack mobility and alternatives and are often the most dependent on specific fisheries, will suffer disproportionately from alterations and occurrence of such changes which have been rated at medium confidence by the IPCC (2007).

Table 8: The total usage of trash fish/low valued fish as a direct feed source in Asian-Pacific aquaculture (from De Silva *et al*., 2008)

Activity	**Countries/ region**	**Grade***	**Quantity (x 1000 tonnes)**		
			Current (range)	**2010a**	**2010b**
Marine fish	SE Asia	A, B	1 603-2 770	913	1 663
S. Blue fin tuna	South Australia	B	50-60	45	50
Freshwater fish	Asia	A,B	332.44	na (332.44)	na (332.44)
Crab fattening	SE Asia	B	480-700	600	700
Mollusc farming	Asia	C	0.035-0.049	0.050	0.055
Total			2 166 280- 3 862 490	1 890 490	2 745 495

Grade A- low grade, unsuitable for human consumption; Grade B- may be suitable for human consumption; Grade C- good quality, suitable for human consumption. 2010 a=low and b=high predictions are based on increased production rates and associated changes in feed management given in previous Tables. For crabs and mollusc the predictions are based on an increase of a percent production from the current. na = not available.

Box 5. Trash fish/low valued fish/forage fish obtained primarily from small-scale artisanal, mostly coastal fisheries are an important entity in aquaculture activities in tropical Asia. This raw material may be used directly to feed the cultured stocks, as in the case of marine finfish or dried and powdered, as a cottage industry, or at the aquaculture facility and used in farm-made feeds in combination with other ingredients. Climatic changes could influence these small-scale fisheries through reduced ocean productivity (Schmittner, 2005), including the Indian ocean (Gianni *et al*., 2003) and consequently the supply of an important feed ingredient in rural small-scale aquaculture. The pictures depict the ingredient (dried fish), grinding and resulting pellet feed, prepared according specification at a farm site, being delivered to catfish in ponds in Viet Nam.

5.4.4 Impacts on diseases

There has been much debate about climate change and the associated risks for human health (e.g. Epstein *et al*., 1998; McMichael, 2003; Epstein, 2005). There is general consensus that the incidence of terrestrial vector borne and diarrhoeal diseases will increase. The potential trends of climatic change on aquatic organisms and in turn on fisheries and aquaculture are less well documented and have primarily concentrated on coral bleaching and associated changes. An increase in the incidence of disease outbreaks in corals and marine mammals, together with the incidence of new diseases has been reported (Harvell *et al*., 1999). Coral bleaching was linked to the high El Niño temperatures in 1997 to 1998 and it was suggested that both climate and human activities may have accelerated global transport of species, bringing together pathogens and previously unexposed populations (Harvell *et al*., 1999; Hughes *et al*., 2003). Daszak *et al*. (2000) suggested that increased agricultural intensification and associated translocations could exacerbate emerging infectious diseases in free living wild animals and impact on biodiversity because of climatic changes, in particular global warming in some arid parts of the globe. However, a decreasing trend is predicted in other areas, such as in Europe (IPCC, 2007).

It has been pointed out that there is a dearth of knowledge about parasites of aquatic animals other than those deleterious parasites that cause disease in humans. In the wake of the associated effects of climate change on circulation patterns and so forth and using predictions from a General Circulation Model, attempts were made to understand changes in parasite populations in temperate and boreal regions of eastern North America (Marcogliese, 2001). The overall conclusion from the simulations was that climatic change may influence selection of different life-history traits, affecting parasite transmission and potentially, virulence. It is difficult to predict the consequences of such changes on aquaculture *per se*, but the exercise points to the need for the aquaculture sector to be aware of potential and new threats from parasitism.

Because of anthropogenic influences, over the last two to three decades, there had been an increase in the rate of eutrophication in some oceans and the associated occurrence of harmful algal blooms-HABs (Smayda, 1990). It has been suggested that the rate of eutrophication and HABs would increase, resulting from oceanic changes brought about by climate change in some oceans and particularly in the North Atlantic and the North Sea (Peperzak, 2003; Edwards *et al.*, 2006), not homogenously but, for example, along the Norwegian coast and elsewhere. HABs will impact marine life and human health through the consumption of affected filter feeding molluscs, commonly referred to as shellfish poisoning. Apart from this impact, the HABs could also bring about harmful effects on cage culture operations of salmon, for example. Accordingly, adaptive measures need to be set in place for regular monitoring and vigilance of aquaculture facilities in areas of potential vulnerability to eutrophication and HABs.
The possibility of climate change enabling both highly competitive species, such as the Pacific oyster (*Crassostrea gigas*) and associated pathogenic species to spread into new areas has been highlighted (Diederich *et al.*, 2005). Related, comparable evidence of the spread of two protozoan parasites (*Perkinsus marinus* and *Haplosporidium nelsoni*) northwards from the Gulf of Mexico to Delaware Bay (Hofmann *et al.*, 2001) has resulted in mass mortalities in the Eastern oyster (*Crassostrea virginica*). It has been suggested that this spread was brought about by higher winter temperatures, when the pathogens otherwise were kept in check by temperatures < 3 ºC. All of the above host species are cultured. With the predicted poleward increase in temperatures brought about by climate change, we could witness the emergence of pathogens that were kept in check by lower winter temperatures and hence see an impact on cultured organisms such as molluscs, in particular. Another such example is emerging: an outbreak of *Vibrio parahaemolyticus* has occurred in oysters in Alaska and in all seafood products in southern Chile (Karunasagar, I., 2008; personal communication). In the latter country, the first important outbreak started in early 2004 and has remained since then during summer months (Paris-Mancilla, 2005), apparently related to warmer seawater temperatures during summer. However, other factors, such as increasing nutrients in coastal zones, cannot be ignored (Hernandez *et al.*, 2005). Main adaptation measures are essentially of two kinds: on the one hand to avoid the edible organisms (especially bivalves) reaching high temperatures while in transit or in storage (since multiplication of the pathogen takes place at an optimum temperature of 37 ºC; H. Lupin, personal communication) and to well cook shellfish and seafood.; Therefore, practices of eating raw seafood ("ceviche"[5]) are being banned in Chile, especially in summer.
It is not difficult to predict a general impact of water warming on the spread of diseases such as bacterial diseases in aquaculture because in most cases, incidence and persistence of these are related to fish stress. Increased water temperatures usually stress the fish and facilitate diseases (Sniesko, 1974). There are plenty of examples in the literature. Very recently it has been shown that ocean acidification could impact on the immune response of mussels, specifically shown for the blue mussel, *Mytilus edulis*, a popular aquaculture species (Bibby *et al.*, 2008). It has been suggested that the impacts are brought through changes in the physiological condition and functionality of haemocytes which in turn are caused by calcium carbonate shell dissolution.
In freshwater aquaculture, an increased uptake of toxicants and heavy metals through accelerated metabolic rates from increased temperature by cultured, filter feeding molluscs is suggested to be plausible (Ficke *et al.*, 2007), consequently leading to food

[5] ceviche, cebiche or seviche, common name for raw fish dishes in Latin America and The Caribbean

safety and certification issues. In the above context there are few adaptation measures that could be utilised; perhaps the most appropriate would be for regular monitoring of the water quality and the cultured product for human health risks would be the primary option.

It is clear that the spread of diseases is the most, or one of the most, feared threats to aquaculture. Examples of disease related catastrophes in the aquaculture industry include the spread of the white spot disease in shrimp farming in Ecuador and other Latin America countries (Morales and Morales, 2005) and more recently the case of ISA (Infectious Salmon Anemia) which is seriously impacting Chile's salmon industry to the point where the industry might shrink in the coming two to five years at least. Given that the spread of pests and diseases is thought to be a major threat under climate change scenarios, the issue must be made a priority for aquaculture considering relevant biosecurity measures as a main adaptation.

5.4.5 Impacts on biodiversity

One of the special issues that received attention from the early stages of the deliberations of the Inter Governmental Panel on Climate Change was the impact on biodiversity (IPCC, 2002). Generally, these impacts on biodiversity are predicted to occur in terrestrial habitats and less so in aquatic habitats, apart from those brought about through coral bleaching and subsequent loss of coral habitats, one of the most biodiverse habitats on earth. However, to date only the extinction of one species is clearly related to climatic change, that of the golden toad (*Bufo periglenes*) from Costa Rica (Crump, 1998). Predictions on overall loss of biodiversity arising from climate change are nevertheless staggering; the study of Thomas *et al*. (2004) for example, when extrapolated, indicates that at least one out of five living species on this planet is destined for extinction by the current levels of emissions of green house gases.

In all climatic regimes, continents and regions one of the main features of the aquaculture sector is its heavy dependence on alien species, (Gajardo and Laikre, 2003; De Silva *et al*., 2005; Turchini and De Silva, 2008) the associated translocations of new species beyond their normal geographical range and constant transfer of seed stocks between nations and watersheds. To date, some introductions of internal parasites associated with such translocations for aquaculture purposes have been reported. But for the devastating impact of one such translocation associated with the introduction of a fungal plague and the consequent dissemination of the native European freshwater crayfish (Edgerton *et al*., 2004), explicit evidence arising from alien species in aquaculture *per se* on biodiversity is not readily available; but this is no reason for complacency (De Silva *et al.,* 2004).

The impacts on biodiversity from alien species have mostly resulted from competition for food and space with indigenous species (e.g. Moyle and Leidy, 1992; Soto *et al*., 2006), alteration of habitats (e.g. Collares-Pereira and Cowx, 2004), the transmission of pathogenic organisms (Dobson and May, 1986), as well as through genetic interactions such as hybridisation and introgression (Dowling and Childs, 1992; Leary *et al*., 1993; Rhymer and Simberloff, 1996; Araguas *et al*., 2004) and other indirect genetic effects (Waples, 1991). Gienapp *et al*. (2008) addressed the issue on possible relatedness between climate change and evolution and concluded that:

- many alterations perceived as adaptation to changing climate could be environmentally induced plastic responses rather than micro evolutionary adaptations, and

- clear cut evidence is lacking to indicate a significant role for evolutionary adaptation to ongoing climate warming.

The question therefore, is whether the continued, if not increasing, dependence on alien species in future aquaculture developments and the associated seed stock translocations, in the wake of the global climatic change induced phenomena, would impact adversely on disease transmission as well as on biodiversity. The balance of evidence suggests that global climate change will not enhance impacts on biodiversity through aquaculture *per se.* However, in view of the changes in temperature regimes and so forth, particularly in the temperate region, the possibilities of diseases occurring amongst filter feeding molluscs and fish, for example, could be higher. Furthermore, any new introductions for aquaculture purposes will have to take into consideration such factors in the initial risk assessments undertaken for purposes of decision making.

In global aquaculture developments there are three major species groups that have been translocated across all geographical regions and have come to play a major role in production; these include salmonids in cool temperate waters and tilapias in warm tropical waters. The two species now account for over a million tonnes of production beyond their native range of distribution, closely followed by the white legged shrimp, *Penaeus vannamei,* and so are among the most important alien species in aquaculture. Climate change could impact the culture of all three species groups; warming in the temperate regions will narrow the distribution range of salmonids aquaculture, whilst the opposite could be true for tilapia and shrimp. In the latter case, extending the distribution well into the subtropics, where currently the culture period is limited to a single growth cycle in the year and the bulk of broodstock is maintained in green-house conditions.

Climatic change impacts on coral bleaching and associated loss of biodiversity have been relatively well documented and understood. The decline of coral reefs, from bleaching, weakening of coral skeletons and reduced accretion of reefs are estimated to be as high as 60 percent by year 2030 (Hughes *et al*., 2003). According to these authors the drivers of coral reef destruction are different from the past and are predominantly climate change associated. The direct relevance of loss of coral reefs and biodiversity to aquaculture is not immediately apparent. However, one of the drivers of coral reef deterioration, destructive fishing methods (McManus *et al*., 1997; Mous *et al*., 2000) employed to supply the luxurious "live fish" restaurant trade (Pawiro, 2005; Scales *et al*., 2007) is on the decline. This decline is primarily related to the fish supplies being met by aquaculture production, mainly the grouper species. There is the possibility that the coral reef supply of fishes could be almost totally replaced through aquaculture which would remove a driver of coral reef destruction and contribute to conserving these critical habitats and hence biodiversity.

Extreme events such as tropical cyclones and storm surges may increase incidence of aquaculture stocks escaping into the wild environment. An impact of alien species on local biodiversity was discussed, but impacts of aquaculture of indigenous species were not. Often the genetic make-up of aquaculture stocks has been altered through selective breeding, breeding practices, genetic drift and adaptation to captive environment and in some instances severe inbreeding (e.g. Eknath and Doyle, 1990). Such alteration in genetic make-up of aquaculture stocks would potentially impact the gene pools of wild counterparts of the cultured species through genetic interactions between escapees and wild individuals. However, as pointed out by Rungruangsak-Torrissen (2002), healthy not genetically manipulated escapees should not threaten wild salmon stocks. This view is diametrically opposed to that of other authors (e.g. Jonsson and Jonsson, 2006), and is indicative of the problem's complexity. Lack of agreement, scientifically or otherwise, is no reason for complacency. A similar problem is being addressed with newly emerging aquaculture species such as cod (Jørastad *et al.*, 2008). Thorstad *et al.* (2008) discuss both the impacts of escaped Atlantic salmon as a native (e.g. in Norway) and as exotic species (e.g. in Chile) and are clear that, regardless of the species being cultured or its genetic background, preventive and mitigation measures to control escapes should always be in place.

Apart from causing genetic changes, escapees from aquaculture are thought to be responsible for increased parasitic infestation of wild stocks, for example, salmon in coastal waters of Canada (Krkosek *et al.*, 2007; Rosenberg, 2008), amongst others. Perhaps mass escapes from aquaculture facilities caused by extreme weather events - very different to the small number of escapees at any one time in normal culture practices -, could influence the genetic makeup of native stocks, to their detriment in the long term. Perhaps the design of aquaculture facilities, particularly those located in areas vulnerable to unusual climatic events, needs to consider measures that would minimise mass scale escape.

5.5 SOCIAL IMPACTS OF CLIMATE CHANGE ON AQUACULTURE

The social impacts of climate change on capture fisheries have received much attention, compared to those on aquaculture (e.g. Allison *et al.*, 2005). This analysis concentrates on the vulnerable, poor fishing communities. In essence, the potential social impacts on fisheries are manifold, and primarily arise from:

- decreased revenues to fishers resulting from declines in catch and stock abundance (Luam Kong, 2002; Mahon, 2002);
- changes in migratory routes and biogeography of stocks affecting fishing effort, an example being increased travel time to fishing grounds (Dalton, 2001; Mahon, 2002);
- changes in harvest technologies and processing costs brought about by the need to capture new species (Broad *et al.*, 1999);
- damage to physical capital from severe weather events (Jallow *et al.*, 1999);
- impacts on transportation and marketing chains/systems (Catto, 2004); and
- reduced human capital from severe weather events, increased incidence of red tides and associated shellfish poisoning (Patz, 2000).

Some of the above, for example, damage to physical capital, impacts on transportation and marketing systems/channels, are most likely to have some effect on aquaculture. Considering the majority of aquaculture practices in the tropics and subtropics are small-scale enterprises, often farmer owned and managed, but clustered together (see Box 6) in areas conducive to aquaculture, damages resulting from extreme weather events will impact on the livelihoods of such clusters and have the potential to affect many poor households.

Such farming communities will be amongst the most vulnerable in the aquaculture sector and the possibilities of reducing their vulnerability are relatively limited. As an adaptive measure, in order to enable such clusters to spring back to their livelihoods, it may be necessary to develop a form of cluster insurance scheme, and in this regard, there could be a need for governmental policy changes and assistance.

Box 6. In most of the tropical and subtropical regions of Asia, which is the mainstay for the great bulk of aquaculture activities, coastal and inland, more often than not individual small holdings are clustered together in areas conducive to aquaculture. Unusual weather events resulting from climatic changes could impact on such clusters and many livelihoods adversely. Pictures show dense marine cage farming in Xin Cuin Bay, Ling Shui County, China, small-scale seaweed farming in Sulawesi, Indonesia and inland cage farming in Cirata reservoir, Indonesia.

In the tropics, currently the fastest growing aquaculture subsector is marine finfish farming, driven by high commodity prices and better profit margins, supported by improved hatchery technologies. Such activities in the tropics are almost always confined to enclosed coastal bays and consist of small holdings clustered together, becoming potentially vulnerable to extreme climatic events such as sea storms and wave surges. These farming communities are very vulnerable to adverse weather events. Bearing in mind that this sector, at least in Asia, is serviced to a significant extent by small-scale artisanal fishers providing the required trash fish or low valued fish to feed the cultured stock, any increased vulnerability of the former will impact on these finfish farming communities, often family managed enterprises. Indeed, climate change impacts will make both groups highly vulnerable, with the potential effects greater on artisanal fishers because they would have no choice but to find alternative livelihoods, whereas finfish farmers could shift to feeding stock with commercial feeds, if economically feasible.

It was pointed out earlier that sea level rise, water stress and extreme climatic events would have a major influence on deltaic regions and the possibility exists that land based agriculture may have to be abandoned and replaced by aquaculture as means of alternative livelihoods. Such changes involve major social upheavals in lifestyles and have to be carefully tailored with the provision of initial capacity building needed to efficiently effect a change in livelihood patterns. Examples of effective change of livelihood patterns from agriculture to aquaculture are known, especially with respect to communities displaced by reservoir impounding. In this regard, in the few reported instances there had been a socio-economic improvement of the incumbents after the adoption of aquaculture (Pradhan, 1987; Abery *et al.*, 2005; Wagle *et al.*, 2007).

There could be indirect negative social impacts in the aquaculture processing sector where relatively low valued cultured products are being processed in the vicinity and with easy access to culture facilities. However, with sea level rise and corresponding saline water intrusion (see Section 5.3.3.) there could be a shift of these culture practices further upstream, perhaps causing the processing plants to follow suit. This would result in loss of employment opportunities in some communities but gains in others, creating at least temporary social problems and capital disengagement. Another indirect factor is that some of the adaptive mechanisms being evolved globally to combat carbon emissions and therefore climatic change could increase the vulnerability of the aquaculture sector. One of the major social cum industrial changes occurring globally is

the increasing emphasis on the production of biofuels and the lobby (Naylor *et al*., 1998; 2000; Aldhous, 2004) that is advocating the use of raw material used for fish meal and fish oil production for direct human consumption. These trends will affect aquaculture by making the availability of key feed ingredients increasingly scarce and expensive, making the culture of carnivorous fish and shrimp almost prohibitive.
Some lobby groups take the view that aquaculture is not ecologically sustainable in a world that is becoming increasingly conscious of carbon emission processes, including those caused by food production. Two decades ago, consumers did not pay much attention to quality, ecolabelling and traceability but now they are becoming important in marketing, particularly in the developed world. It has been pointed out that some cultured commodities are energy costly but command a high consumer price at the upper scale of markets. It is possible that in the near future, consumers could create a demand for carbon emission labelling, with the result that eco-labelling of products such as shrimp and salmon could increase causing a drop in demand for energy costly products over the years. The above scenario is not unrealistic and would result in very significant socio-economic impacts in the producing countries and the upmarket end of aquaculture production and processing. On the positive side, however, is the possibility that there could be a return, particularly in the case of shrimp, to indigenous species such as *P. monodon* cultured using Better Management Practices (BMPs) that are less energy demanding (see Table 11).
An increase of diseases affecting aquaculture because of climate change will have important social impacts on small producers and on workers associated with the sector. This is presently being seen in Chile's salmon farming industry, which was badly affected by the ISA virus[6] although the disease have not been connected to climate change so far.

6. Potential impacts of aquaculture on climate change

Aquaculture, on a global scale and in comparison to animal husbandry, became a significant contributor to the human food basket relatively recently. The aquaculture sector has experienced very strong growth over the last two decades, making it the fastest growing primary production industry (FAO, 2007). It began to blossom during a period when the world was becoming increasingly conscious and concerned about sustainability, use of primary resources and the associated environmental degradation issues. Sustainability, biodiversity and conservation became an integral part of all development efforts following the publication of the Brundtland Report, "Our common future' in 1987 (UNEP, 1987), and follow-up global initiatives such as the establishment of the Convention on Biological Diversity (1994).
In this scenario of increasing global awareness and public "policing" the sector has been targeted on many fronts. Foremost among these has been the use of fish meal and fish oil, obtained through reduction processes of raw material supposedly suitable for direct human consumption; (Naylor *et al*., 1998; 2000; Aldhous, 2004). Another target has been that of mangrove clearing during the shrimp farming boom (Primavera, 1998; 2005). Admittedly, in the past, mangrove clearing was a major issue with respect to shrimp farming but the practise no longer takes place. In fact, it has been estimated that less than five percent of mangrove areas have been lost due to shrimp farming, most

[6] www.salmonchile.cl/frontend/seccion.asp?contid=1109&secid=4&subsecid=61&pag=1

losses occurring due to population pressures and clearing for agriculture, urban development, logging and fuel (GPA, 2008).

A counter argument is that positive contributions from aquaculture may not have been totally quantified because benefits other than those to the human food basket have not been taken into consideration. Aquaculture's positive influence, on issues such as climate change has gone unheeded while society at large needs to consider that all food production has environmental costs which have to be compared in a fair way (Bartley *et al.*, 2007). Consequently, an attempt is made below to outline the positive contributions of aquaculture towards the global problem of climate change.

6.1 COMPARISON OF CARBON EMISSIONS/CONTRIBUTIONS TO GREEN HOUSE GASES FROM ANIMAL HUSBANDRY AND AQUACULTURE

Carbon emissions, viz. green house gases, in one form or the other, driven by anthropogenic activities, are a root cause of climate change (Brook *et al.*, 1996; Flattery, 2005; Friedlingstein and Solomon, 2005; IPCC, 2007) and all mitigating measures revolve around reducing the carbon emissions. Itis therefore relevant to consider the degree of carbon emissions of the various animal food production sectors with a view to gauging the degree to which aquaculture contributes to this primary cause. It is conceded that accurate and/or even approximate estimations of total emissions from each of the sectors is difficult, if not impossible, to compute. However, any approximation will bring to light the indirect role that aquaculture plays in this regard.

The United States Environmental Protection Agency (EPA) recognised 14 major sources responsible for methane emissions in the USA and ranked enteric fermentation and manure management from animal husbandry as the third and fifth highest emitters, respectively. The emissions from these two animal food production sources were 117.9 and 114.8, and 31.2 and 39.8 TgCO_2 Equivalents for years 1990 and 2002, respectively.[7] Domesticated livestock, the ruminant animals (cattle, buffalo, sheep, goats, etc.) produce significant amounts of methane in the rumen in the normal course of food digestion, through microbial fermentation (= enteric fermentation) that is discharged in the atmosphere. Equally, the solid waste produced – manure - needs to be managed and this process results in the emission of significant amounts of methane. The atmospheric methane level has increased from 715 ppb in the pre-industrial revolution period to 1775 ppb at present. Comparable trends have been recorded from ice cores from Greenland (Brook *et al.*, 1996). It has been suggested that the world's livestock accounts for 18 percent of greenhouse gases emitted, more than all transport modes put together, and most of this is contributed by 1.5 billion cattle (Lean, 2006). Overall, the livestock sector is estimated to account for 37 percent of all human-induced methane emissions. The global warming potential (GWP) of methane is estimated to be 23 times that of carbon dioxide. Farmed aquatic organisms do not emit methane and therefore are not direct contributors to the causative problems. Surprisingly and unfortunately this has not been taken into account, particularly by those who tend to advocate the view that aquaculture is polluting and non-sustainable (e.g. Allsopp *et al.*, 2008).

The world is requiring more animal food products, fuelled by rising incomes and urbanization, particularly in the developing world. It is estimated that in the developing world the per capita meat consumption rose from 15 kg in 1982 to 28 kg in 2002 and is expected to reach 37 kg by 2030 (FAO, 2003). The increasing demand for animal food products in developing countries has resulted in an accelerated rate of production and in 1995 surpassed that of the developed world (Gerber *et al.*, 2007). Any analysis has to

[7] www.epa.gov/methane/sources.html#anthropogenic

revolve around human food needs and the proportionate contribution of each food producing sector to green house gas emissions.

6.1.1 Carbon sequestration

One of the major causative factors of climatic change, if not the major causative factor, is the accumulation of green house gases in the atmosphere, irrespective of the source(s) of emission (Brook *et al*., 1996; Flattery, 2005; Friedlingstein and Solomon, 2005; Kerr, 2006; IPCC, 2007). Carbon sequestration is the process through which agriculture and forestry practices remove atmospheric carbon dioxide, Forestation, reforestation and forest preservation are considered to be favourable practices that sequester and/or preserve carbon and all help alleviate climate change by enhancing carbon storage (Lal, 2004; Miller, 2008).[8]

6.1.1.1 Methods used in determining energy costs

A number of different methods, direct and indirect, can be used for estimating carbon sequestration. An indirect measure is to estimate the energy costs of production of a commodity, also referred to as "environmental costs" for an entity/commodity. Amongst such methods are "Ecological Footprints (EF)" and "Ecoindicator 99", for example. It is acknowledged that the methodologies used are far from perfect and there is a need for standardization to obtain meaningful and comparable results (Bartley *et al.*, 2007). More recently, Huijbregts *et al*. (2007) attempted to compare the use of EF and Ecoindicator 99 methods to evaluate 2 360 products and services, including agriculture. These authors concluded that the usefulness of EF as a stand-alone indicator for environmental impact is limited for the life cycles of certain products and that the use of land and fossil fuels are important drivers of overall environmental impact.

6.1.1.2 Comparisons on energy costs from aquaculture and other food types

Notwithstanding the relative uncertainties in assessing the eco ogical costs of production processes, there have been many studies on the energy costs of production of farmed animals (Bartley *et al.*, 2007). For example, a comparison of energy costs of some aquaculture produce and selected farmed animals and a ranking of food according to edible protein energy and industrial energy inputs are given in Tables 9 and 10, respectively. What is most obvious is the degree of discrepancy in the data by different authors for the same commodity and reiterates the need for standardization of the techniques and the units to facilitate direct comparisons. (Bartley *et al.*, 2007; Huijbregts *et al*., 2007; Tyedmers and Pelletier, 2007).

In spite of such discrepancies some general trends are evident. With regard to aquaculture the total energy cost for culturing shrimp and carnivorous finfish such as salmon are rather high and results in relatively low protein output compared to the energy inputs. In fact, the percent protein output to energy inputs to produce a unit weight of shrimp and salmon are even lower than that for chicken, lamb and beef (Table 10). On the other hand, salmon and marine fish provide other nutritional elements that are relevant for human health and these should also be taken into account in such comparisons.

Similarly, the relative returns from omnivorous finfish culture and other commodities such as mussels and seaweeds are far better than those from carnivorous finfish and/or

[8] www.epa.gov/sequestration/forestry.html

other husbanded livestock. It is evident that the culture of carps, an omnivorous species group, feeding low in the food chain, is profitable energy wise; a fact that was also evident from the previous analysis in relation to fish meal and fish oil usage in aquaculture (Section 5.4.1). Carp culture provides a return of over 100 percent on protein output to energy input (Table 10), unmatched by any other farming system. It is timely for the aquaculture sector, in the context of pressing issues such as climatic change, to develop quantitative models on these aspects to help in planning major aquaculture developments globally. These analyses are particularly relevant for developing countries where the bulk of aquaculture occurs and provide not only livelihoods but also make significant contributions to foreign exchange earning.

Table 9. Energy used in different farming systems. Data from: @- Bunting and Pretty, 2007; #- Munkung and Gheewala, 2007; $- Troell *et al*., 2004. na = not available.

System	Industrial energy consumption			
	Direct energy	**Indirect energy**	**Total**	**Units**
Semi-intensive shrimp f.@	55	114	169	GJ t^{-1}
Thai shrimp#	na	na	45.6	MJ kg^{-1}
Marine shrimp$	54.2	102.5	156.8	MJ kg^{-1}
Salmon cage f. @	9	99	105	GJ t^{-1}
Salmon cages intensive@	na	na	56	GJ t^{-1}
Salmon$	11.9	87	99	MJ kg^{-1}
Norwegian farmed salmon#	na	na	66	MJ kg^{-1}
Trout ponds@	na	na	28	GJ t^{-1}
Grouper/seabass cage f. @	na	na	95	GJ t^{-1}
Carps, intensive recycle@	na	na	56	GJ t^{-1}
Carp, recirculating$	22	50	50	MJ kg^{-1}
Carp ponds feeding & fertilizer@	na	na	11	GJ t^{-1}
Carp, semi-intensive$	26	01	27	
Catfish ponds@	na	na	25	GJ t^{-1}
Catfish$	5.4	108	114	MJ kg^{-1}
Tilapia$	0	24	24	MJ kg^{-1}
Norwegian chicken#	na	na	55	MJ kg^{-1}
Swedish beef#	na	na	33	MJ kg^{-1}

6.2 ESTIMATING AQUACULTURE'S POTENTIAL CONTRIBUTION TO CLIMATIC CHANGE

It has to be accepted that all forms of farming will incur some energy costs and in this regard aquaculture is no exception. This must be balanced against other factors including that, unlike for terrestrial agriculture and animal husbandry, there are potentially over 300 species to choose from in aquaculture (FAO, 2007). In a good number of instances, the practices to be adopted are driven by market forces.
Good examples in this regard are shrimp, salmonid and marine finfish aquaculture, the latter gradually witnessing a major growth phase in the wake of market demand for species such as groupers, snappers and wrasses, all of which are on the decline in the capture fisheries. The increased market demand for such high valued species is also driven by factors similar to those that have resulted in increased meat consumption in developing countries.

Table 10. Ranking of selected foods by ratio of edible protein energy (PE) output to industrial energy (IE) inputs, expressed as a percentage. Data from Tyedmers and Pelletier, 2007. Please refer to these authors for original references.	
Food type including technology, environment and locality	**% PE/IE**
Carp extensive, freshwater, various	100-111
Seaweed, mariculture, Caribbean	50-25
Chicken, intensive, USA	25
Tilapia, extensive, freshwater ponds, Indonesia	13
Mussels, marine long lines, Scandinavia	10-5
Tilapia, freshwater, Zimbabwe	6.0
Beef, pasture, USA	5.0
Beef, feed lots, USA	2.5
Atlantic salmon, intensive, marine net pen, Canada	2.5
Shrimp, semi intensive, Colombia	2.0
Lamb, USA	1.8
Sea bass, intensive marine cage culture, Thailand	1.5
Shrimp, intensive culture, Thailand	1.4

Of all aquaculture commodities, the environmental cost of shrimp aquaculture is the highest. Shrimp aquaculture is economically very important to a number of tropical regions in Asia and South America. Because it needs constant aeration and water exchange, in general shrimp culture consumes a lot of energy compared to most other cultured commodities. Furthermore, shrimp culture is essentially destined for export markets and consequently needs a high level of processing, which is relatively costly in terms of energy. Recent publications on the "life cycle assessments" of "Individually Quick Frozen", Pacific white leg shrimp, *Penaeus vannamei* production, (Munkung, 2005; Munkung *et al.*, 2007, Table 11) revealed that the culture of the native tiger shrimp, *P. monodon,* in Asia is far more ecologically cost effective than that of the alien *P. vannamei*. In all ecological aspects and from the point of view of contribution to global warming, culture of *P. monodon* is better. Such factors need to be taken into account in debates around the introduction of alien species, such as the recent one in relation to Asian shrimp farming in Asia (De Silva *et al*., 2007). Perhaps it is time that as an adaptive measure to climate change, aquaculture should be considered not only in the light of straight forward economic gains (which often tend to be short term), but also in its contribution to factors impacting on climate change as a whole. A case in point is the issue of the introduction of *P. vannamei,* a high yielding species with quick economic returns, (Wyban, 2007) as opposed to the native *P. monodon*.

Table 11. Comparative life cycle impact assessment results of block tiger prawn and IQF Pacific white-leg shrimp (Pws). #- Munkung, 2005; @- Munkung *et al.*, 2007			
Impact category	**Unit**	**Block (1.8 kg) of black tiger prawn[#]**	**4 (x 453 g) pouches of IQF Pws [@]**
Abiotic depletion potential (ADP)	kg Sb eq*	0.32	0.19
Global warming (GWP100)	kg CO_2 eq	19.80	27.31
Human toxicity	kg 1,4-DB eq	1.79	3.04
Fw aquatic ecotoxicity	kg 1,4-DB eq	0.25	0.41
Mar. aquatic ecotoxicity	kg 1,4-DB eq	1660.00	2071.00
Terrestrial ecotoxicity	kg 1,4-DB eq	0.02	0.02
Acidification	kg SO_2 eq	0.07	0.14
Eutrophication	kg PO_4 eq	0.22	0.19

* equivalents of Antimony extraction (depletion); ** kg 1,4-dichlorobenzene equivalents (1,4-DB)/kg emission, as normalized units for toxicity

The great bulk of aquaculture production is slanted towards relatively more environmentally cost effective commodities than shrimp (Table 12). The table shows that overall, global growth in finfish aquaculture production has tended towards organisms feeding low on the food chain, and maximally ecologically less energy consuming. Consequently, global growth in finfish aquaculture carbon emissions is minimal and less than the great majority of other food commodities.

In addition, aquaculture of molluscs and the expanding seaweed culture (also see Figures 10, 12), particularly in tropical regions contributes significantly to carbon sequestration. Moreover, the rapid turnover in seaweed culture, approximately three months per crop (in the tropics) with yields of over 2500 tonnes per ha, far exceeds the potential carbon sequestration that could be obtained through other agricultural activity for a comparable area. Cultivation of shrimp and carnivorous finfish are the most energy consuming activities in aquaculture and have been the basis for criticism from environmental lobby groups of the entire sector. Much of the criticism is unfair because it is based on two commodities, which account for far less than ten percent of global aquaculture production.

Table 12. **The production of cultured finfish (x10^3t) feeding low on the trophic chain in 1995 and 2005 and the overall growth in the ten year period.**			
Species	**1995**	**2005**	**Growth %**
Silver carp	2,584	4,153	60.7
Grass carp	2,118	3,905	84.4
Common carp	1,827	3,044	66.6
Bighead carp	1,257	2,209	75.7
Crucian carp	538	2,086	287.7
Nile tilapia	520	1,703	227.5
Rohu	542	1,196	120.7
Catla	448	1,236	175.9
Mrigal carp	330	421	21.6
Black carp	104	325	212.5
Total	10,359	20,187	94.9
Fw fish (nei)	2,581	5,591	116.6
Total (fw)	12,940	25,778	99.2
All finfish	15,616	31,586	102.2

7. Other adaptive measures

In the foregoing sections, plausible adaptive measures for combating or mitigating the impacts of climatic change on aquaculture are examined, primarily from a technical viewpoint, including the associated social aspects. It has been demonstrated recently that successes in aquaculture almost always had to be complemented with relevant institutional, policy and planning changes or adaptations (De Silva and Davy, in press), and one would expect climatic change impact adaptations to follow suite if they are to be effective and sustainable.

7.1 INSTITUTIONAL, POLICY AND PLANNING MEASURES

In terms of institutional and policy measures the following are priority areas for development of the sector:

- to implement an Ecosystem Approach to Aquaculture (EAA) as a global strategy;
- to prioritize and enhance mariculture and specially non-fed aquaculture (filter feeders, algae);
- to enhance the use of suitable inland water bodies through culture-based fisheries and appropriate stock enhancement practices.

The Ecosystem Approach to Aquaculture (EAA) aims to integrate aquaculture within the wider ecosystem in such a way that it promotes sustainability of interlinked social-ecological systems (SOFIA, 2006; Soto *et al*., 2008).
As with any system approach to management, EAA encompasses a complete range of stakeholders, spheres of influences, and other interlinked processes. In the case of aquaculture, applying an ecosystem-based approach must involve physical, ecological, social and economic systems in the planning of community development, and must take into account stakeholder aptitudes and experiences in the wider social, economic and environmental contexts of aquaculture.

The EAA emphasizes the need to integrate aquaculture with other sectors (e.g. fisheries, agriculture, urban development) that share and affect common resources (land, water, feeds, etc.) also focusing on different spatial scales; i) the farm, ii) the aquaculture zone, water body or watershed where the activity takes place, and iii) the global scale (Soto *et al.*, 2008).

Perhaps the implementation of EAA at the waterbody scale is one of the most relevant adaptations to climate change. Geographical remit of aquaculture development authorities (i.e. administrative boundaries) often do not include watershed boundaries and this is a particular challenge because climate change prevention and adaptation measures need watershed management, e.g. protecting coastal zones from landslides, siltation, discharges, or even simply providing enough water for aquaculture. On the other hand, aquaculture can provide adaptation for coastal agricultural communities that may face salinization effects because of rising sea levels. In coastal regions, mariculture can provide an opportunity for producing animal protein when freshwater becomes scarce. Such a watershed perspective needs policy changes and integration between different sectors (e.g. agriculture-aquaculture) aside from capacity building and infrastructure requirements. Because climate change does not recognize political boundaries, adaptation policies and planning within international watersheds can be a major challenge. However, the common threat of climate change impacts can provide the opportunity for such trans-boundary management.

For the aquaculture sector, the watershed scale approach is also needed for an organized–cluster-type adaptation to negotiate collective insurance, to implement appropriate bio-security measures, etc. Instances of such adoptions, initiated not necessarily as an adaptive measure for climate change impacts, are best exemplified in the shrimp farming sector on the east coast of India (Umesh *et al.*, in press). This case has proven the ability to extend this approach to other comparable small-scale farming sectors.

An Ecosystem Approach to Aquaculture (EAA) is being increasingly considered as a suitable strategy to ensure sustainability, including adequate planning required to take into account climate change impacts. Other relevant elements to consider in the policies and planning are described below.

7.1.1. Aquaculture Insurance

An adaptive measure that will help limit bankruptcies in aquaculture businesses as a result of losses caused by climatic events is to encourage aquaculture participants to take insurance against damage to stock and property from extreme climatic events. Appropriate insurance cover will at least ensure that finance is available for businesses to recommence operations. Aquaculture insurance is well established for major commodities such as salmon and shrimp produced at industrial scales but this is not the case for small farmers. This is particularly relevant for Asia (Secretan *et al.*, 2007) where the bulk of small-scale farming takes place; governments could consider making insurance mandatory for aquaculture businesses above a certain size and accordingly reduce long term losses in production, livelihoods and potential environmental damages, such as those associated with escapes.

7.1.2 Research and technology transfer

Relevant research is required for aquaculture to adapt to climate change and countries and regions need to streamline work on issues such as new diseases and preventive treatments, aquatic animal physiology, the search for new and better adapted species, better feeds and feeding practices that are more ecosystem friendly. Technology transfer mechanisms must reach farmers, especially small farmers. It is in this context that application of Better Management Practices (BMPs) into small-scale farming practices need to be integrated into EAA strategies. Some practical measures available for many countries are explored below.

7.1.2.1 Using lessons from the expansion of farming species outside their natural range of distribution

Global warming is an imminent potential threat and there is a clear need to assess the required adaptations for cultured species, especially in temperate regions. A simple approach can be "learning from the experience of expansion of farming species outside their original range". A great deal of the "adaptation knowledge" may be already available within the aquaculture sector amongst pioneer farmers and perhaps it is time to collect such information globally. For example, there is a body of knowledge about salmon aquaculture beyond its natural range of distribution, facing different climates and weather conditions and vulnerability to old and new diseases. Similar examples can be found with tilapia and the white legged shrimp. Perhaps it is also possible to use the genetically improved strains that have been more successful under certain alien conditions. But care should be taken with the movement of live organisms.

7.1.2.2 Aquaculture diversification

In many countries and regions, there is a clear tendency to diversify farmed species and technologies (FAO, 2006). Duarte *et al*. (2007) show the very fast diversification process and what they call "domestication of new species for aquaculture" and particularly mariculture. According to the authors, this process is developing much faster than happened in animal or plant husbandry and they highlight the potential adaptive significance. Figure 12 shows the relatively fast aquaculture diversification in China and Spain. In China, there is a high leap in aquaculture diversification, rising from 13 species being cultured in 2000 to 34 species in 2005. In evolutionary terms, it is commonly understood that diversity provides the ground for natural selection and for adaptation, it can also be proposed that culturing more species provides a form of insurance and offers better adaptation possibilities under different climate change scenarios, especially unexpected events such as diseases or market issues. Diversification requires educating consumers and providing them with adequate information about new species and products, hand in hand with the successful transfer of the technologies to new practitioners. National and global policies can facilitate aquaculture diversification while strengthening the consolidated species.

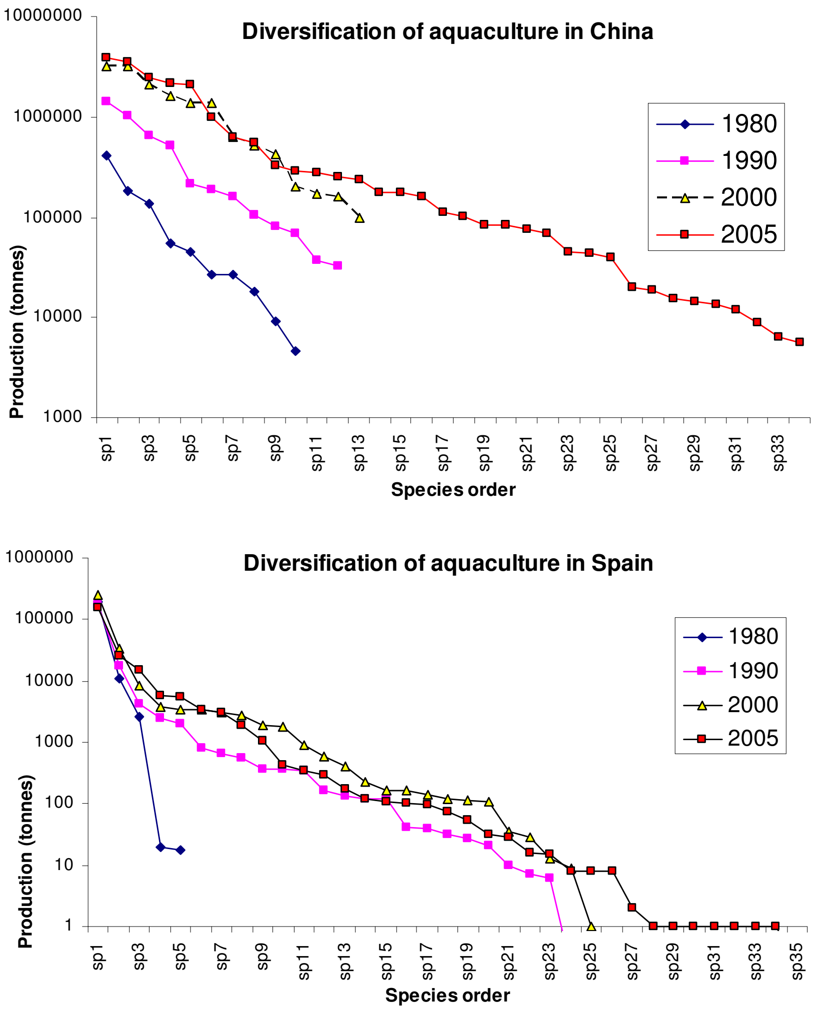


Figure 12. Species diversification in China and in Spain based on FAO statistics (FAO Fishstat, 2008). Figures show species organized according to production from left to right (log scale in the Y axes) in such a way that Sp1 is the species with the largest production. A steeper slope indicates one or few species monopolizing production. This is the case in Spain and China in 1980. However the increase in number of species cultured is noteworthy by 1990, and further on in Spain and by 2005 in China with 34 cultured species and a softer slope of the curve in the later case, that is a more even production.

Diversification can be part of an insurance programme for the sector at the country and regional levels.

7.1.3 Aquaculture zoning and monitoring

Adequate site selection and aquaculture zoning can be important adaptation measures to climate change. When selecting aquaculture sites it is very important to determine likely threats through risk assessment analysis. When selecting the best locations for aquaculture farms, particularly in coastal and more exposed areas, weather related risks must be considered. For example, coastal shrimp farms may need levies or other protective structures. Fish cages have to be securely fastened to the bottom or a holding structure; submersible cages have been proposed and are being used in a few offshore sites where they can withstand adverse weather events. Water warming and related low oxygen, potential eutrophication enhancement, etc. can be avoided or minimized in deeper sites with better circulation. However there are always tradeoffs with exposure to more extremes conditions. The likelihood of disease spread can be minimized by increasing the minimum distance between farms and by implementing tight biosecurity programmes for aquaculture clusters or zones. Implementing proper risk communication is also very important but communications have to be reliable and fast and the information accurate. In this regard, weather information systems around the world are improving in a bid to prevent major damages to infrastructure and biomass.

For aquaculture, some of the most important prevention systems must rely on critical and effective monitoring of water bodies and aquatic organisms. A very important adaptation measure at local level and at the water body/watershed scale is the implementation of effective integrated monitoring systems. Such monitoring systems should provide adequate information on physical and chemical conditions of aquatic environments, early detection of diseases and presence of pest species, including harmful algal blooms. Often, rural farmers may not have the conditions and facilities to implement such monitoring by themselves. However, some very simple measurements can be implemented such as water temperature and Secchi disk readings. The latter can often be used for early detection of algal blooms. Ideally, local authorities can assist in implementing integrated monitoring systems with accompanying risk communication strategies and early warning systems to prepare and warn stakeholders. Some interesting examples are the monitoring programmes for red tides in connection with mussel farming in the coastal inlets (rías) in Galicia, Spain and the monitoring programmes for salmon farming. In Galicia the Technological Institute for the control of the marine environment (INTECMAR) has a permanent monitoring programme on the internet which is easy to access; it provides alerts and early warnings regarding red tides and other water conditions relevant to mussel farming.[9] The salmon farming industry in Chile through the Salmon Farmers Association maintains an integrated monitoring system which provides different water parameters through a permanent recording mechanism (automatic buoys plus manual samplings) and the information is provided daily to farmers through the web and also through local radio programmes that can reach the more remote areas[10].

8. Conclusions

Over the last two to three decades, aquaculture has successfully established itself as a major food sector providing a significant proportion of the animal protein needs across all communities irrespective of living standards. It has done so through many adversities during which it has shown resilience and adaptability. As in all food producing sectors, aquaculture now confronts another major challenge, that of the impacts of climatic change. It is likely that aquaculture, in view of its resilience and adaptability and its cultivation of a wide array of species/species groups will be able to respond positively to climate change impacts. In order to do so there needs to be related policy, institutional and socio-economic changes, backed up and supplemented by relevant technical developments. Preferably, there should be a holistic approach and one that works from the bottom up rather than top down. The latter is crucial because the great bulk of aquaculture is small- scale, farmer owned, operated and managed, particularly in Asia - the epicenter of global aquaculture. Only by incorporating indigenous knowledge

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[9] http://www.intecmar.org/informacion/biotoxinas/EstadoZonas/Mapas.aspx?sm=a1

[10] www.pronosticos.salmonchile.cl/antecedentes.asp

and obtaining cooperation at grass root level will it be possible for adaptive changes to be implemented effectively and in a timely manner.

Over many thousands of millennia, many climatic changes are thought to have occurred on our planet, bringing about major floral and faunal changes. The reasons for such changes are not always obvious and/or universally accepted But we know that the climate change now facing the earth is primarily brought about by anthropogenic activities and started at the beginning of the last industrial revolution. The causative agents of the changes and therefore the required mitigating measures are well understood and have been subjected to rigorous scientific scrutiny (IPCC, 2007). Human food needs and food production are impacted by climate and such changes in the coming decades are a major concern, particularly for developing nations. Considering the predicted human population growth over the next few decades coupled with the fact that food production is not evenly distributed throughout the globe and nor is the ability to attain food security (Kerr, 2006), it is predicted that climate change impacts will be most negative for the poor developing countries and hit them hardest. Another casualty will be the flora and fauna least capable of adapting to the changes; it is believed that even a modest climate change in the next few decades will begin to decrease crop production in low latitudes (Kerr, 2006) - these include the very regions where aquaculture is most predominant. It is heartening to note, however, that a significant proportion of innovations regarding aquaculture have originated from grass roots initiatives, which have been quick to take the lead and adapt crucial technical advances. In this sense, the rural, small-scale aquaculture farmers can be expected to be alert to climate change impacts and make the necessary adaptations.

In the overall scenario of animal protein food sectors, the contribution of fish falls far behind terrestrial animal protein sources. For example, the per capita consumption of meat in the developing world is much greater, rising from 15 kg in 1982 to 28 kg in 2002, and is expected to reach 37 kg by 2030 (Gerber *et al.*, 2007), as opposed to 16.6 kg of fish in 2005 (FAO, 2007). Meat production and fish production sectors have witnessed a shift of dominance from developing to developed countries (Gerber *et a*l., 2007 and Delgado *et al.*, 2003). We know that daily meat consumption has increased linearly in relation to per capita income (Houtman, 2007) but such analysis is not available for fish.

The main difference between the two sectors is that food fish supplies are still predominantly capture fisheries, as opposed to farmed, but future increases in demand will be met mostly by aquaculture (see Sections 2.1, 2.2.). The importance of capture fisheries will at best be static and there is a high probability that climate change will cause it to decline. Consequently aquaculture will fill the supply gap and meet growing human fish food needs.

Although it is only a relatively small food production sector, aquaculture is a significant contributor to the animal protein component of the food basket. Aquaculture has increased from 0.7 kg per capita in 1970 to 6.4 kg per capita in 2002, with approximately 10 million people active in the production sector. This increase is significantly higher than that witnessed for terrestrial livestock farming which grew only at a rate of 2.8 percent per year for the same period (Bunting and Pretty, 2007) and reflects the late emergence of aquaculture as a significant contributor to the human food basket. It is also important to stress that aquaculture has been overly scrutinised from an environmental impact viewpoint; presumably because this sector gained prominence only in the last three decades or so, coinciding with a surge of global awareness about sustainable development and environmental integrity (UNEP, 1987; CBD, 1994).

Unlike many other animal meat production sectors, aquaculture, which farms poikilothermic animals, is patchily distributed with concentrations in tropical and subtropical regions of Asia, inland and coastal and to a lesser extent on the temperate coasts of Europe and South America. Given this distribution, it would be expected that major climatic change impacts on aquaculture would be through global warming and consequent temperature increases in water. These are predicted to be most significant in cooler waters and would affect aquaculture practices the temperate regions, where salmonid and mollusc farming take place.

Table 13. A summary of the important impacts of the different elements of climate change on aquaculture and potential adaptive measures. Temp.- temperate; Tr.- tropical; STr.- Sub- tropical; LFRT- live fish restaurant trade; CBF- Culture based fisheries. * instances where more than one climatic change element will be responsible for the change			
Aq. /other activity	**Impact(s)**		**Adaptive Measures**
	+/-	**Type/form**	
All: cage, pond; fin fish	-	Raise above optimal range of tolerance	Better feeds; selective breeding for higher temperature tolerance
FW; all	+	Increase in growth; higher production	Increase feed input
FW: cage	-	Eutrophication & upwelling; mortality of stock	Better planning; sitting, conform to cc, regulate monitoring
M/FW; mollusc	-	Increase virulence of dormant pathogens	None; monitoring to prevent health risks
Carnivorous fin fish/shrimp*	-	Limitations on fish meal & fish oil supplies/price	Fish meal & fish oil replacement; new forms of feed management; shift to non-carnivorous commodities
Artificial propagation of species for the “luxurious” LFRT*	(+)	Coral reef destruction	None; but aquaculture will impact positively by reducing an external driver contributing to destruction and help conserve biodiversity
Sea level rise and other circulation changes			
All; primarily in deltaic regions	+/-	Salt water intrusion	Shift upstream stenohaline species- costly; new euryhaline species in old facilities
	+/-	Loss of agricultural land	Provide alternative livelihoods- aquaculture: capacity building and infrastructure
Marine carnivorous fin fish*	- /+	Reduced catches from artisanal coastal fisheries; loss of income to fishers	Reduced feed supply; but encourages use of pellet feeds- higher cost/environmentally less degrading
Shell fish	-	Increase of harmful algal blooms- HABs	Mortality and increased human health risks by eating cultured molluscs
Habitat changes/loss	-	Indirect influence on estuarine aquaculture; some seed availability	None
Acidification			
Mollusc /seaweed culture	-	Impact on calcareous shell formation/deposition	None
Water stress (+ drought conditions etc.)			
Pond culture	-	Limitations for abstraction	Improve efficacy of water usage; encourage non-consumptive water use aquaculture, e.g. CBF
Culture-based fisheries	-	Water retention period reduced	Use of fast growing fish species; increase efficacy of water sharing with primary users e.g. irrigation of rice paddy
Riverine cage culture	-	Availability of wild seed stocks	Shift to artificially propagated seed; extra cost

		reduced/period changed	
Extreme climatic events			
All forms; predominantly coastal areas	-	Destruction of facilities; loss of stock; loss of business; mass scale escapement with the potential to impacts on biodiversity	Encourage uptake of individual/cluster insurance; improve design to minimize mass escapement; encourage use of indigenous species to minimize impacts on biodiversity

There is also the possibility of warming resulting in a more frequent occurrence of harmful algal blooms and emergence of hitherto dormant pathogens, which would particularly threaten mollusc cultivation. There are very few adaptive measures to counteract these negative effects, apart from being more vigilant through regular monitoring measures.
For salmonid farming, an adaptive measure could be to explore possibilities of developing strains tolerant to higher temperatures of 19 to 20 ºC.
The predicted increases in water temperatures are often well within the optimal temperature range of most cultured species, particularly in the tropics and subtropics. This means that warming would actually enhance growth of cultured stocks in these regions and increase production, (see Table 13).
Sea level rise and associated salt water intrusion, compounded by monsoonal weather pattern changes are a concern in the tropical and subtropical regions where the bulk of aquaculture activities take place. The impact is likely to be more profound in major deltaic areas in the tropics. However, adaptive measures are feasible such as changing a species or moving major current aquaculture operations away from the shore. Seawater intrusion would make some land based agricultural practices impossible or less cost effective. Aquaculture may provide alternative livelihoods and perhaps increase its contribution to the human food basket. This process might be fuelled in part by the fact that financial returns from aquaculture production tend to be significantly higher than those from traditional agriculture on a unit area basis and is relatively less energy demanding than terrestrial animal husbandry.
In the tropics and subtropics, inland aquaculture is predominant and is likely to remain so in the near future. However, considering the potential increased pressure on freshwater availability and quality and the potential impacts of climate change on water resources, it is difficult to predict the expansion of freshwater aquaculture in the mid term. Inland water aquaculture in existing water bodies such as lakes, reservoirs and rivers is increasing, primarily through cage culture. Expected climatic changes could have a profound influence on static water bodies through enhanced eutrophication and stratification and bring about mortality of cultured stocks through upwelling, oxygen depletion and the like. However, there are many adaptive measures available to avoid such calamities, foremost being the development of aquaculture activities in accordance/compliance with the potential carrying capacities of the water bodies and continual monitoring of environment variables in relation to nutrient loading, externally and internally.
The impacts of climate change on wild fish populations are likely to have a significant impact on aquaculture, in particular with regard to the availability of raw materials for the production of fish meal and fish oil. Feeds for farmed animals bear a very high ecological cost (Bartley *et al.*, 2007) and aquaculture of carnivorous species, which currently constitute only a small proportion of all cultured commodities, is no exception. Such fish are highly valued so the most appropriate way to address this issue would be for the development of suitable diets that use decreasing amounts of fish meal and fish oil. This process got underway 15 years ago, with the development of high energy diets for salmonids but since then there has been a hiatus.
It is also important to curtail the use of diets containing fish oil through the grow-out phase and adopt “finishing diets” (Jobling, 2003, 2004; Turchini *et al.*, 2007) prior to harvesting in order to satisfy consumer demands and maintain the fish quality (Menoyo, 2004; Mourente *et al.*, 2005).

On the other hand, the uncertainty associated with fish meal and fish oil supplies and their projected reduction as a result of climate change do not apply only to aquaculture. The same ingredients are used in other animal husbandry sectors and in the pet food industry and recently this latter use for non-human food production has been highlighted (Naylor *et al.*, 2000: Aldhous, 2004). There is a need for dialogue around the use of a potentially limiting biological resource (De Silva and Turchini, 2008).

The present analysis also points out the wide range in the returns from use of a unit of fish meal and or fish oil on the overall production of aquaculture commodities. Aquaculture, unlike terrestrial animal husbandry, relies on a wide range of species, currently around 300 (FAO, 2007). In an attempt to make a meaningful comparison of the environmental costs of aquaculture and other food production sectors, the need to present a balanced picture of the environmental costs of all food producing sectors and to formulate environmental policies considering the impacts of all sectors were considered as a priority (Bartley *et al.*, 2007). However, it is evident that aquaculture is in a stand alone situation, in that the differences between the ecological costs of culturing a carnivorous species such as salmon and an omnivorous/herbivorous fish such as common carp are so widely apart and far different to poultry husbandry and any of the above species, and therefore calls for treating different cultured commodities as separate entities.

Coral bleaching exacerbated by climatic changes and its effects on biodiversity is a major and a growing concern. It is important to consider the process in conjunction with coral destruction caused by destructive fishing methods undertaken to meet the demands of the live fish restaurant trade, a growing luxury trade in limited locations in Asian tropics and subtropics. In view of growing public concern the dependence on wild caught fish for this trade has markedly declined and this niche market is increasingly making use of cultured fish (see Section 5.4.4.). This indicates that aquaculture seems capable of helping lessen the exacerbation of coral reef destruction and enhancing the preservation of biodiversity.

More often than not aquaculture is criticised as ecologically costly and environmentally degrading.. Such conclusions are almost always based on aquaculture of high value commodities such as shrimp and carnivorous finfish species such as salmonids and have created erroneous perceptions amongst public, planners, developers and investors. The fact is that the great bulk of aquaculture is still dependent on fish and molluscs feeding low in the food chain and seaweed commodities that essentially act as carbon sinks and aid in carbon sequestration.

In the wake of climate change, aquaculture has an increasingly important role to play by increasing carbon sequestration, furthering the increased production of fish and molluscs feeding low in the food chain and of seaweeds. Aquaculture offers a high degree of elasticity and resilience to adapt to changes that would even further reduce the sector's contribution to climatic change. For example, the adoption of simple techniques of providing a suitable and/or enhanced food source(s) for cultured stock through measures to increase periphyton growth could be a major energy saving measure (e.g. van Dam *et al.*, 2002).

Overall, climatic changes impacts on aquaculture are predicted to be very variable, depending on the current climatic zones of activity. The more negative impacts are likely to be on aquaculture operations in temperate regions, viz:

- impinging on the growth rates of cultured, cold water species, resulting from exceeding the optimal temperature ranges for body function, and

- increasing the potential hazards of diseases through the increase of virulence resulting from increased temperatures beyond the dormancy range of these pathogens.

In tropical and subtropical regions, where aquaculture activities predominate, increase in water temperature would bring about the opposite, resulting in increased production. In addition, sea level rise will also impact aquaculture positively, with the possibility of it providing an alternative livelihood means for many practitioners of terrestrial agriculture in deltaic areas. Most importantly, aquaculture offers a less energy consuming food production alternative in comparison to all others and needs to be recognised as such. Life cycle assessment studies indicate that certain cultured aquatic commodities; in particular shrimp and carnivorous finfish or any aquatic organism relying mainly on fish meal and fish oil for feeds are energy costly. However, these are increasingly sought after commodities, as a consequence of improvements in living standards and disposable income in developed and developing countries. Production of such commodities are driven by market forces and because there is demand, production will continue to contribute to carbon emissions overall, as compared to the bulk of other aquaculture commodities that are essentially carbon sequestering. A possible solution lies in persuading consumers to move away from the consumption of commodities that are net contributors to carbon emissions. Such a shift will invariably have major social and economic impacts on the producing countries and there is a need to strike a balance in this regard. Perhaps the adaptive measure of including potential carbon emissions from high value food products, as much as eco-labelling, could be most appropriate.

Finally, it has to be conceded there is a need to collate robust quantitative information to address issues regarding the role of aquaculture with relation to climatic change. The efforts of the world are directed towards reducing all forms of carbon emissions, be they from food production processes or transport. With regard to food production, one may wonder if the analysis of impacts in terms of industrial energy is sufficient. For example, carp aquaculture uses minimal industrial energy but has a potential significance in the carbon cycle, fixing CO_2 through phytoplankton, some of which end as fish by way of the food web. Equally, are fertilization and phytoplankton based aquaculture systems more climate/carbon friendly than more intensive forms which utilise considerable amounts of external energy inputs? All of the above questions have to be balanced against the food and development needs; to arrive at considered decisions a large amount of data would be needed as well as global political will.

This treatise cannot end by addressing climatic change influences on aquaculture *per se*. After all, aquaculture does not occur in a vacuum. In order to mitigate further exacerbation of global climate change the world has accepted there should be unified actions to reduce green house gas (GHG) emissions. In this regard, one option is to reduce dependence on fossil fuels as an energy source and to do so by increasing dependence on biofuels. The first generation production of biofuels is from conversion of plant starch, sugars, oils and animal fats into an energy source that could be combusted to replace fossil fuels. Of the biofuels, currently, the most popular is bio-ethanol, produced by fermentation of a number of food crops such as maize, cassava and sugar cane (Worldwatch Institute, 2006). At present, and accounting for energy inputs, Brazilian sugarcane bio-ethanol is observed to have the highest net GHG mitigating potential (Macedo *et al.*, 2004). Whilst the world looks to biofuels as an alternative it has had a ripple effect on food crops, prices, availability, access, food security and poverty and an overall impact on sustainable development (Naylor *et al*., 2006). Aquaculture and most forms of animal husbandry depend, to varying extents, on some of the same food crops used for biofuels production, for feeds. The equation on climatic changes on aquaculture therefore, is not straight forward; many other factors have to be built into this complex equation to bring about adaptive measures and they have to evolve collectively, with an ecosystem perspective rather than sector by sector.

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