Climate change impacts: challenges for aquaculture

Invited Guest Lecture 3

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De Silva, S.S. 2012. Climate change impacts: challenges for aquaculture, *In* R.P. Subasinghe, J.R. Arthur, D.M. Bartley, S.S. De Silva, M. Halwart, N. Hishamunda, C.V. Mohan & P. Sorgeloos, eds. *Farming the Waters for People and Food.* Proceedings of the Global Conference on Aquaculture 2010, Phuket, Thailand. 22–25 September 2010. pp. 75–110. FAO, Rome and NACA, Bangkok.

Abstract

In spite of all the debates and controversies, a global consensus has been reached that climate change is a reality and that it will impact, in diverse manifestations that may include increased global temperature, sea level rise, more frequent occurrence of extreme weather events, change in weather patterns, etc., on food production systems, global biodiversity and overall human well being. Aquaculture is no exception. The sector is characterized by the fact that the organisms cultured, the most diverse of all farming systems and in the number of taxa farmed, are all poikilotherms. It occurs in fresh, brackish and marine waters, and in all climatic regimes from temperate to tropical. Consequently, there are bound to be many direct impacts on aquatic farming systems brought about by climate change. The situation is further exacerbated by the fact that certain aquaculture systems are dependent, to varying degrees, on products such as fishmeal and fish oil, which are derived from wild-caught resources that are subjected to reduction processes. All of the above factors will impact on aquaculture in the decades to come and accordingly, the aquatic farming systems will begin to encounter new challenges to maintain sustainability and continue to contribute to the human food basket.

The challenges will vary significantly between climatic regimes. In the tropics, the main challenges will be to those farming activities that occur in deltaic regions, which also happen to be hubs of aquaculture activity, such as in the Mekong and Red River deltas in Viet Nam and the Ganges-Brahamaputra Delta in Bangladesh. Aquaculture in tropical deltaic areas will be mostly impacted by sea level rise, and hence increased saline water intrusion and reduced

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water flows, among others. Elsewhere in the tropics, inland cage culture and other aquaculture activities could be impacted by extreme weather conditions, increased upwelling of deoxygenated waters in reservoirs, etc., requiring greater vigilance and monitoring, and even perhaps readiness to move operations to more conducive areas in a waterbody.

Indirect impacts of climate change on tropical aquaculture could be manifold but are perhaps largely unknown. The reproductive cycles of a great majority of tropical species are dependent on monsoonal rain patterns, which are predicted to change. Consequently, irrespective of whether cultured species are artificially propagated or not, changes in reproductive cycles will impact on seed production and thereby the whole grow-out cycle and *modus operandi* of farm activities. Equally, such impacts will be felt on the culture of those species that are based on natural spat collection, such as that of many cultured molluscs.

In the temperate region, global warming could raise temperatures to the upper tolerance limits of some cultured species, thereby making such culture systems vulnerable to high temperatures. New or hitherto non-pathogenic organisms may become virulent with increases in water temperature, confronting the sector with new, hitherto unmanifested and/or little known diseases.

One of the most important indirect effects of climate change will be driven by impacts on production of those fish species that are used for reduction, and which in turn form the basis for aquaculture feeds, particularly for carnivorous species. These indirect effects are likely to have a major impact on some key aquaculture practices in all climatic regimes. Limitations of supplies of fishmeal and fish oil and resulting exorbitant price hikes of these commodities will lead to more innovative and pragmatic solutions on ingredient substitution for aquatic feeds, which perhaps will be a positive result arising from a dire need to sustain a major sector.

Aquaculture has to be proactive and start addressing the need for adaptive and mitigative measures. Such measures will entail both technological and socio-economic approaches. The latter will be more applicable to small-scale farmers, who happen to be the great bulk of producers in developing countries, which in turn constitute the “backbone’ of global aquaculture. The sociological approaches will entail the challenge of addressing the potential climate change impacts on small farming communities in the most vulnerable areas, such as in deltaic regions, weighing the most feasible adaptive options and bringing about the policy changes required to implement these adaptive measures economically and effectively.

Global food habits have changed over the years. We are currently in an era where food safety and quality, backed up by ecolabelling, are paramount; it was not so 20 years ago. In the foreseeable future, we will move into an era where

consumer consciousness will demand that farmed foods of every form will have to include in their labeled products the green house gas (GHG) emissions per unit of produce. Clearly, aquaculture offers an opportunity to meet these aspirations. Considering that about 70 percent of all finfish and almost 100 percent of all molluscs and seaweeds are minimally GHG emitting, it is possible to drive aquaculture as the most GHG-friendly food source. The sector could conform to such demands and continue to meet the need for an increasing global food fish supply. However, to achieve this, a paradigm shift in our seafood consumption preferences will be needed.

KEY WORDS: *Aquaculture, Climate change, Global warming, Deltaic regions, Paradigm changes in food habits.*

Introduction

Perhaps in modern history it will be difficult to find a more global science-based evaluation and associated documentation than that on climate change, its causative factors and potential impacts, and plausible mitigating and adaptive measures to combat such changes. In spite of the intensive science-based findings and scrutiny (IPCC, 2007), it still has its critics and non-believers (e.g. Lomborg, 2001; Hulme, 2009; Washington and Cook, 2011). However, it is correct to say that the overwhelming scientific consensus (IPCC, 2007) on climate change makes its dismissal no longer tenable and the associated risk of making the world an even hungrier place unacceptable. Climate change impacts do not discriminate between the rich and the poor, nor do these make distinctions on where the severity of impacts will occur; all impacts are almost totally universal, with a degree of geographical variation. It is in the above context and in recognition of the importance and urgency of the issues related to climate change and its impacts that many global fora (e.g. United Nations Framework Convention on Climate Change, 1992; Kyoto Protocol, Kyoto, Japan, December 1997; Copenhagen Climate Change Conference, November 2009) have been convened, often bringing together global leaders, to explore potential mitigating measures and adaptabilities.

One of the greatest fears arising from climate change is its impacts on the world's food production systems. The gross predictions suggest there is going to be a reduction in agricultural productivity in the tropics and subtropics, hubs of population concentration and where most of the poor live (IPCC, 2007). If this is not addressed appropriately, it will have a bearing on the Millennium Development Goals (MDGs) (www.beta.undp.org/content/undp/en/home/mdgoverview.html), the most persuasive strategy to end world poverty and hunger. Aquaculture, like all production sectors, is not immune to the impacts of climate change.

Climate change impacts on food production have been considered on many occasions, and the broader aspects with regard to stressors on a growing human population have been discussed in detail (e.g., McMichael, 2001). On the other hand, the climate change issues for the fisheries sector have received relatively little attention (Cochrane *et al*., 2009), with the emphasis, if any, being on impacts on biodiversity and habitat (e.g. coral reefs). It is in this context that the fisheries sector as a whole has responded to improve its profile in the arena of climate change impact discussions, at all levels and relevant fora (Anon., 2009). Overall, there is a much better understanding of the impacts that climate change will have on the capture fisheries sector, particularly the marine fisheries; the latter still account for nearly two thirds of the global fish production.

It is estimated that fisheries and aquaculture support some 520 million people (approximately 8 percent of the current global population) for their livelihoods and incomes, and as the main source of animal protein. Allison *et al.* (2009) have suggested that the great bulk of the potentially affected are from vulnerable communities in tropical and low-lying areas and in small-island developing states. Furthermore, these are also among the world's poorest and twice as dependent upon fish for food as are those of other nations, with 27 percent of dietary protein derived from fish compared with 13 percent elsewhere (Allison *et al*., 2009).

The general consensus on climate change impacts on capture fisheries is that even recent changes in the distribution and production of a number of fish species are ascribed to climate variability, such as the El Niño-Southern Oscillation. It is predicted that there could be an increase in production of 30 to 70 percent in high latitude regions (Cheung *et al.,* 2010) brought about by warming and reduced ice cover, but a decrease of 40 percent in production in low-latitude regions (Cheung *et al*., 2010) as a result of reduced vertical mixing and hence the reduced recycling of nutrients (Brander, 2007). Brander (2007) also suggested that there could be negative impacts on inland fish production as a result of changes in precipitation patterns in certain areas. Until now there has been relatively little emphasis on climate change implications for aquaculture (Handisyde *et al*., undated; De Silva and Soto, 2009), even though the sector is increasing in importance in global food fish supplies (FAO, 2009; Subasinghe *et al*., 2009). For example, aquaculture currently accounts for 76 percent of global freshwater finfish production and 65 percent of mollusc and diadromous fish production (FAO, 2009) and is estimated to contribute approximately 50 percent to all seafood consumed (FAO, 2010).

Water is life. Aquaculture is synonymous with water, as it entails farming in waters – fresh, brackish and marine. Water stressors, of varying forms, are crucial to all food production, and these are being gradually addressed at both the global and regional levels, particularly by the larger countries. Vörösmarty *et al*. (2010) suggested that 80 percent of the world's population is exposed to high levels of threat to water security and that the poor nations remain very vulnerable. These authors also pointed out that this vulnerability is associated with a lack of precautionary investment that jeopardizes biodiversity, with habitats associated with 65 percent of continental discharge classified as moderately to highly threatened; they thus called for a cumulative threat framework that offers a tool for prioritizing policy and management responses to this crisis. On the other hand, Piao *et al*. (2010), dealing with the climate change impacts on water resources and agriculture in China, showed that there are major changes taking place in river water flows, with significant regional differences within the country. For example, the authors indicated significantly reduced annual flows occurring in the Yellow River, thought to be at least partially brought about through climate change. These changes were shown to impact on agriculture, and most of the river deltas, being hubs of aquaculture activity, will also be impacted. It is important to note that there is a serious dearth of information linking the problems of water stress/availability brought about by climate change to impacts on aquaculture.

De Silva and Soto (2009) reviewed the climate change impacts on aquaculture. The present synthesis attempts to evaluate the challenges that climate change would impose on the sector. Accordingly, those facets of climate change that would impact on aquatic farming systems are considered, together with the ways and mechanisms that these impacts are likely to act. The Asia-Pacific region dominates global aquaculture (FAO, 2010); it is inevitable, therefore, that the main emphasis in this synthesis is on this region. Equally, it has to be appreciated that there are only a limited number of explicit studies of climate change impacts on aquaculture *per se*. Consequently, in some instances the synthesis also draws on the broader literature for examples of possible climate change impacts on aquatic farming systems.

Uniqueness of aquaculture

The great bulk of global food fish supplies, unlike all the other commodities, are of hunted origin. The change from a hunted supply to a farmed supply is only recent for most species, even though aquaculture is a millennia-old tradition for other species. Currently, aquaculture or farmed food fish supplies account for nearly 50 percent of the global food fish consumption (Subasinghe *et al*., 2009; FAO, 2010), and its contribution is on the increase.

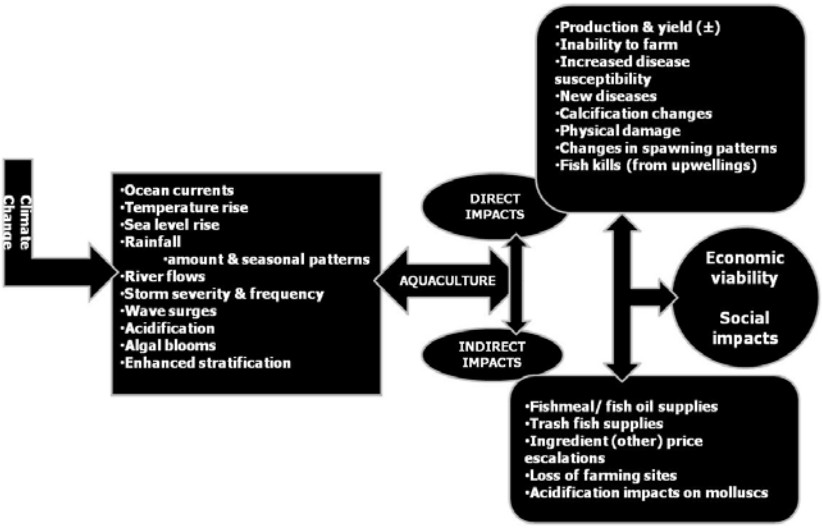
Unlike other farming sectors for animal protein, aquaculture is unique in that all the farmed animals are poikilothermic. It should also be noted that aquaculture includes the farming of plants, most notably seaweeds, for human consumption as well as industrial use. Aquaculture is also unique in the number of taxa farmed, which has been increasing over the years. In 2006, over 336 species of animals and plants, representing 115 families, were farmed, and the number is thought to be underestimated (Bartley *et al*., 2009).

Finally, the commodities cultured are spread across a wide climatic range. Aquaculture is practiced in the tropics, subtropics, sub-temperate and temperate regions, literally extending from 40–45 °S to N. De Silva and Soto (2009) demonstrated that the current aquaculture activities, based on the four major commodities (viz. finfish, shrimp, molluscs and aquatic plants) are spread from south to north, and that the great bulk of aquaculture production occurs in tropical regions. They also demonstrated that there have been changes in the production profiles of the different climatic regions, in respect of each of the commodities, over the years. Perhaps some of these changes are driven by market changes; however, detailed treatment of these aspects is beyond the scope of the present review.

Potential impacts of climate change on aquaculture

Climate change impacts are manifested in many forms. The impacts on aquaculture can be direct or indirect, some impacts being what could be categorized as second-order impacts. The potential climate change facets that could have an impact on aquaculture together with the potential manifestations of climate change elements on aquaculture are schematically depicted in Figure 1. Those facets of climate change that influence, either directly and/or indirectly, are perhaps relatively easily discernible (Figure 1). It is also important to note that climate change facets could impact singly or in combination, and equally, some of the impacts may be hidden and not very obvious. Similarly, the impacts

FIGURE 1
Schematic representation of the potential major climate change impacts on aquaculture and the possible forms of their manifestation



may not be evenly distributed, being dependent on current climatic regimes. For example, temperature increases are likely to primarily influence those aquaculture activities which are located in temperate regions.

The main facets of climate change that could potentially impact directly or indirectly on aquaculture can be identified as:
- ocean currents;
- temperature changes;
- sea level rise;
- rainfall (amount and seasonal patterns);
- river flows;
- storm severity and frequency;
- wave surges;
- algal blooms;
- enhanced stratification;
- ocean acidification; and
- pests and diseases.

The above impacts are not arranged in any known order of importance of impacts on aquaculture, this being a relatively unknown factor. In the following section some of the above, either singly or in combination, and thought to be most relevant to this synthesis are dealt with.

Ocean currents

Impacts of climate change on ocean currents and the related follow-on effects on ocean productivity, fish population changes and migratory patterns, coral reefs and so forth are relatively well documented. Some of the more important changes that are predicted to occur are a loss in ocean biological productivity, or net primary productivity (NPP), that is translated through the food web to fish productivity (Brander, 2007). For example, it is estimated that productivity in the North Atlantic Ocean will plummet 50 percent and ocean productivity world wide by 20 percent (Schmittner, 2005). Cheung *et al*. (2010) further elaborated these predictions based on latitudinal difference, suggesting that high-latitudinal regions could experience a 30 to 70 percent increase in production as opposed to a decrease of about 40 percent in low-latitudinal regions.

The predicted changes in ocean circulation patterns, in turn, will result in the occurrence of El Niño-type influences being a more frequent possibility. The latter, in turn, will influence the stocks of small pelagics (e.g. anchovetta, *Engraulis ringens*), as had occurred in the past. Similarly, the changes in the North Atlantic Oscillation winter index (Schmittner, 2005) resulting in higher winter temperatures could influence sandeel (*Ammodytes* spp.) recruitment. These changes in oceanic current patterns and the associated events such as changes in ocean productivity are unlikely to impact on aquaculture directly, but will do so indirectly and to a very significant extent, as the above species are a main raw material for the reduction (fishmeal and fish oil production) industry.

On the other hand, ocean currents could directly impact on aquaculture activities through bringing about changes in temperature (increases or decreases depending on the climatic region) causing stress effects and maybe even mortality. For example, in December 2009, such a cold current into Phuket Bay in Thailand reduced the water temperature by up to four degrees and is thought to have lead to mass mortality of cage-cultured brown-marbled grouper (*Epinephelus fuscoguttatus*) (personal observation).

Temperature changes

All cultured aquatic organisms are poikilothermic, and as such would be impacted by changes in water temperature. As previously mentioned, changes in water temperature could be brought about by alterations in circulation patterns which would impact on mariculture activities in particular. It is also important to note that the impacts of temperature changes (in particular, increases) are also linked to interactions involving declining pH and increasing nitrogen and ammonia, resulting in increased metabolic costs. For example, experimental studies on rainbow trout (*Oncorhynchus mykiss*) have shown that a 2 °C temperature increase improved appetite, growth, protein synthesis and oxygen consumption in the winter, but the reverse occurred in the summer (Morgan, McDonald and Wood, 2001). All this indicates the difficulty in predicting the climate change impacts on specific culture systems.

One of the main manifestations of climate change is often accepted as the global temperature increase, which in turn would result in water temperature increases. The temperature tolerance range of important cultured species in the temperate region in particular is close to the upper range of tolerance of these species (Table 1). An increase in temperature of a few degrees is likely to impact on the

TABLE 1
Temperature tolerances (°C) of selected, cultured species of different climate distribution

Climatic/temperature guild/species	Incipient lethal temperature		Optimal range
	Lower	Higher	
Tropical			
Redbelly tilapia (*Tilapia zillii*)	7	42	28.8–31.4
Guinean tilapia (*T. guineensis*)	14	34	18–32
Warmwater (subtropical)			
European eel (*Anguilla anguilla*)	0	39	22–23
Channel catfish (*Ictalurus punctatus*)	0	40	20–25
Temperate/polar			
Arctic char (*Salvelinus alpinus*)	0	19.7	6–15
Rainbow trout (*Oncorhynchus mykiss*)	0	27	9–14
Atlantic salmon (*Salmo salar*)	-0.5	25	13–17

Source: De Silva and Soto (2009), based on Ficke, Myrick and Hansen (2007).

culture and well being of such species. On the other hand, the situation is not so severe for cultured tropical species, because the predicted water temperature increases are likely to be still within the optimal range of tolerances.
Temperature increases in the temperate regions will also bring about negative, indirect impacts on aquaculture, such as inducing hitherto non-pathogenic organisms to become virulent and also increasing the range of distribution of pathogenic organisms. For example, it has been reported that mass mortalities of the turberculate abalone (*Haliotis tuberculata*) in the Brittany and Normandy coasts were caused by the increased temperature and the presence of the pathogen *Vibrio harveyi*, and the resulting loss in reproductive potential (Travers *et al*., 2009). Many such examples are known (for further details see, De Silva and Soto, 2009).

In the recent past, a high level of mortality has been recorded in Pacific cupped oyster (*Crassostrea gigas*) (http://oceanacidification.wordpress.com/2009/06/15/oysters-in-deep-trouble). Studies have demonstrated a link between the energy expended during reproduction and the compromised thermo-tolerance and immune status of oysters, leaving them easily subject to mortality if heat stress occurs in the post-spawning stage (Li *et al*., 2007). The authors suggested that the findings improve the understanding of oyster summer mortality and its implications for the long-term persistence of molluscs under the influence of global warming.

Sea level rise

Sea level rise is considered as an important and significant result of climate change, impacting on coastal states and river salinities. Apart from general impacts on coastal communities and oceanic islands, the very existence of which are threatened, sea level rise will have major influences on aquaculture. Problems associated with sea level rise and consequent potential salinity intrusion are further exacerbated through reduced river flows, as well as by coastal land subsidence in certain areas.

Foremost is the impact on those agricultural and aquaculture activities in deltaic regions (Ericson *et al*., 2006), particularly in the tropics, such as the Mekong Delta, Viet Nam and the Ganges-Brahamaputra Delta, Bangladesh, which are hubs of aquaculture activity, providing millions of livelihoods. In the deltaic regions of the tropics, the primary cultured species are shrimp and euryhaline finfish such as barramundi or Asian seabass (*Lates calcarifer*). However, the Mekong Delta (8°33’–10°55’ N; 104°30’-106°50’ E), aptly termed the “food basket” of Viet Nam (implicit in its importance to the total food supplies in the country as a whole), and the lower reaches of the Mekong River is the home to a thriving striped catfish (*Pangasianodon hypophthalmus*) farming industry, a truly freshwater finfish farming activity, (Phan *et al*., 2009; De Silva and Phuong, 2011). This farming activity will be impacted over time due to increased seawater intrusion along the river, further exacerbated by reduced water flow, with this catfish species unlikely to be able to tolerate the predicted salinity increases.

Rainfall, river flows and water stress

Rainfall patterns and quantity, river flows and water stress are intricately connected. In the tropics in particular, the monsoonal rain patterns and the associated changes in riverine habitats, etc. act as triggers for the maturation and spawning of many aquatic animal species, in contrast to the temperate regions, where the day-light cycle changes act as a primary stimulus (Welcomme, 1985). Furthermore, in the tropics most floodplain areas act as nursery grounds for a significant number of cultured finfish species (Welcomme, 1985) thus, losses in floodplain areas and the associated changes in the migratory patterns could bring about impacts on some ongoing aquaculture practices associated primarily with stock enhancement (Welcomme and Bartley, 1998).

Changes in monsoonal rain patterns and the total amount of rainfall have already been documented, and the impacts of some of these on terrestrial agriculture are well known (McMichael, 2001; Goswami *et al.*, 2006; Piao *et al.*, 2010). Overall, the predicted water stress is expected to result in decreased water availability in the major rivers in Central, South, East and Southeast Asia, as well as in Africa (IPCC, 2007), areas where major aquaculture activities are present, such as the major river deltas. Indeed, the predicted reduced water availability in the deltas of major Asian rivers 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/ monsoon patterns (Goswami *et al.*, 2006). De Silva and Soto (2009) summarized the possible impacts of the above climatic change factors on aquaculture. It is also important to note that eight of the ten major rivers in the world (O'Connor and Costa, 2004), based on basin area, peak discharge and unit runoff are found in the tropics, where aquaculture is predominant.

Storm severity and frequency, and wave surges

The frequency of extreme weather events such as typhoons, hurricanes and unusual floods has increased dramatically over the last five decades. For example, the number of such events increased from 13 to 72 in the decades 1950 to 1960 and 1990 to 2000, respectively (IPCC, 2007). These extreme events result in huge economic losses and for the above two decades, the mean annual losses have been estimated at between USD4 billion and USD38 billion (fixed dollars, 2000), and in some individual years in the latter decade were as high as USD58 billion (IPCC, 2007). Extreme climatic events, currently attributed to climate change (IPCC, 2007) are predicted to occur mostly in the tropical and subtropical regions.

All forms of aquaculture will be impacted by extreme events, primarily through destruction and damage to infrastructure, mostly outdoor structures such as

BOX 1. Asian aquaculture

The great bulk of Asian aquaculture is small scale. One of the important aquaculture developments in Asia is the small-scale aquaculture practices in coastal bays. These include an increasing number of seaweed farms and the small-scale cage culture of high-valued species such as groupers, wrasses and lobster. In the coastal areas, culture of milk fish (*Chanos chanos*), conducted traditionally in ponds (tambaks) using tidal exchange is also common. All these activities are conducted with relatively fragile infrastructure and are at high risk to storms, wave surges and high winds, and consequently the chances of livelihoods being impacted are also high.

pond dykes, which in turn will also bring about loss of stocks, including, for example, valued broodstock. On the other hand, most closed systems, which are generally more robust constructions, are likely to withstand most extreme events. Some of the recent extreme climatic events that have impacted on aquaculture were summarized by De Silva and Soto (2009); also see Soto, Jara and Moreno (2001), Muralidhar, Ponniah and Jayanthi. (2009). For example, during heavy storms in 1994–1995, salmon farms in southern Chile lost several million fish, mostly rainbow trout (*Oncorhynchus mykiss*), coho salmon (*O. kisutch*) and Atlantic salmon (*Salmo salar*), all alien species which are commonly cultured in Chile (Soto, Jara and Moreno, 2001). The authors cautioned that such escapees could compete with indigenous species and that colonization and establishment in new habitats are possible.

There are many aquaculture practices that are small-scale and farmer owned/ leased, operated and managed that occur in coastal regions throughout the Asia-Pacific. These small-scale practices contribute significantly to production, almost always providing the sole form of livelihood and food security to thousands. Wave surges and storm activities will bring about adverse impacts on these practices (Box 1).

Algal blooms and enhanced stratification

It is reported that in the oceans, there had been a noticeable drop in net primary productivity brought about by a combination of factors, mostly through warming and reduced nutrient mixing, particularly so in the lower latitudes (Brander, 2007). On the other hand, in inland waters climate change may bring about increased stratification of lakes and reservoirs in some areas. In stratified waters, changes in the weather conditions could bring anoxic waters from the deeper layers, often also containing relatively high concentrations of toxic gases such as hydrogen sulphide, to the upper layers, impacting, for example, on cage farming and in extreme cases even resulting in fish kills (Abery *et al*., 2005). Equally, eutrophication could be exacerbated and consequently could impact (mostly negatively) on food webs and habitat availability and quality (Ficke, Myrick and Hansen, 2007); in turn, both aspects could have a bearing on aquaculture activities, in particular for inland cage and pen aquaculture.

Ocean acidification

Ocean acidification is attributed to the increased atmospheric carbon dioxide from anthropogenic activities, a significant proportion of which ends up in the oceans (Cladeira and Wickett, 2003; Doney, 2006), resulting in a decrease in pH, carbonate ion concentrations (CO_3^{-2}) and the saturation states of calcium carbonate minerals such as calcite (Ω_{ca}) and aragonite (Ω_{ar}) (Cooley, Kite-Powell and Doney, 2009). It is believed that since the industrial revolution, the release of CO_2 from anthropogenic activities has resulted in the decrease of oceanic surface pH by 0.1 (Doney, 2006). Based on the prediction by IPCC (2007) that atmospheric CO_2 will range between 467 and 555 ppm by the year 2050, Cooley and Doney (2009) predicted that the surface ocean pH would drop by a further 0.3 and decrease global Ω_{ca} and Ω_{ar} by 25 percent relative to 2009. On the other hand, Caldeira and Wickett (2003) concluded that unabated CO_2 emissions over the coming centuries could produce changes in ocean pH that are greater than any experienced over the last 300 million years (Myr) and that a pH reduction of 0.7 is a possibility.

Decrease in pH of oceanic water from acidification is expected to impact on coral and calcareous skeletal formation, i.e. in corals, some planktonic organisms, molluscs, etc. The impacts of the above on marine ecosystems services were reviewed by Cooley, Kite-Powell and Doney (2009). In regard to aquaculture, the potential impacts could be varying, some even being unpredictable at present. The most likely impacts will be on mollusc culture; some of these are gradually becoming evident, such as the high level of mortality recorded in Pacific cupped oysters (http://oceanacidification.wordpress.com/2009/06/15/oysters-in-deep-trouble/) and reduced larval settlement due to improper calcification of the skeleton at metamorphosis. It has been suggested that ocean acidification may impact on the immune response of blue mussel (*Mytilus edulis*) through its influence on physiological condition and the functionality of the haemocytes, which could have a significant effect on cellular pathways, in particular those that rely on specific concentrations of calcium (Bibby *et al*., 2008). In addition, data are being accumulated to suggest sub-lethal impacts of acidification on morphology, physiology and behaviour of molluscs, as well as gonadal development (Ishimatsu and Dissanayake, 2010). The above impacts are likely to bear on mollusc aquaculture globally, although admittedly to varying degrees in the different climatic regimes. Although ocean acidification is a reality, there are very few strategies available to reduce these impacts apart from adopting mitigating measures to reduce atmospheric carbon dioxide levels, perhaps excepting the hatchery production of cultured molluscs, which could be carried out under controlled conditions.

Challenges for aquaculture

All of the above climate change elements could impact aquaculture directly and/or indirectly. As previously mentioned, such impacts cannot always be attributed to one single facet of climatic change, in most cases the impacts due to being a combination of many factors.

Direct impacts

Direct impacts of climate change events on aquaculture are those climate changes that would impact on farming activities where the impacts could be attributed to single or multiple facets of climate change.

Sea level rise

It is believed that exacerbated sea level rises are a direct impact of climate change. Sea level rises will impact on coastal regions, as well as deltaic areas, particularly of the tropics, where the increases in sea level are expected to be highest. As previously noted, most tropical deltaic regions, particularly those in the developing world, are hubs of farming activity (including aquaculture) that support millions of livelihoods.

Challenges to on-going aquaculture practices

Direct impacts of sea level rise will be through salinity intrusion and flooding, and will be mostly prevalent in deltaic areas. Sea level rise is expected to result in the slow flooding of aquaculture activities in areas such as in the Mekong Delta and the Ca Mau region, in southern Viet Nam. These are hubs of giant tiger prawn (*Penaeus monodon*) culture, including alternate rice culture in the wet season and shrimp culture in the dry season (Vuong and Lin, 2001). Similar situations occur in the Ganges-Brahmaputra Delta in Bangladesh and elsewhere.

The main challenge that the existing shrimp farming sector is likely to encounter is through flooding (with increased sea level making it harder to discharge flood waters). As a result of increased flooding, new water management schemes will have to come into being as a mitigating measure (Tan, 2008). In the process, there are likely to be conflicts between shrimp farmers and other stakeholders, and this will be a major challenge. Increased duration of flooding due to lowering of salinity below optimal level will also shorten the period available for shrimp culture and change the dynamics of the rice-shrimp culture systems. On the other hand, the situation will impact less on the shrimp farming in the Ganges-Brahmaputra Delta, as alternate rice-shrimp cropping is not practiced.

The predicted conditions that will be encountered by the striped catfish farming sector, a truly freshwater aquaculture activity, along the lower reaches of the Mekong River, Viet Nam will be in contrast to those anticipated for shrimp farming. This farming system provides nearly 180 000 livelihoods and is a major seafood export industry of Viet Nam (Phan *et al*., 2009; De Silva and Phuong, 2011). With the predicted sea level rise of 3 mm/year, and concurrent with reduced river flow, seawater intrusion is predicted to cause increased salinity of up to 17–20 ppt along the river up to 70–80 km from its mouth. The current farming system relies on regular water exchange from the river that enables very high stocking densities to be maintained and high productivity averaging 250–400 tonnes/ha/crop (Phan *et al*., 2009). Phan *et al*. (2009) have reported that catfish farms in the lowest reaches presently have a reduced productivity attributed to diurnal salinity fluctuations (to approximately 5 ppt) brought about by the tides. Consequently, as sea level rises over the years, catfish farms in the lower reaches will be subjected to significantly higher levels of salinity and are thus likely to become unproductive and economically unviable.

The major challenge therefore, is to retain the viability of this sector and safeguard the livelihoods of thousands through adoption of suitable strategies. One plausible strategy would be to develop a higher-salinity tolerant strain of striped catfish and disseminate the improved strain to farmers. This option will be a science-based solution and will necessarily involve extensive capacity building among farmers and a significant deviation from the current farming methods. This would involve selective breeding and protocols for transfer. The use of molecular genetic tools can reduce the time required to produce a salinity-tolerant strain, but such a development will also have to go hand in hand with relevant risk management measures, particularly in respect of potential impacts on biodiversity. On the other hand, the farmers may be given the choice to change to a different species, such as a salinity-tolerant barramundi or shrimp. Any such change will have to go hand in hand with changes in the whole farming system, capacity building among the farming community and major infrastructural changes, which will be exorbitantly costly.

New challenges

Salinity increases in deltaic regions in the tropics, hubs of agricultural and aquacultural activity (Ericson *et al.*, 2006) and the home to nearly 15 percent of the global population, will bring a major challenge to aquaculture but could also result in positive changes to some sectors of society. Saline water intrusion and associated flooding are likely to make a large acreage of current agricultural activities, primarily rice cultivation, untenable in such areas. However, such areas can continue to be utilized for aquaculture, thereby continuing to provide alternative livelihoods and much-needed food production.

As an example, the predicted changes in the Mekong Delta, literally the food basket of Viet Nam, accounting for 46 percent of the nation's agricultural production and 80 percent of rice exports (Hõ, 2008), are considered here. A one meter sea level rise is predicted to inundate 15 000 to 20 000 km^2, with a loss of 76 percent of arable land. Predictions by Khang *et al*. (2008) suggest that a 2.5 g/liter salinity front is likely to shift upstream by 10 to 20 km in the main river channel and by 20 to 35 km in the paddy fields by mid-2030. Overall, the simulations show that the area of triple rice crops will be reduced by 71 000 to 72 000 ha. Additionally, there are estimates that suggest that a one meter sea level rise will inundate 40 000 km^2 and displace 17.1 million persons from their normal livelihoods.

In the Ganges-Brahmaputra Delta in Bangladesh, inundation of 2 500, 8 000 and 14 000 km^2 have been predicted for 0.1, 0.3 and 1.0 m sea level rises, respectively (Handisyde *et al.*, undated). It has been shown that the Bengal delta area has one of the highest subsidence rates (Ericson *et al*., 2006), and this, together with sea level rise, would have a compounded impact of loss of agricultural land. Increased salinization in the delta has been reported over the period 1973–1997, and this, with the expected sea level rise, suggests that the impacts are likely to be further aggravated (Handisyde *et al*., undated). For example, the World Bank (2000) predicted a reduction of 0.5 million tonnes in rice production associated with a 0.3 m level sea level rise.

The major challenge confronting aquaculture, therefore, is to commence new farming systems in salinity-intruded areas. In order to meet this challenge, the planning processes have to be put in place soon. These processes would involve:

- making essential policy decisions on the need for a transformation of the farming systems and the livelihoods of the farmers;
- making a step-wise determination of the extent of inundation in relation to a time scale;
- determining the most suitable culture species, based on ecological, biological and potential market features;
- obtaining concurrence with the current farming communities on a potential shift in the livelihood pattern;
- planning the required infrastructural needs (e.g. hatcheries, pond nature and type) required to facilitate the transition; and
- providing the necessary capacity building in aquaculture practices to the farming communities through relevant extension and dissemination mechanisms.

The above steps of transformation of farming on land to farming in water will be a major change that may not necessarily be embraced easily and readily by all stakeholders. However, there appears to be no other easy option available to maintain livelihoods and food production. Obviously, the transformation will require determination to meet the varying range of challenges from all sectors, and a holistic approach to make it cost effective and efficient.

It is also possible that the above transformations could lead to new species emerging as major contributors to aquaculture production. After all, a decade back one would not have expected the striped catfish farmed in the Mekong Delta to impact upon the global aquaculture production and consequent food fish supply so significantly.

Changes in temperature

It has been clearly pointed out that temperature impacts on aquaculture can be direct or indirect, the latter being induced through different pathways, such as in relation to pathogens, changes to immune mechanisms, exacerbated post-reproductive stress and the like. Also in some instances, it will be a combination of climatic elements, including temperature, that could bring about impacts on aquaculture.

Among the major challenges to aquaculture triggered through temperature changes is a very direct one, whereby temperature rises in the temperate regions would approach and/or exceed the tolerance levels of some of the important cultured species such as salmonids. This challenge can be combated only through a shift to species with higher temperature tolerance, the development of strains of the currently cultured species with increased temperature tolerance range, and/or moving to intensive closed systems in which the environment is controlled.

It is generally conceded that the realization of the genetic potential of cultured aquatic animals and plants through selective breeding has lagged behind that of the animal husbandry sector. On the other hand, genetic improvements on salmonids, for example, have had major impacts on the culture of this group (Gjedrem, 2010). As such, it is expected that meeting the challenges confronting the production of strains of cultured salmonids with increased range of temperature tolerance would be possible, and it is heartening to note that the initial research on meeting these challenges has already been launched (Fish Farmer, 2008).

Seawater temperature increases in the temperate regions have resulted in the expression of virulence in pathogenic organisms that were relatively nonpathogenic at lower temperatures. These changes have resulted in an increase in the range of pathogens such as *Vibrio harveyi* (Travers *et al*., 2009), posing new challenges to existing aquaculture operations, mainly mollusc culture. Similarly, as previously mentioned, in the recent past a high level of mortality has been recorded in Pacific cupped oysters.

These challenges have to be met by introducing adequate risk management measures, together with developing effective preventive measures, early diagnostic tools and new treatment profiles, as well as capacity building to adapt to changed farming systems.

Rainfall, river flows and water stress

The global freshwater supply is at a premium and is often considered as a primary commodity that could be limiting and to be conserved vigilantly (Falkenmark, Rockstöm and Karlberg 2009; Economist, 2010). For example, it has been pointed out that in the Asian continent, the backbone of global aquaculture, the amount of available freshwater per capita is the least among all continents (Nguyen and De Silva, 2006). In the context that freshwater finfish aquaculture is the leading subsector, globally, and that the Asia-Pacific region leads aquaculture production by contributing in excess of 90 percent to the global total (FAO, 2010), increased attention will have to be paid to the climate change impacts of changes in rainfall, river flows and water stress on aquaculture.

In general, and in the above context, water stress is likely to impact tropical aquaculture most (also see Allison *et al*., 2009). The main challenges confronting the sector will be manifold. Changes in monsoonal rain patterns and consequent water availability will impact on a number of existing practices, and adaptive measures have to be put in place in order to maintain the current development impetus of the sector. For example, in most finfish cultured in the tropics, the spawning season is related to the rainfall pattern, even in the case of the bulk of hatchery-reared species, which are more often than not maintained outdoors. Equally, there is significant dependence on natural stocks for broodstock. There is emerging evidence that changes in rainfall regimes (and hence, flood regimes) have impacted on the breeding seasons of, for example, Indian major carps, in their natural habitats, with consequences on hatchery production (Vass *et al*., 2009).

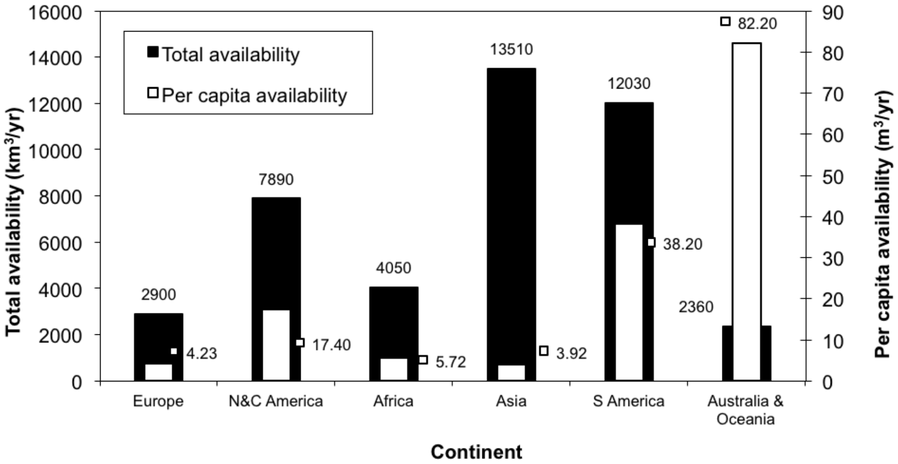
Thackery *et al*. (2010) pointed out that recent changes in the phenology (seasonal timing) of familiar biological events for all types of environments and taxa have been one of the most conspicuous signs of climate change. These authors further demonstrated the relationship of phenological changes and trophic levels. It is plausible that phenological changes will impact on cultured animals, in particular their reproductive seasonality, not only of those species that are artificially propagated but also those whose culture is based on natural spat and seed collection. These changes will impact the production cycles and the supply chains as a whole.

The aquaculture sector will have to evaluate the potential changes that may impact on the reproductive seasonality of the important cultured species. These evaluations should lead to adjustments in broodstock management, hatchery production and the production (grow-out) cycles for each of the major cultured species (also see Vass *et al*., 2009).

Water availability

Our planet is estimated to have only 35 029 000 km^3 of freshwater, or only 2.5 percent of all water resources, of which only 23.5 percent is useable

FIGURE 2
Total and per caput freshwater availability in the different continents



Source: Nguyen and De Silva (2006).

(Shiklomanov, 1993, 1998; Smith, 1998). The naturally available freshwater in the form of rivers, lakes, wetlands, etc. amounts only to 0.01 percent of the earth's water resources, or only 113 000 km^3. The available water is not evenly distributed on the continents, and the amount available per caput (Figure 2) also varies among continents (Nguyen and De Silva, 2006). Even prior to climate change, impacts began to be manifested; water has been recognized as one of the most limiting resources on our planet (Falkenmark, Rockstöm and Karlberg, 2009; Economist, 2010). Consequently, issues related to present and future water requirements for humanity have been addressed many times, but almost totally in respect of terrestrial agriculture (e.g. Ward and Michelsen, 2002; Falkenmark, Rockstöm and Karlberg, 2009; Zimmer and Renault, undated; Piao *et al*., 2010). Falkenmark, Rockstöm and Karlberg (2009) estimated the global water deficit by 2050 to be approximately 3 800 km^3/year. On the other hand, fisheries–water issues have hitherto been scarcely addressed, having gained some attention only recently (Renwick, 2001; De Silva, 2003; Dugan, Dey and Sugunan, 2006).

Considering climate change impacts, the inland aquaculture sector, which currently contributes in excess of 60 percent of global aquaculture production, will need to strongly enhance management of freshwater resources if it is to maintain its significance in the coming decades.

Water recirculation technologies

Recirculation technology is not new (Hart and O'Sullivan, 1993; Losordo, Masser and Rakocy, 1998; McGee and Cichra, 2000) and it, in many diverse forms, is currently in use for many freshwater aquaculture systems and even attempts are being extended to marine systems. Equally, the advantages of recirculation aquaculture are well documented, the foremost of these being saving on water, preventing and containing diseases, and providing biosecurity. However, recirculation systems are mostly used for the culture of high-valued species and/or the production of seed stocks of high-valued species such as shrimp. Recirculation systems entail high energy, capital and recurrent costs, and require skilled technical personnel for management.

The challenge to the use of recirculation systems will be to reduce the energy costs and thereby maintain the GHG emissions per unit production at an acceptable level, through engineering innovations. On the other hand, there is the possibility and the challenge of adopting outdoor recirculation systems that are less energy costly and are based on once-a-year water intake, but still provide the biosecurity and production capacities of indoor, high-tech systems. Such practices are currently in operation, for example, in Thailand and are utilized for the production of specific pathogen free (SPF) postlarvae of giant tiger prawn. Some of these enterprises have been very innovative, for example, some of the intermediate ponds in the system being used for the production of algae and finfish (barramundi), and with the tail end of the system producing *Artemia* biomass (approximately 100 kg/day), destined for the aquarium trade as a food source.

Water usage procedures

Currently, particularly in the tropics, large numbers of small-scale aquaculture practices tend to be clustered together in areas with access to water. Water is often abstracted for these aquaculture practices (e.g. pond culture) relatively freely and in an uncoordinated manner, independently of the surrounding aquaculture farms. Similarly, pond effluent is discharged to the primary water source in a uncoordinated manner. Indeed, from an environmental view point, the situation will be further exacerbated with higher scrutiny on the discharges. Added to all this is the general agreement that climate change will result in reduced water flow in many major river systems in the tropics (IPCC, 2007), further increasing the demand and competition for water for different primary production activities and farming systems (Falkernmark, Rockstöm and Karlberg, 2009).

As such, aquaculture dependent on common water resources has to develop suitable and appropriate water usage strategies. First and foremost, aquaculture farms in a given area abstracting water from a common source will need to coordinate water abstraction and discharge in a collective manner, with the goals of reducing the overall quantity abstracted and avoiding cross contamination via staggering of abstraction and discharge. Such coordination can be brought about through stakeholder consultations and concurrence on adoption of appropriate "water abstraction and discharge calendars" along river lengths (Umesh *et al.*, 2010). Development of such calendars will increase the efficacy of water management and coordination with other users, in particular for agricultural purposes, enhance efficacy and lead to a net water saving.

The above should go hand in hand with development of better water management practices, which could be relatively easily incorporated in to better management practices (BMPs) that are being increasingly developed and adopted for specific cultured commodities through farmer cluster organizations (Umesh, 2007; Umesh *et al*., 2010; www.enaca.org/modules/inlandprojects/index.php?content_id=1).

The ultimate challenge will be to increase vigilance and accountability on water use in freshwater aquaculture through the above processes. Perhaps this is best achieved through education and demonstration of water conservation strategies. An ecosystem approach to aquaculture (EAA) also offers an opportunity to address aquaculture planning with a clear consideration of the other coastal zone and watershed users (FAO, 2010). Clearly, aquaculture adaptation cannot take place in isolation from other users of common resources.

Culture based fisheries

Culture based fisheries (CBF) is considered an environmentally friendly aquaculture practice which is often rural and community based. It is a practice that is a good example of a secondary use of water resources for food fish production and can be conducted in small perennial and non-perennial water bodies (De Silva, 2003). This practice is being adopted by a number of developing countries (Lorenzen *et al.,* 1998; Quiros,1998; Quiros and Mari, 1999; Song, 1999; Phan and De Silva, 2000; Amarasinghe and Nguyen, 2010) to improve the food fish supplies in rural communities and to improve farmer incomes, thereby improving prospects for food security. As the availability of small non-perennial water bodies in developing countries is rather high (e.g. in Asia alone, estimated at 66 710 052 ha; FAO, 1999), and as CBF is a low-cost aquaculture activity, it is attractive to many developing countries as a strategy to increase food fish production and improve rural livelihoods (Quiros,1998; Quiros and Mari, 1999; Amarasinghe and Nguyen, 2010).

The bulk of inland water bodies suitable for CBF activities being rain fed, climate change impacts (as discussed previously) will have a bearing on both water availability and retention capacity. The challenge to CBF practices would be to assess the long-term availability and the relative suitability of such water bodies, as well as to determine the water retention periods appropriate for the stocked fish to attain a marketable size. In turn, the latter information needs to be used to estimate the fingerling (species wise) requirements for each growth cycle, and plan harvesting and marketing processes.

Algal blooms and enhanced stratification

In inland waters, particularly in lakes and reservoirs, cage culture is becoming increasingly important. Such activities are also adopted by governments to provide alternative livelihoods to displaced communities, and they are known to have had much success in this regard (Abery *et al.*, 2005). Ficke, Myrick and Hansen (2007) suggested that climate changes could exacerbate eutrophication and produce more pronounced stratification in lentic systems, in the tropics in particular. Increased eutrophication could result in oxygen depletion in the dawn hours, and changes in wind patterns, rain fall, etc. could result in upwelling bringing deoxygenated deep/bottom waters, often containing toxic gases such as hydrogen sulphide, to the surface, with adverse effects not only on cultured stocks but also on the naturally recruited fish stocks occurring in a water body. Similarly, in marine environments increased temperatures associated with eutrophication and harmful algal blooms (Peperzak, 2003) could enhance the occurrences of red tides and consequently impact on production, resulting in fish kills, and also increase the possibility of human health risks through the consumption of molluscs cultured in such areas. In particular, freshwater and marine cage culture in tropical areas tends to be located in enclosed bays and at high intensity.

The challenge for aquaculture is therefore, to ensure that high nutrient loads do not build up in the respective water bodies, and as far as possible, to spread out the activities into areas where the water circulation is better. In general, cage culture in reservoirs, lakes and enclosed bays tends to be concentrated in coves, primarily for ease of access to land facilities, transportation of feeds, marketing of produce, etc. Such areas also tend to have reduced water circulation and consequently act as “nutrient and waste sinks”, with the potential to bring about adverse impacts, as stated earlier. In the wake of climate change impacts with the potential to exacerbate algal blooms and upwelling of deoxygenated waters, it will be necessary to limit the concentration of aquaculture practices to restricted areas in a water body, and also to utilize areas with better water circulation at the expense of easy access to land-based facilities.

Aquaculture operations will have to adopt optimal stocking densities and feed management protocols, and act in unison rather than in single entities in a water body. It may, therefore, be necessary to come to agreement to reduce the density and the intensity of operations on a collective basis, in accordance with the potential carrying capacity of a water body. Where there has been nutrient build up over the years, the aquaculture operators, in conjunction with other stakeholders, will also need to adopt measures for nutrient stripping, for example, by the use of suitable planktivorous fish species, a form of stock enhancement which will also improve the livelihoods of fishers who are dependent on such water bodies, essentially moving towards a more pragmatic ecosystems approach to aquaculture development (FAO, 2010) that incorporates all aspects of watershed management.

Ocean acidification

The general impacts of ocean acidification on marine biota have been briefly discussed. Some direct impacts of ocean acidity on aquaculture are becoming apparent, best exemplified by the decreased reproductive success of the Pacific cupped oyster in the last few years in Washington State, United States of America that has been attributed to ocean acidification (http://blogs.discovery.com/animal_news/2009/07/seems-like-theres-a-lot-of-bad-news-out-there-with-regards-to-the-worlds-oceans-this-time-the-bad-news-is-that-ocean.html). This lack of reproductive success, which commenced in 2004, has continued, not only in wild populations but also in hatchery stocks, which tend to use the same sea water, thereby impacting on the industry at large. Studies have shown that the impacts of acidification on reproduction in oysters are species specific. For example, it has been demonstrated that larvae of two closely related oyster species, the American cupped oyster (*Crassostrea virginica*), native to the western Atlantic, and the Suminoe oyster (*C. ariakensis*), both closely related to the Pacific cupped oyster, were very sensitive to elevated CO_2 (i.e. reduced pH or more acidic water). On the other hand, Suminoe oyster populations, native to the western Pacific, were apparently not affected by changes in CO_2 levels (Miller *et al*., 2009).

Extreme weather events

One of the biggest challenges that will be encountered, not only for aquaculture but for all forms of human endeavour, is the occurrence of extreme weather events. The unpredictability of the nature, frequency and intensity of extreme weather events poses challenges to planning to combat such events. There are few means available to meet these challenges except to know well the risks and take precautionary measures (e.g. improve the physical strength of infrastructure facilities, provide facilities to minimize loss/escape of stocks) so that the impacts, if any, are kept at a minimum. Equally important is that measures are put in place so that activities can be revitalized after the event with the least degree of hardship. The siting of new facilities and maintenance of natural barriers such as, for example, mangrove, forest and reef belts will provide an extra degree of protection to withstand calamities from extreme weather events.

The major challenge is to develop suitable policy guidelines that would ensure increased risk assessment and improved preparedness, such as that aquaculture facilities in the most vulnerable areas will be constructed to comply with minimal requirements to withstand identified extreme climatic events, and that such facilities also incorporate all possible measures to prevent the escape of stock into the wild. The latter policy could be further strengthened in respect of those facilities that culture alien species. Governments are faced with the challenge of providing suitable policies and incentives to small-scale farmers to take insurance so that practices could be revitalized after such events with minimal economic hardship. In this regard, governments need to pursue the possibility of providing insurance facilities to "farm clusters" – farms organized into legalized, cooperative entities – thereby reducing the burden on individual farmers. This may become acceptable to financial institutions, as had been demonstrated in the case of small-scale shrimp farmers in India (Umesh *et al*., 2010).

Indirect impacts

It was estimated that aquaculture in 2006 used 3 724 000 of fishmeal and 835 000 tonnes of fish oil, accounting for 68.2 and 88.5 percent of global production of these commodities, respectively (Tacon and Metian, 2008). Jackson (2010) suggested that fishmeal usage in aquaculture was 58.8 percent of the global production and predicted that 76 percent of the global supply of fish oil would be used in 2010. Irrespective of these estimates, as well as other controversies associated with fishmeal and fish oil usage (e.g. Naylor *et al*., 2000; Aldhous, 2004; De Silva and Turchini, 2008), it has to be conceded that aquaculture will continue to remain a very significant user of global fishmeal and fish oil.

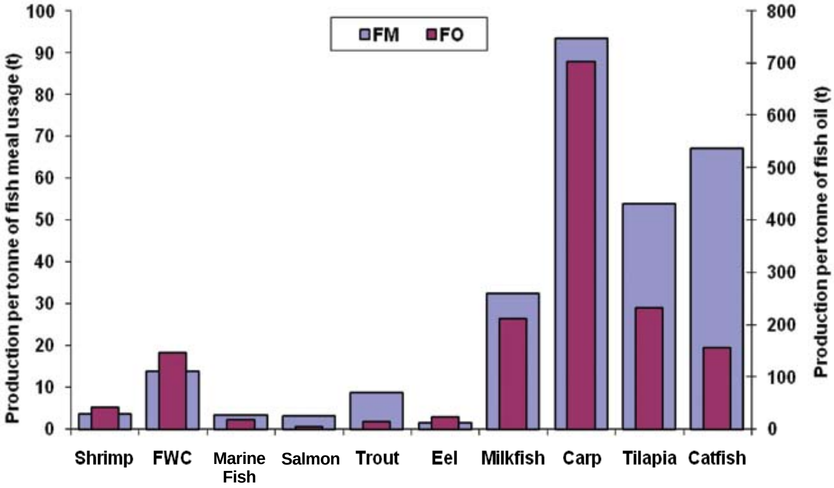
It has been previously mentioned that ocean net productivity is likely to decrease in the wake of climate change, and specifically, some of the fish populations that provide the basic raw material for the reduction industry are likely to decrease. Added to this reduction in the available raw material base, the growing public pressure on the use of a potential human food source for animal feed production purposes is likely to intensify, as MDG on poverty reduction appear unlikely to be attained within the originally stipulated time frame.

Accordingly, aquaculture, as it expands and intensifies, will have to confront the challenge of coping with a potential reduction of fishmeal and fish oil supplies. Many strategies have been suggested and are being attempted in this respect. The major ones include a reduced usage of fishmeal and fish oil in aquafeeds through the use of alternative ingredients, the possible genetic manipulation of cultured fish species to induce the capability to elongate and desaturate base fatty acids into highly unsaturated fatty acids (HUFA), better feed management and so forth. It is also important to note that the return of food fish per tonne of fishmeal or fish oil used (Figure 3) differs widely between cultured species; omnivorous species such as carps and tilapias are many times more productive than carnivorous species (salmonids, eels, etc.). It is conceded, however, that there is an increasing trend for the production systems for the former species to shift to use of pelleted feeds containing fishmeal (but very little fish oil), which could change the balance to some degree. All in all, what is needed are improved feed management strategies for all cultured species, which unfortunately has not received the attention it should.

Aquaculture will not only have to find technological solutions, including genetic manipulation, but also management strategies to significantly reduce the use of fishmeal and fish oil. In the wake of climate change impacts and other global aspirations, in order to do so and achieve long-term sustainability, the sector will have to adopt a fresh paradigm.

In the preceding sections, adaptive strategies were suggested to combat climate change impacts, including the development of new strains specific to certain

FIGURE 3
Aquaculture production per tonne of fishmeal (FM) and fish oil (FO) used in the different cultured groups that are provided with aquafeeds containing these commodities



Source: De Silva and Soto (2009).

farming systems. Development of strains having, for example, increased salinity tolerance or increased temperature tolerance is not only technologically feasible but could be done relatively rapidly compared to the time taken in the past using technologies such as genomic selection (Meuwissen, Hayes and Goddard, 2001). The development of new strains should, however, go hand in hand with appropriate risk management strategies to minimize escapes into the wild that may impact on the gene pools of wild stocks, either directly or indirectly.

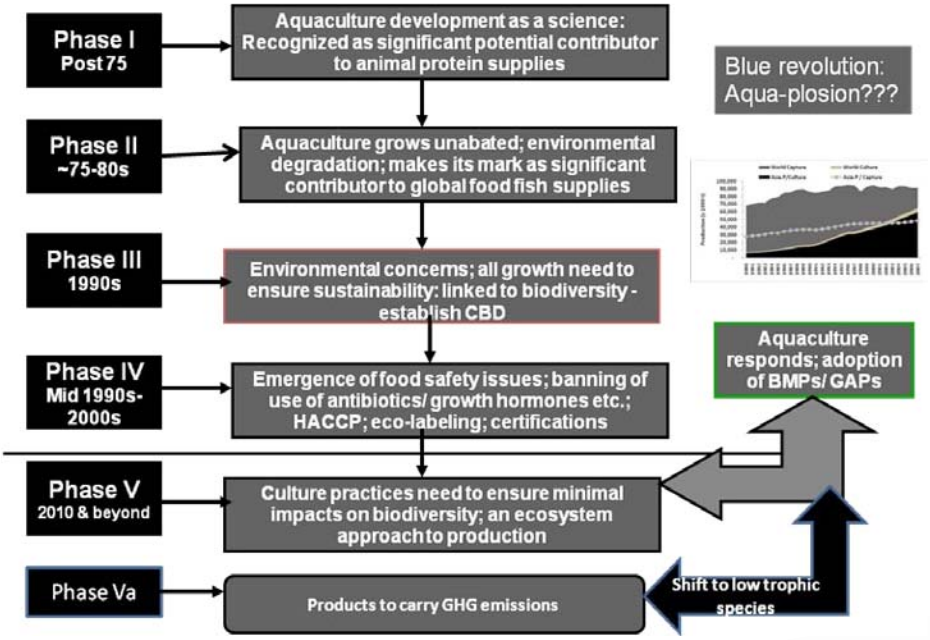
Aquaculture in some regions is dependent, to varying degrees, on alien species (Gajardo and Laikre, 2003; De Silva *et al*., 2006, 2009). The use of alien species in aquaculture is often cited as impacting biodiversity, particularly in freshwaters (e.g. Moyle and Leidy, 1992; Naylor, Williams and Strong, 2001). In extreme weather events, it is possible that broodstock of such cultured alien species could be lost, as was the case in southern China when a very cold spell of weather caused the loss of large stocks of tilapia. In such instances, broodstocks will need to be replenished to sustain those farming systems, preferably using animals of the same origin as the founder stocks. In view of emerging international protocols and access and benefit-sharing issues (Bartley *et al*., 2009) on genetic resources, such procurements may not be easy or straightforward, even if proper risk analyses are undertaken. As such, there may be need for these emerging protocols to consider introducing clauses that would facilitate rather than hinder the exchange of genetic resources in such special circumstances.

Mollusc culture is typically conducted in "open water" where there is free intermingling with the wild biota. Equally, in some areas it is still dependent on wild spat. Although genetic solutions, through the development of strains to regain spawning potential and/or disease resistance are possible, the question arises as to the use of these strains in open waters. There are no easy answers to this problem, and global agreements will have to be pursued to address these issues.

The major challenge of a paradigm shift

Aquaculture, a millennia-old tradition, became a significant food production sector relatively recently. It is cited as the fastest-growing food production sector in the last three decades, and is still in a growth phase (Subasinghe *et al*., 2009). De Silva and Davy (2010) attempted to conceptualize the growth phases of modern aquaculture, as depicted in Figure 4. In this depiction, it is predicted that in the coming era the driving consumer force and aspiration will be an assessment of the green house gases (GHG) emitted from farm to fork, the emerging consumer opting for food types that are minimally GHG emitting.

FIGURE 4
Schematic representation of the phases of aquaculture growth in the modern era (BMPs – best management practices, CBD – Convention on Biological Diversity, GAPs – good aquaculture practices, GHG – green house gas, HAACP – Hazard Analysis and Critical Control Points)

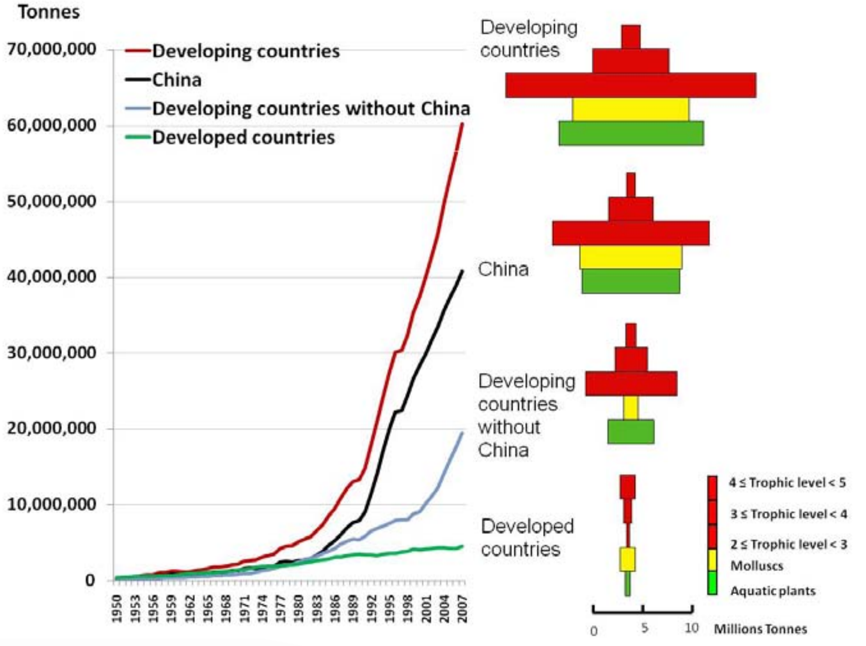


Source: De Silva and Davy (2010).

Tacon *et al*. (2010) demonstrated that the aquaculture sector is essentially comprised of two broad groupings: developing countries (with and without China) and developed countries. These authors went on to show that aquaculture production within developing countries has focused, by and large, on the production of lower trophic-level species (e.g. carps, tilapias and catfishes), while developed countries have focussed mainly on the culture of high-value, high-trophic-level, carnivorous fish species (Figure 5). In essence, the latter is almost equivalent to providing food fish positioned high in the aquatic food chain, as in the case of many marine capture fisheries. As had previously been discussed, the long-term sustainability of these production systems is questionable unless the industry can reduce its dependence upon capture fisheries for sourcing raw materials for feed formulation and seed inputs (Tacon *et al*., 2010). Sustainability issues, exacerbated by changing consumer preferences for eco-friendly food types, primarily measured through GHG from farm to fork, will necessarily be a major challenge to the aquaculture sector. This challenge calls for a major paradigm shift in the sector, perhaps the only option available to it in the coming decades.

A paradigm shift is a challenge that is not easily achievable, as it will entail major changes in farm management, as well as commercial and market-chain changes, which will entail a shift to increased preference for consumption of commodities

FIGURE 5
Global trends in aquaculture production expressed in weighted mean trophic level by economic country grouping, including China



Source: Tacon et al. (2010).

lower in the food chain. Such a shift, of course, will encounter resistance from certain quarters, including some producers. However, a paradigm shift does not necessarily have to be a total "black or white" solution. The shift can, in the early stages at least, be gradual but entail a long-term global consensus and a desire to bring the shift to fruition, as far as possible.

Conclusions

Climate change impacts and the challenges that the aquaculture sector faces in the wake of these are summarized in Table 2. Clearly, the situation and the issues are not straightforward, and aquaculture, as well as other food production sectors, will have to address many compounding impacts and corresponding challenges. Equally, challenges, adaptations and mitigating measures are also interactive; they are often difficult to discern from each other, leading to the conclusion that a more holistic approach is needed to meet these challenges.

Climate change impacts on aquaculture are varying and are both direct and indirect. The challenges that aquaculture confronts need both technological and

TABLE 2
A summary of the important impacts of the different elements of climate change on aquaculture and the potential challenges these impacts may present to aquaculture. (FW – freshwater, M – marine) [1]

Aquaculture/other activity	Impact(s)		Challenges
	+/-	Type/form	
All; cage, pond; finfish (temperate regions)	-	Rise above optimal range of tolerance	Selective breeding for higher temperature tolerance; other options needed
All; cage, pond; finfish (tropical regions)	-	Sudden occurrence of cold currents/weather	Vigilance; be prepared to move stock
All; tropical finfish	+	Increase in growth; higher production	Meet increasing feed demands
FW; cage	-	Eutrophication & upwelling; stock mortality	Better siting, conform to carrying capacity, need to reduce intensification; use stock enhancement practices for nutrient stripping; regulate monitoring
M/FW; mollusc (temperate)	-	Increased virulence of pathogens; new diseases & increase in the range of others	Monitoring to prevent health risks; develop prophylactic measures; improvise proper risk management when using specially developed pathogenic resistant strains in open water culture
Carnivorous finfish/ shrimp[2]	-	Limitations on fishmeal & fish oil supplies/price	Fishmeal & fish oil replacements; improve feed management; shift to non-carnivorous culture commodities
Artificial propagation of species for the "luxurious" live fish restaurant trade[2]	(+)	Coral reef destruction	Continue development of artificial propagation techniques; reduce dependence on wild seed supplies; impress upon the public the indirect impacts on biodiversity conservation through aquaculture
Sea level rise, ocean productivity reduction and other circulation changes			
All; primarily in deltaic regions in the tropics	+/-	Saltwater intrusion; flooding	Develop salinity-resistant strains for some; reduce possible conflicts with other users; develop a holistic approach to water management
	+/-	Loss of agricultural land	Provide alternative livelihoods –aquaculture: capacity building and infrastructure

TABLE 2 (Continued)

Aquaculture/other activity	Impact(s)		Challenges
	+/-	Type/form	
Fishmeal and fish oil supplies	-/+	Reduction & high cost	Find alternatives to fishmeal & fish oil; genetic manipulation to enable fatty acid chain elongation & desaturation; paradigm shift to transform aquaculture to omnivorous & herbivorous species
Shellfish	-	Increase of harmful algal blooms (HABs)	Alertness; risk assessment on culture sites
Acidification			
Mollusc/seaweed culture (primary impact in temperate waters)	-	Impact on calcareous shell formation	To use areas of least acidification potential
Water stress (and drought conditions, etc.)			
Pond culture	-	Water abstraction & discharge	Improve efficacy of water usage by introducing water calendars; initiate collective action along river lengths; incorporate water use & management into better management practices (BMPs); encourage non-consumptive water use in aquaculture (e.g. culture based fisheries (CBF); improve energy efficacy of recirculation systems; popularize open, small-scale, less energy-demanding recirculation systems
Culture based fisheries	-	Water retention period reduced	Model water regimes & determine the extent of water bodies usable for CBF; use fast-growing fish species; increase efficacy of water sharing with primary users (e.g. irrigation of rice paddies)
Riverine cage culture (tropical/artisanal)	-	Availability of wild seed stocks reduced/ period changed	Use artificially propagated seed
Extreme climatic events			
All forms; predominantly coastal areas	-	Destruction of facilities; loss of stock; loss of business; large-scale escapes with potential impacts on biodiversity	Develop suitable policies to strengthen physical facilities; policies to make insurance available to all culture activities irrespective of scale, including group/cluster insurance
Changes in fishmeal and fish oil supplies, general consumer aspirations for less green house gas (GHG)-emitting food types (from farm to fork)			
All aquaculture	+	General problem of feed availability & high cost & market demand for reduced GHG emissions in food production	To make a paradigm shift through increasing the culture of commodities that need lower protein feeds; encourage culture of herbivorous & omnivorous species

[1] *Source:* Modified from De Silva and Soto (2009).
[2] Instances where more than one climate change element will be responsible for the change.

adaptive approaches. By and large, the adaptive approaches dominate in this regard. Bearing in mind that the great bulk of aquaculture practices occur in the tropics and are mostly small-scale operations that are often clustered in areas conducive for the practices, the challenge is to bring all stakeholders together for collective action to adopt relevant measures. For example, in pervious sections, it was pointed out that the challenges to the sector lie in developing "water calendars" and in reducing the density (stocking density as well as farm density) and intensity of culture. These challenges can be met and the practices sustained only through collective action among all stakeholders. Meeting the challenges posed by climate change requires both political will and relevant policies to guide the actions.

There are other potential climate change impacts for which the challenges posed to the sector have very few options available. Foremost of these is the impact of extreme weather events, where the degree of predictability and intensity are also very low. Here again, there is a need for political will and effective associated policies to be put in place.

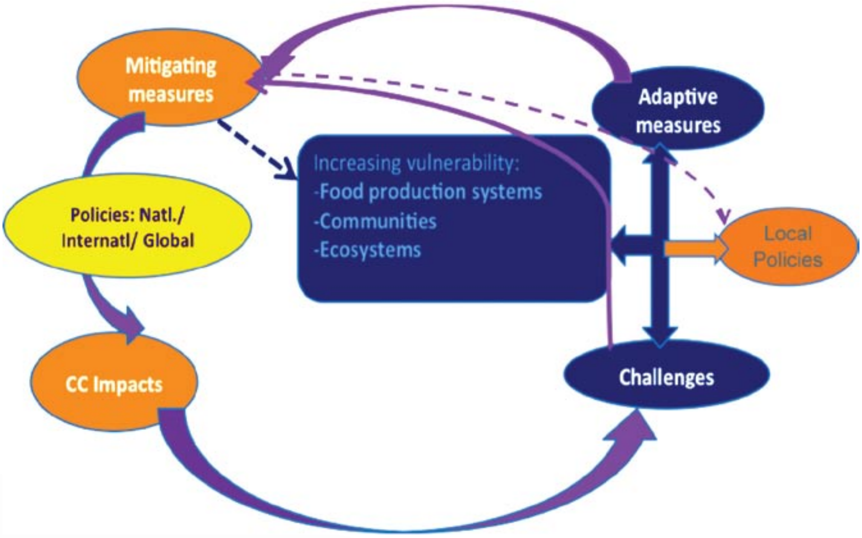
There is a unique challenge likely to confront aquaculture as a result of climate change impacts, at least in certain population hubs of the developing world, albeit at the expense of current livelihoods; the challenge of adopting an alternative livelihood to agriculture such as rice farming though aquaculture, in areas that will be made unsuitable for rice farming. This challenge can be met with major success only if preparations, in respect of acceptance of the strategy to utilize aquaculture development as an alternative livelihood opportunity are done well in advance. This major challenge of transformation from agriculture to aquaculture will not be smooth nor easy; it will involve millions of people and their families, giving up old traditions and thereby inflicting substantial cultural changes in communities – hence the very reason to start the processes early. Apart from the direct technological challenges that climate change impacts will pose to the aquaculture sector, all the other challenges will have to be addressed in a holistic manner, in cooperation with related production sectors, primarily agriculture. On the positive side, therefore, is the potential to bring sectors together and develop common strategies, such as those for addressing the situation of water stress. This is a major challenge for all, and the degree of effectiveness of this strategy will perhaps be pivotal to all of the primary production sectors, all of which are dependent on two of the most limiting physical resources on our planet – land and water.

Aquaculture became a globally significant food production sector only in the last three to four decades. It is a sector that is gradually reducing our dependence on hunted food sources. Its major developments took place and continue to take place in an era when public perceptions on development have had a major shift, where sustainability and environmental integrity have become crucial and indeed essential elements of development, and also in an era where the public is often misinformed (De Silva and Davy, 2010). It is not surprising that all this has lead to a continued scrutiny of the sector. The major challenge now confronting aquaculture is to convince the public that it is an important production sector that can contribute significantly to mitigating climate change impacts through the production of food types that are minimally GHG emitting and some commodities which are carbon sequestering. As previously discussed, a corresponding paradigm shift together with the above will facilitate the need to meet climate change impacts through political will and associated policy changes.

It is also important to point out that the aquaculture sector when proposing strategies to meet the challenges of impacts of climate change should develop holistic approaches that take into consideration potential secondary influences. A case in point is the advocacy of the use of krill for reduction as a partial substitute for fishmeal and fish oil (Olsen *et al*., 2006; Suontama *et al*., 2007). However, it is becoming increasingly apparent that krill populations, which are a main food source of highly protected marine mammals, the whales, are being impacted significantly by climate change. In this regard, Atkinson *et al*. (2004) demonstrated that there had been a decrease in the density of Antarctic krill (*Euphausia superba*) and correspondingly, an increase in salps (mainly *Salpa thompsonii*), one of the main grazers of krill. This trend is likely to be exacerbated by climatic changes, sea temperature increases and the decrease in polar ice. The situation is being further exacerbated by the fact that reduction of the polar ice cover has enabled the fishing season for krill to be extended, and it has been suggested that this extension may have compounding impacts on krill populations (Kawaguchi, Nicole and Press, 2009). In summary, this alternative may not be an option to meet the challenge of reducing fishmeal and fish oil content in aquafeeds.

Certain possible strategies to combat climate change impacts through the application of genetic technologies may pose problems, and such use will have to be balanced against potential impacts on the gene pools of wild organisms. Finally, all adaptive and mitigating measures need to be interactive and cannot stand alone (Figure 6); even straight-forward technological developments can be applied through a holistic approach.

FIGURE 6
Schematic representation of the interactive phases of climatic change (CC) impacts on aquaculture



References

Abery, N.W., Sukadi, F., Budhiman, A.A., Kartamihardja, E.S., Koeshendrajana, S., Buddhiman & De Silva, S.S. 2005. Fisheries and cage culture of three reservoirs in West Java, Indonesia; a case study of ambitious developments and resulting interactions. *Fisheries Management and Ecology,* 12: 315–330.

Aldhous, P. 2004. Fish farms still ravage the sea. Sustainable aquaculture takes one step forward, two steps back. *Nature online*, 17 February 2004; doi:10.1038/news040216-10.

Allison, E.H., Perry, A.L., Badjeck, M.-C., Adger, W.N., Brown, K., Conway, D., Halls, A.S., Pilling, G.M., Reynolds, J.D., Andrew, N.L. & Dulvy, N.K. 2009. Vulnerability of national economies to the impacts of climate change on fisheries*. Fish and Fisheries,* 10: 173–196.

Amarasinghe, U.S. & Nguyen, T.T.T. 2010. Enhancing rural farmer income through fish production: secondary use of water resources in Sri Lanka and elsewhere. *In* S.S. De Silva & F.B. Davy, eds. *Success stories in Asian aquaculture*, pp. 103–130. Dordrecht, Springer.

Anon. 2009. *Fisheries and aquaculture in our changing climate*. 4 pp. (available at: ftp://ftp.fao.org/FI/brochure/climate_change/policy_brief.pdf)

Atkinson, A., Slegel, V., Pakjomov, E. & Rothery, P. 2004. Long-term decline in krill stocks and increase in salps within the Southern Ocean. *Nature*, 432: 100–103.

Bartley, D., Nguyen, T.T.T., Halwart, M. & De Silva, S.S. 2009. Use and exchange of aquatic genetic resources in aquaculture: information relevant to access and benefit sharing. *Reviews in Aquaculture*, 1: 157–162.

Bibby, R., Widdicombe, S., Parry, H., Spicer, J. & Pipe, R. 2008. Effects of ocean acidification on the immune response of the blue mussel *Mytilus edulis*. *Aquatic Biology*, 2: 67–74.

Brander, K.M. 2007. Global fish production and climate change. *Proceeding of the National Academy of Sciences of the United States of America,* 104: 19709–19714. (available at: www.pnas.org/cgi/doi/10.1073/pnas.0702059104).

Caldeira, K. & Wickett, M.E. 2003. Anthropogenic carbon and ocean pH. *Nature,* 425: 365.

Cheung, W.L., Lam, V.Y., Sarmientoz, J.L., Kearney, K., Watson, R., Zeller, K. & Pauly, D. 2010. Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Global Change Biology*, 16: 24–35.

Cochrane, K., De Young, C., Soto, D. & Bahri, T. (eds.) 2009. *Climate change implications for fisheries and aquaculture: overview of current scientific knowledge.* FAO Fisheries and Aquaculture Technical Paper No. 530. Rome, FAO. 212 pp.

Cooley, S.R. & Doney, S.C. 2009. Anticipating oceans acidification's economic consequences for commercial fisheries. *Environmental Research Letters*, 4, 024007, 8 pp. doi:10.1088/1748-9326/4/2/024007.

Cooley, S.R., Kite-Powell, H.L. & Doney, S.C. 2009. Ocean acidification's potential to alter global marine ecosystem services. *Oceanography*, 22: 172–182.

De Silva, S.S. 2003. Culture-based fisheries: an underutilized opportunity in aquaculture. *Aquaculture,* 221: 221–243.

De Silva, S.S. & Davy, F.B. 2010. Aquaculture successes in Asia: contributing to sustained development and poverty alleviation. *In* S.S. De Silva & F.B. Davy, eds. *Success stories in Asian aquaculture*, pp. 1–14. Dordrecht, Springer.

De Silva, S.S., Nguyen, T.T.T., Abery, N.W. & Amarasinghe, U.S. 2006. An evaluation of the role and impacts of alien finfish in Asian inland aquaculture. *Aquaculture Research,* 37: 1–17.

De Silva, S.S., Nguyen, T.T.T., Turchini G.M., Amarasinghe, U.S. & Abery, N.W. 2009. Alien species in aquaculture and biodiversity: a paradox in food production. *Ambio,* 38: 24–28.

De Silva, S.S. & Phuong, N.T. 2011. Striped catfish farming in the Mekong Delta: a tumultuous path to a global success. *Reviews in Aquaculture*, 3: 45–73.

De Silva, S.S. & Soto, D. 2009. Climate change and aquaculture: potential impacts, adaptation and mitigation. In K. Cochrane, C. De Young, D. Soto & T. Bahri, eds. Climate change implications for fisheries and aquaculture: overview of current scientific knowledge, pp. 156–212. FAO Fisheries and Aquaculture Technical Paper No. 530. Rome, FAO.

De Silva, S.S. & Turchini, G.M. 2008. Towards understanding the impacts of the pet food industry on world fish and seafood supplies. *Journal of Agriculture and Environmental Ethics*, 21: 459–467.Doney, S.C. 2006. The dangers of ocean acidification. *Scientific American,* March 2006, pp. 58–65.

Dugan, P., Dey, M. & Sugunan, V.V. 2006. Fisheries and water productivity in tropical river basins: enhancing food security and livelihoods by managing water for fish. *Agricultural Water Management*, 80: 262–275.

Economist. 2010. *A special report on water.* 26th June 2010, 4 pp.

Ericson, J.P., Vorosmarty, C.J., Dingman, S.L., Ward, L.G. & Meybeck, M. 2006. Effective sea level rise and deltas: causes and human dimension implications. *Global and Planetary Change*, 50: 63–82.

Falkernmark, M., Rockstöm, J. & Karlberg, L. 2009. Present and future water requirements for feeding humanity. *Food Security*, 1: 59–69.

FAO. 1999. *Irrigation in Asia in figures.* Water Reports, 18. Rome, FAO. 228 pp.

FAO. 2009. The state of world fisheries and aquaculture 2008. Rome, FAO. 176 pp.

FAO. 2010. The state of world fisheries and aquaculture 2010. Rome, FAO. 218 pp.

Ficke, A.D., Myrick, C.A. & Hansen, L.J. 2007. Potential impacts of global climate change on freshwater fisheries. *Reviews in Fish Biology and Fisheries*, 17: 581–613.

Fish Farmer. 2008. *Norwegian study on impact of climate change on farmed salmon*. p.1. (available at: www.fishfarmer-magazine.com/news/fullstory.php/aid/1490/).

Gajardo, G. & Laikre, L. 2003. Chilean aquaculture boom is based on exotic salmon resources: a conservation paradox. *Conservation Biology,* 17: 1173–1174.

Gjedrem, T. 2010. The first family breeding program in aquaculture. *Reviews in Aquaculture*, 2: 2–15.

Goswami, B.N., Venugopal, V., Sengupta, D., Madhusoodanan, M.S. & Xavier, P.K. 2006. Increasing trend of extreme rain events in a warming environment. *Science*, 314: 1442–1445.

Handisyde, N.T., Ross, L.G., Badjeck, M-C. & Allison, E.H. (undated) *The effect of climate change on world aquaculture: a global perspective.* Department for International Development, United Kingdom. 151 pp.

Hart, P. & O'Sullivan, D. (eds.) 1993. *Recirculation systems: design, construction and management*. Launceston, Turtle Press. 121 pp.

Hõ, T.L. 2008. Adapting to global warming. *Outlook, Viet Nam News Monthly Publication*, 51 (March 2008), pp. 8–11.

Hughes, T.P., Baird, A.H., Bellwood, D.R., Card, M., Conolly, S.R., Folke, C., Grosberg, R., Hoegh-Guldberg, O., Jackson, J.B.C., Kleypas, J., Lough, J.M., Marshall, P., Nyström, M., Palumbi, S.R., Pandolfi, J.M., Rosen, B. & Roughgarden, J. 2003. Climate change, human impacts, and the resilience of coral reefs. *Science*, 301: 929–934.

Hulme, M. 2009. *Why we disagree about climate change*. Cambridge, Cambridge University Press. 432 pp.

IPCC. 2007. *Climate change 2007: synthesis report.* Geneva, Intergovernmental Panel on Climate Change. 104 pp. (available at: www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4-syr-topic/pdf).

Ishimatsu, A. & Dissanayake, A. 2010. Life threatened in acidic coastal waters. *In* A. Ishimatsu & H.-J. Lie, eds. *Coastal environmental and ecosystem issues of the East China seas,* pp. 283–303. Tokyo, TERRAPUB and Nagasaki University.

Jackson, A. 2010. Sustainability of fish meal/fish oil: fish-in fish-out ratios. *AQUAculture Asia-Pacific Magazine*, 6(1): 2.

Khang, N.D., Kotera, A., Sakamoto, T. & Yokozawa, M. 2008. Sensitivity of salinity intrusion to sea level rise and river flow change in Vietnamese Mekong Delta – impacts on availability of irrigation water for rice crops. *Journal of Agricultural Meteorology*, 64: 167–176.

Kwaguchi, S., Nicol, S. & Press, A.J. 2009. Direct effects of climate change on the Antarctic krill fishery. *Fisheries Ecology and Management*, 16: 424–427.

Li, Y., Qin, J.G., Abbott, C.A., Li, X. & Benkendorff, K. 2007. Synergistic impacts of heat shock and spawning on the physiology and immune health of *Crassostrea gigas*: an explanation for summer mortality in Pacific oysters. *American Journal of Physiology –Regulatory, Integrative Comparative Physiology,* 293: 2353–2362.

Lomborg, B. 2001. *The sceptical environmentalist: measuring the real state of the world.* Cambridge, Cambridge University Press. 554 pp.

Lorenzen, K., Juntana, J., Bundit, J. & Tourongruang, D. 1998. Assessing culture fisheries practices in small waterbodies: a study of village fisheries in north-east Thailand. *Aquaculture Research*, 29: 211–224.

Losordo, T.M., Masser, M.P. & Rakocy, J. 1998. *Recirculation aquaculture tank production systems. An overview of critical considerations.* SRAC Publication No. 451. 6 pp. Southern Regional Aquaculture Center.

McGee, M. & Cichra, C. 2000. *Principles of water recirculation and filtration in aquaculture.* Institute of Food and Agricultural Sciences, University of Florida. 4 pp. (available at: www.aces.edu/dept/fisheries/education/documents/Principlesofwaterrecirc.pdf).

McMichael, A.J. 2001. Impact of climatic and other environmental changes on food production and population health in the coming decades. *Proceedings of the Nutrition Society*, 60: 195–201.

Meuwissen, T.H.E., Hayes, B.J. & Goddard, M.E. 2001. Prediction of total genetic value using genome-wide dense marker maps. *Genetics*, 157: 1819–1829.

Miller, A.W., Reynolds, A.C., Sobrino, C. & Riedel, G.F. 2009. Shellfish face uncertain future in high CO_2 world: influence of acidification on oyster larvae calcification and growth in estuaries. *PLoS ONE*, 4(5), e5661. doi:10.1371/journal.

Morgan, I., McDonald, D.G. & Wood, C.M. 2001. The cost of living for freshwater fish in a warmer, more polluted world. *Global Change Biology*, 7: 345–355.

Moyle, P.B. & Leidy, R.A. 1992. Loss of biodiversity in aquatic ecosystems; evidence from fish faunas. *In* P.L. Fielder & S.K. Jain, eds. *Conservation biology: the theory and practice of nature conservation*, pp. 129-161. New York, Chapman and Hall.

Muralidhar, M., Pnniah, A.G. & Jayanthi, M. 2009. Impacts of extreme climatic events on brackishwater aquaculture in India. Draft Report Sumbiited to the Netwwork of Aquaculture Centres in Asia-Pacific, 65 pp.

Naylor, R.L., Goldburg, R.J., Primavera, J., Kautsky, N., Beveridge, M.C.M., Clay, J., Folke, C., Lubchenco, J., Mooney, H. & Troell, M. 2000. Effects of aquaculture on world food supplies. *Nature*, 405: 1017–1024.

Naylor, R.L., Williams, S.L. & Strong, D.R. 2001. Aquaculture – a gateway for exotic species. *Science,* 294: 1655–1666. Nguyen, T.T.T. & De Silva, S.S. 2006. Freshwater finfish biodiversity and conservation: an Asian perspective. *Biodiversity and Conservation,* 15: 3543–3568.

O'Connor, J.E. & Costa, J.E. 2004. *The world's largest floods, past and present – their causes and magnitudes.* U.S. Geological Survey Circular No. 1254. 13 pp.

Olsen, R.E., Suontama, J., Langmyhr, E., Mundheim, H., Ringø, E., Melle, W., Malde, M.K. & Hemre, G.-I. 2006. The replacement of fish meal with Antarctic krill, *Euphausia superba* in diets for Atlantic salmon, *Salmo salar*. *Aquaculture Nutrition*, 12: 280–290.

Peperzak, L. 2003. Climate change and harmful algal blooms in the North Sea. *Acta Oecologica*, 24: S139–S144.

Phan, L.T., Bui, T.M., Nguyen T.T.T., Gooley G.J., Ingram, B.A., Nguyen, H.V., Nguyen, P.T. & De Silva, S.S. 2009. Current status of farming practices of striped catfish, *Pangasianodon hypophthalmus* in the Mekong Delta, Vietnam. *Aquaculture*, 296: 227–236.

Phan, P.D. & De Silva, S.S. 2000. The fishery of Ea Kao Reservoir, southern Vietnam: a fishery based on a combination of stock and recapture, and self-recruiting populations. *Fisheries Management and Ecology*, 7: 251–264.

Piao, S., Ciais, P., Huang, Y., Shen, Z., Peng, S., Li, J., Zhou, L., Liu, H., Ma, Y., Ding, Y., Friedlingstein, P., Liu, C., Tan, K., Yu, Y., Zhang, T. & Fang, J. 2010. The impacts of climate change on water resources and agriculture in China. *Nature*, 467: 43–51.

Quiros, R. 1998. Reservoir stocking in Latin America, an evaluation. *In* T. Petr, ed. *Inland fishery enhancements,* pp. 91–118. FAO Fisheries Technical Paper No. 374. Rome, FAO.

Quiros, R. & Mari, A. 1999. Factors contributing to the outcome of stocking programmes in Cuban reservoirs. *Fisheries Management and Ecology*, 5: 241–254.

Renwick, M.E. 2001. Valuing water in a multiple-use system. Irrigated agriculture and reservoir fisheries. Irrigation and Drainage Systems, 15: 149–171.

Schmittner, A. 2005. Decline of the marine ecosystem caused by a reduction in the Atlantic overturning circulation. *Nature*, 434: 628–633.

Shiklomanov, I.A. 1993. World freshwater resource. *In* P.H. Gleick, ed. *Water in crisis: a guide to the world's fresh water resources,* pp. 13–24. New York, Oxford University Press.

Shiklomanov, I.A. 1998. *Archive of world water resources and world water use*. Global Water Data Files: State Hydrological Institute. Data archive on CD-ROM from State Hydrological Institute, St. Petersburg, Russia.

Smith, D.I. 1998. *Water in Australia*. Oxford, Oxford University Press. 384 pp.

Song, Z. 1999. *Rural aquaculture in China*. RAPA Publication 1999/22. Bangkok, FAO RAPA. 71 pp.

Soto, D., Jara, F. & Moreno, C. 2001. Escaped salmon in the inner seas, southern Chile: facing ecological and social conflicts. *Ecological Applications*, 11(6): 1750–1762.

Subasinghe, S., Soto, D. & Jia, J. 2009. Global aquaculture and its role in sustainable development. *Reviews in Aquaculture* 1: 2-9.

Suontama, J., Kiessling, A., Melle, W., Waagbø, R. & Olsen, R.E. 2007. Protein from northern krill (*Thysanoessa inermis*), Antarctic krill (*Euphausia superba*) and the Arctic amphipod (*Themisto libellula*) can partially replace fish meal in diets to Atlantic salmon (*Salmo salar*) without affecting product quality. *Aquaculture Nutrition*, 13: 50–58.

Tacon, A.G.J. & Metian, M. 2008. Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: trends and future prospects. *Aquaculture,* 285: 146–158.

Tacon, A.G.J., Metian, M., Turchini, G.M. & De Silva, S.S. 2010. Responsible aquaculture and trophic level implications to global fish supply. *Reviews in Fisheries Science*, 18: 94–105.

Tan, X.H. 2008. Study on climate change scenarios assessment for Ca Mau Province. Technical report. Southern Institute for Water Resources Planning. 194 pp.

Thackery, S.J., Sparks, T.H., Frederiksen, M., Burthe, S., Bacon, P.J., Bell, J.R., Botham, M.S., Brereton, T.M., Bright, P.W., Carvalho, L., Clutton-Brock, T., Dawson, A., Edwards, M., Elliott, J.M., Harrington, R., Johns, D., Jones, I.D., Jones, J.T., Leech, D.I., Roy, D.B., Scott, W.A., Smith, M., Smithers, R.J., Winfield, I.J. & Wanless, S. 2010.Trophic level asynchrony in rates of phenological change of marine, freshwater and terrestrial environments. *Global Change Biology*, 16: 3304–3313.

Travers, M.-A., Basuyaux, O., Le Goic, N., Huchette, S., Nicolas, J.-L., Koken, M. & Paillard, C. 2009. Influence of temperature and spawning effort on *Haliotis tuberculata* mortalities caused by *Vibrio harveyi*: an example of emerging vibriosis linked to global warming. *Global Change Biology*, 15: 1365–1376.

Umesh, N.R. 2007. Development and adoption of BMPs by self-help farmer groups. *Aquaculture Asia,* 12: 8–10.

Umesh, R.N., Chandra Mohan, A.B., Ravibabu, G., Padiyar, P.A., Phillips, M.J., Mohan, C.V. & Vishnu Bhat, B. 2009. Implementation of better management practices by empowering small-scale farmers through a cluster-based approach: the case of shrimp farmers in India. *In* S.S. De Silva & F.B. Davy, eds. *Success stories in Asian aquaculture,* pp. 43–65. Dordrecht, Springer.

Vass, K.K., Das, M.K., Srivastava, P.K. & Dey, S. 2009. Assessing the impact of climate change on inland fisheries in River Ganga and the plains in India. *Aquatic Ecosystem Health & Management*, 2: 138–151.

Vörösmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S.E., Sullivan, C.A., Liermann, C.R. & Davies, P.M. 2010. Global threats to human water security and river biodiversity. *Nature*, 467: 555–561.

Vuong, D.Q.T. & Lin, C.K., 2001. *Rice-shrimp farming in the seawater intrusion zone of the Mekong Delta, Vietnam*. ITCZM Monograph No. 6, 166 pp.

Ward, F.A. & Michelsen, A. 2002. The economic value of water in agriculture: concepts and policy applications. *Water Policy*, 4: 423–446.

Washington, H. & Cook, J. 2011. *Climate change denial: heads in the sand.* London, Earthscan. 168 pp.

Welcomme, R.L. 1985. *River fisheries*. FAO Fisheries Technical Paper No. 262. Rome, FAO. 330 pp.

Welcomme R.L. & Bartley, D.M. 1998. Current approaches to the enhancement of fisheries. *Fisheries Management and Ecology*, 5: 351–382.

World Bank. 2000. *Bangladesh: climate change and sustainable development.* Report No. 21104-BD, Rural Development Unit, South Asia Region. Dhaka, World Bank. 95 pp.

Zimmer, D. & Renault, D. (undated). Virtual water in food production and global trade. Review of methodological issues preliminary results. 19 pp. (available at: www.fao.org/nr/water/docs/VirtualWater_article_DZDR.pdf).