



## **Impact of climate change on fisheries and aquaculture in the developing world and opportunities for adaptation**

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## **Abstract**

This paper reviews the importance of fisheries and aquaculture, with particular reference to poor people in the developing world, and the likely impact of climate change on these activities and on food security. It highlights some practical measures that can be taken to adapt to the expected effects of climate change. These focus in particular on building the capacity of communities to adapt to climate change in ways that allow them to moderate potential damage, to take advantage of new opportunities and to cope with the consequences of climate change, and on enhancing the resilience of communities and the ecosystems on which they depend. The authors recommend basing interventions as much as possible on local practices and traditions.

## **Key words**

Adaptation, aquaculture, climate change, fisheries, food security, rural poor

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## Introduction

It is now widely accepted that climate change is no longer simply a potential threat, it is unavoidable; a consequence of 200 years of excessive greenhouse gas (GHG) emissions from fossil fuel combustion in energy generation, transport and industry, deforestation and intensive agriculture (IPCC, 2007a). IFAD and other development agencies have recognized climate change as one the greatest threats facing mankind today (IFAD, 2007; World Bank, 2010) and have highlighted the fact that the poorest and most vulnerable will be disproportionately affected by its impacts (IFAD, 2008).

Small-scale fisheries and aquaculture have contributed little to the causes of climate change but will be amongst the first sectors to feel its impacts. Some anticipated consequences include falling productivity, species migration and localized extinctions, as well as conflict over use of scarce resources and increased risks associated with more extreme climatic events such as hurricanes. These result from direct impacts on fish themselves as well as from impacts on the ecosystems on which they depend, such as coral reefs. In general the consequences of climate change will be negative for fishers at low latitudes. In contrast, fish-farmers may benefit from expansion of the areas where aquaculture is viable due to increased temperatures and rising sea levels. However, these benefits may be tempered by reduced water quality and availability, increased disease incidence and damage to freshwater aquaculture by salinization of groundwater.

The precise and localized impacts of climate change on fisheries are, however, still poorly understood (FAO, 2008a; WorldFish Center, 2007a; Stern, 2007). This is because “the inherent unpredictability of climate change and the links that entwine fishery and aquaculture livelihoods with other livelihood strategies and economic sectors make unravelling the exact mechanisms of climate impacts hugely complex” (WorldFish Center, 2007b). Furthermore, tropical fisheries, which are the most important to small-scale fishers in developing countries, have received less scientific study than those in the waters of developed countries (Roessig *et al.*, 2004). This uncertainty means that direct adaptation is difficult; the focus must therefore be on boosting adaptive capacity and resilience to shocks by improving the health of fish stocks, freshwater, marine and coastal ecosystems and the communities that depend on them.

This paper reviews the importance of fisheries and aquaculture to the rural poor around the world, and outlines the expected consequences of climate change for fisheries and aquaculture, focusing on the consequences for the rural poor in developing countries. It also highlights some practical adaptation measures that can be taken in response to and in anticipation of the consequences of climate change.

## The importance of fisheries and aquaculture

In 2006, fisheries and aquaculture produced a total of 143.6 million tonnes of fish (FAO, 2009a), 81.9 million tonnes from marine capture fisheries, 10.1 million tonnes from inland capture fisheries, 31.6 million tonnes from inland aquaculture and 20.1 million tonnes from marine aquaculture. China is by far the largest producer of fish, producing 51.5 million tonnes of fish in 2006, 17.1 million tonnes from capture fisheries and 34.4 million tonnes from aquaculture (FAO, 2009a).

The Asia-Pacific region dominates both fisheries and aquaculture, particularly in terms of the number of people working in these sectors: 86% of fishers and fish farmers worldwide live in Asia, with the greatest numbers in China (8.1 million fishers and 4.5 million fish farmers) (FAO, 2009a). Asia is also a major producer of fish, accounting for 52% of the world's wild

caught fish, while aquaculture in the Asia-Pacific region accounts for 89% of world production by quantity and 77% by value (FAO, 2009a).

## **Livelihoods**

The livelihoods of 520 million people depend on fisheries and aquaculture (FAO, 2009a), 98% of whom live in developing countries (World Bank, 2005). FAO data reported by the World Bank (2005) indicates that the number of fishers in the world has grown by 400% since 1950, compared with a 35% increase in the number of agricultural workers over the same period. Most of the growth has been in small-scale fisheries in the developing world. It is likely that more poor people will turn to fishing and other common-pool resources in future as a result of the negative impacts of climate change on agriculture and other sectors.

## **Trade**

Fish is the most widely traded foodstuff in the world: 37% of fish produced (live weight equivalent) is traded internationally (FAO, 2009a). In 2006 exports of fish were worth a total of \$85.9 billion (FAO, 2009a), more than half of which originated in developing countries (Paquotte and Lem, 2008). In 2002, net exports of fish generated more foreign exchange earnings for developing countries than rice, coffee, sugar, and tea combined (World Bank, 2005, p. 4). Aquaculture has grown by 6.9% per annum since 1970 (FAO, 2009a) and now provides half of global fish supply (Naylor *et al.*, 2009). As global demand continues to grow, there are opportunities for poverty reduction within the sector if supplies of wild fish can be maintained and aquaculture expanded sustainably.

## **Health and nutrition**

One third of the world's population rely on fish and other aquatic products for at least 20% of their protein intake (Dulvy and Allison, 2009) and fish provides more than 50% of all the protein and minerals consumed by 400 million of the world's poorest people (MAB, 2009) and is also an important source of other nutrients such as vitamins A, B and D, calcium, iron and iodine (FAO, 2005). Even in small quantities, fish can have a positive effect on nutritional status by providing essential amino acids that are deficient in staple foods such as rice or cassava. Fish accounts for 30% of animal protein consumed in Asia, 20% in Africa and 10% in Latin America and the Caribbean (Prein and Ahmed, 2000). It is thus central to the food security of many of the world's poor, especially in coastal areas and small island developing states.

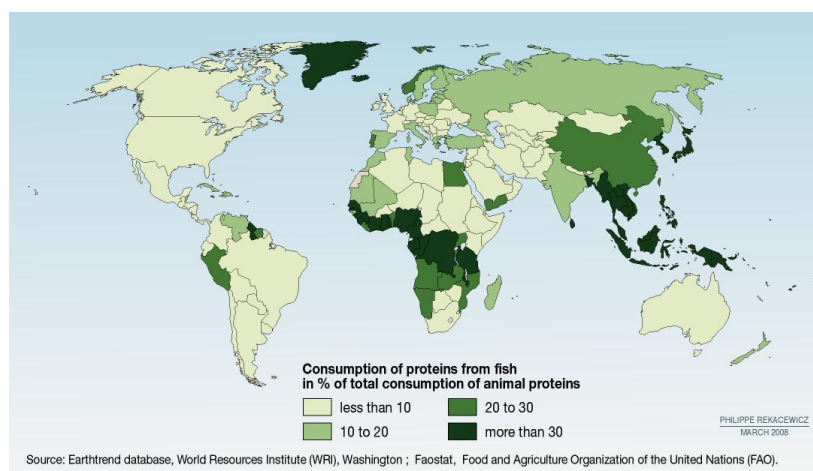


Image 2: Fish protein as a % of total consumption of animal proteins (UNEP/GRID-Arendal 2009)

## Climate change, fisheries and aquaculture

A number of changes already evident can be attributed to the impacts of rising GHG emissions.

Global average air temperatures rose by 0.74°C in the period 1906–2005 (IPCC, 2007a). Global average sea surface temperatures have also risen since 1950 as the ocean has absorbed 80% of heat added to the climate system; temperature increases are also being detected as deep as 3000 m. Increasing water temperature and associated thermal expansion accounts for 57% of the global average sea level rise of 1.8 mm per year between 1961 and 2003; a further 28% of the rise is attributed to the melting of glaciers and polar ice sheets (IPCC, 2007a). Oceans also absorb approximately 25% of anthropogenic CO<sub>2</sub> causing ocean acidification (Eakin *et al.*, 2008). To date average alkalinity has declined from 8.2 to 8.1 (IPCC, 2007b), equivalent to a 30% increase in acidity.

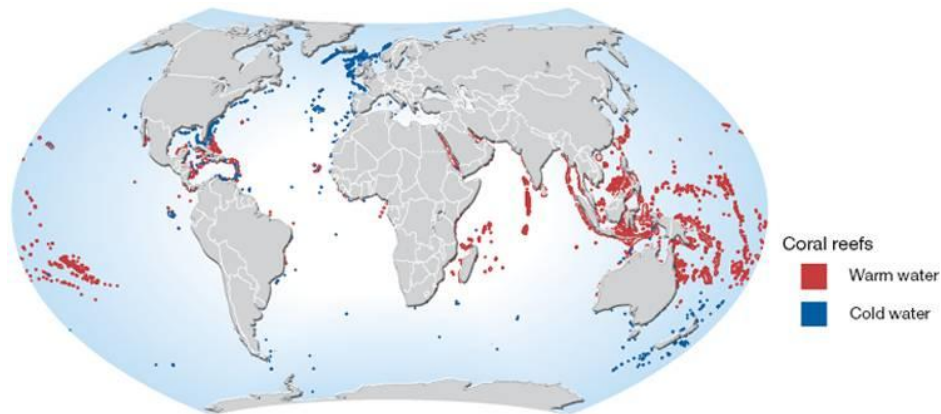
Changing patterns and seasonality of snow melt are affecting freshwater hydrology in glacier and snow-fed rivers and lakes and rivers are warming in many regions (IPCC, 2007a). Deep water in large East African lakes including Lake Tanganyika and Lake Malawi has warmed by 0.2–0.7°C over the past 100 years (Rosenzweig *et al.*, 2007). This warming has resulted in increasing thermal stratification, reducing mixing of cold deep and warm surface waters. This prevents upwelling of nutrients and lowers primary productivity.

In both freshwater and oceanic water bodies changes are being observed in salinity, oxygen levels, currents and circulation (IPCC, 2007a).

Though their consequences are often difficult to distinguish from damage caused by overfishing and pollution, these climatic changes are having impacts on aquatic ecosystems (IPCC, 2007a). In the North East Atlantic there is evidence of changes in abundance of algae, plankton and fish species as well as rapid poleward shifts in their ranges (Brander, 2007). In just 40 years the range of some plankton species has moved north by over 1100km (IPCC, 2007a). Changes in the abundance, productivity, community composition, distribution and migration of freshwater aquatic species are all being detected. In Lake Tanganyika, which supplies 25–40% of the protein in the areas that surround it, primary production has fallen by 20% and fish catches by 30% (Brander, 2007; FAO, 2007; WorldFish Center, 2007b). Reduced availability of food is even forcing aquatic species to develop longer growing periods. Reduced thermal movement of the water also affects water quality by allowing pollutants to accumulate in upper layers of the water and has led to increased levels of mercury and other contaminants in fish. In some areas local extinctions of freshwater and diadromous species are occurring (Brander, 2007).

Rising water temperatures and ocean acidification are damaging coral reefs. When sea temperatures exceed long-term summer averages by 1°C for more than 4 consecutive weeks coral reefs suffer ‘bleaching’ (Nicholls *et al.*, 2007), rejecting the colourful algae with which they normally have a symbiotic relationship, resulting in loss of colour, greater exposure to disease and often to death. When this occurs on a global scale it is referred to as a “mass bleaching event”. Six such events have occurred since 1979. In 1998 a mass bleaching event killed almost 16% of the world’s reef building corals. The severity of bleaching in the Caribbean in 2005 has led to predictions that the entire coral ecosystem in the Caribbean is likely to collapse between 2060 and 2070 (Vergara *et al.*, 2009). Bleaching severely affects those species which are most dependent on coral reefs and thus the fishers who depend on them (Roessig *et al.*, 2004). The most optimistic climate projections would lead to the bleaching of 80–100% of the world’s corals by 2080 (Nellemann *et al.*, 2008).

In addition ocean acidification slows the rebuilding of coral reefs and weakens their structure and anticipated increases in extreme weather events as a result of climate change will further damage reefs (Vergara *et al.*, 2009; Roessig *et al.*, 2004; Eakin *et al.*, 2008).



Location of the world's warm-water and cold-water coral reefs (UNEP 2008)

The compounding effects of climate changes on existing anthropogenic stresses have been described as the 'final insult' to the world's coral reefs (Hoegh-Guldberg *et al.*, 2007). Unless significant measures to protect reefs from anthropogenic stresses and significant natural adaptation to new environmental conditions occur soon few of the world's coral reefs will survive this century.

By 2100 the most optimistic scenario analysed by the IPCC (B1) predicts a temperature rise of 1.8°C above pre-industrial levels and 0.18–0.38 m rise in sea levels relative to 1980–1999 based on thermal expansion alone (IPCC, 2007a). The most pessimistic scenario (A1F1) would likely result in temperatures rising by 4°C by 2100, causing widespread extinctions, ecosystem collapses and sea level increase of 0.26–0.59 m, again from thermal expansion alone (IPCC, 2007a). Glacier meltwater, the main contributor to sea level rise in most popular accounts, is not included in these models hence there is potentially significant underestimation. Currently emissions are rising by more than 3% per annum, a rate close to the fastest considered in the IPCC reports, suggesting the future may hold something "worse than the worst-case scenario" (Hamilton, 2009).

Based on current rates of GHG emissions increases, the results of future climate change and GHG emissions for fisheries and aquaculture are therefore likely to include:

- Average sea level rise of at least 0.6m by 2100 (IPCC, 2007a).
- Increased average sea surface temperatures (Nicholls *et al.*, 2007)
- An overall increase in marine primary productivity of 0.7–8.1% by 2050 but with large regional variations (IPCC, 2007a). Productivity is likely to decline at lower latitudes (FAO, 2008a).
- Continued increases in ocean acidification (IPCC, 2007a).
- Intensification of extreme weather events, potentially including a stronger and more prolonged El Nino (Nicholls *et al.*, 2007).
- Changing hydrological conditions including reduced water levels and flow rates as a result of reduced snow cover, increased frequency of heat waves and heavy precipitation events (even where average rainfall decreases), decreases in subtropical rainfall (IPCC, 2007a).



- Increases in run-off of 10–40% in some wet tropical areas (East and Southeast Asia) but decreases of 10–30% in some dry regions (North Africa and the Mediterranean, Southern Africa) due to declining rainfall, increased evaporation and increased demand for irrigation water (IPCC, 2007a).

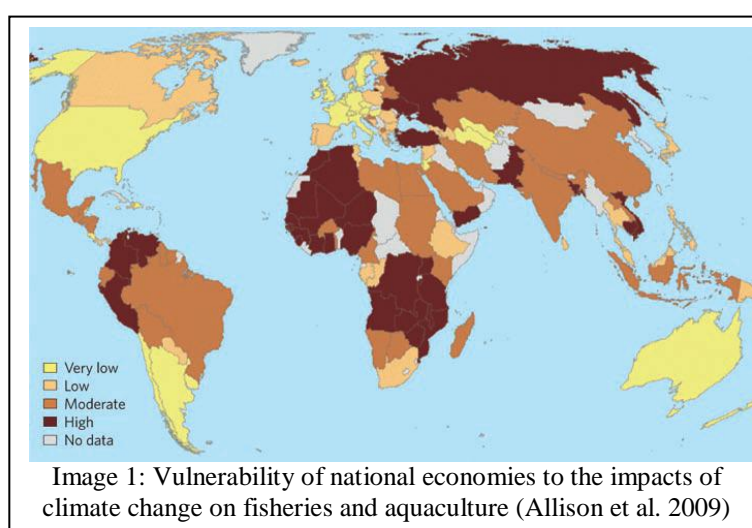
### ***Impacts of climate change on fisheries***

The links between fisheries and their ecosystems are deeper and more significant than those that exist in mainstream agriculture (FAO, 2008b). The productivity of a fishery is tied to the health and functioning of the ecosystems on which it depends for food, habitat and even seed dispersal (MAB, 2009); generally the only control humans can exert over a fishery's productivity is adjustment of fishing effort (Brander, 2007). Estuaries, mangroves, coral reefs and seagrass beds are particularly significant in the provision of ecosystem services, especially as nurseries for young fish (UNEP-WCMC, 2006; MAB, 2009), and are also amongst the most sensitive and highly exposed to the negative impacts of coastal development, pollution, sedimentation, destructive fishing practices and climate change. Fish also tend to live near their tolerance limits of a range of factors; as a result, increased temperature and acidity, lower dissolved oxygen and changes to salinity can have deleterious effects (Roessig *et al.*, 2004). Particular characteristics of the aquatic environment which will be affected by climate change are temperature and primary production.

**Table 1: Twenty national economies most vulnerable to the impacts of climate change on fisheries and aquaculture (with IFAD Regional Division indicated)**

Rank	Country	Rank	Country	Rank	Country	Rank	Country
1	Angola (WCA)	6	Mali (WCA)	11	Morocco (NEN)	16	Uganda (ESA)
2	DR Congo (WCA)	7	Sierra Leone (WCA)	12	Bangladesh (APR)	17	Zimbabwe (ESA)
3	Russia	8	Mozambique (ESA)	13	Zambia (ESA)	18	Côte d'Ivoire (WCA)
4	Mauritania (WCA)	9	Niger (WCA)	14	Ukraine	19	Yemen (NEN)
5	Senegal (WCA)	10	Peru (LAC)	15	Malawi (ESA)	20	Pakistan (APR)

Source: Allison et al. (2009)





## Temperature

All marine and aquatic invertebrates (molluscs, crustaceans, worms etc.) and fish are poikilotherms; their internal temperature varies directly with that of their environment. This makes them very sensitive to changes in the temperature of their surrounding environment. When changes do occur they move to areas where the external temperature allows them to regain their preferred internal temperature. This “behavioural thermoregulation” (Roessig *et al.*, 2004) is resulting in rapid migrations poleward or into cooler bodies of water (FAO, 2008a), corresponding to the poleward shift of climatic zones. As a result, benefits are likely to accrue at higher latitudes and losses will be experienced in the tropics. Some species will also shift from shallow coastal waters and semi-enclosed areas, where temperatures will increase fastest, into deeper cooler waters (Cheung *et al.*, 2009a). Recent predictions suggest this migration alone could reduce maximum catch potential in some areas of the tropics by up to 40% (Cheung *et al.*, 2010), but this may be a conservative estimate as it does not take into account predicted negative effects of climate change on coral reefs or the impact of ocean acidification (Cheung *et al.*, 2009b). Recruitment is also strongly affected by climate variability (Walther *et al.*, 2002) and some stocks may become vulnerable to overfishing at levels of fishing effort that had previously been sustainable (Easterling *et al.*, 2007).

Where fish continue to inhabit warming bodies of water the increases in temperature will increase their metabolic rate slowing growth and reducing maximum size (Roessig *et al.*, 2004).

There are likely to be local extinctions of fish species at the edges of their ranges, especially among freshwater and diadromous species (IPCC, 2007a). However, overall extinction rates for marine species are lower than those predicted for terrestrial species (15–37%), in part due to their higher potential for migration (Cheung *et al.*, 2009b).

As mentioned above, a 1–3°C temperature rise relative to 1990–2000 would result in the bleaching and possible death of most of the world’s coral reefs (IPCC, 2007a). This would have serious negative effects on coastal reef fisheries. It would also increase the risk of Ciguatera, a form of poisoning contracted by eating fish that have grazed on the toxic algae that grow on dead coral reefs (IPCC, 2007a).

## Primary production

Primary productivity is affected by availability of nutrients in the water, which in turn depends on freshwater run-off and ocean mixing as well as levels of light and temperature. In some areas reduced precipitation could lead to reduced run-off from land, starving wetlands and mangroves of nutrients and damaging local fisheries. In other areas increased precipitation or increased extreme weather events, including flooding, will lead to excessive nutrient levels in rivers, lakes and coastal waters as sewage and fertilizer is washed into water bodies causing harmful algal blooms, also known as red tides (Roessig *et al.*, 2004; Epstein, 2000).

With climate change primary productivity is predicted to decline at lower latitudes (FAO, 2008a), where the majority of the world’s small-scale fisheries are located, reducing the productivity of the fisheries.

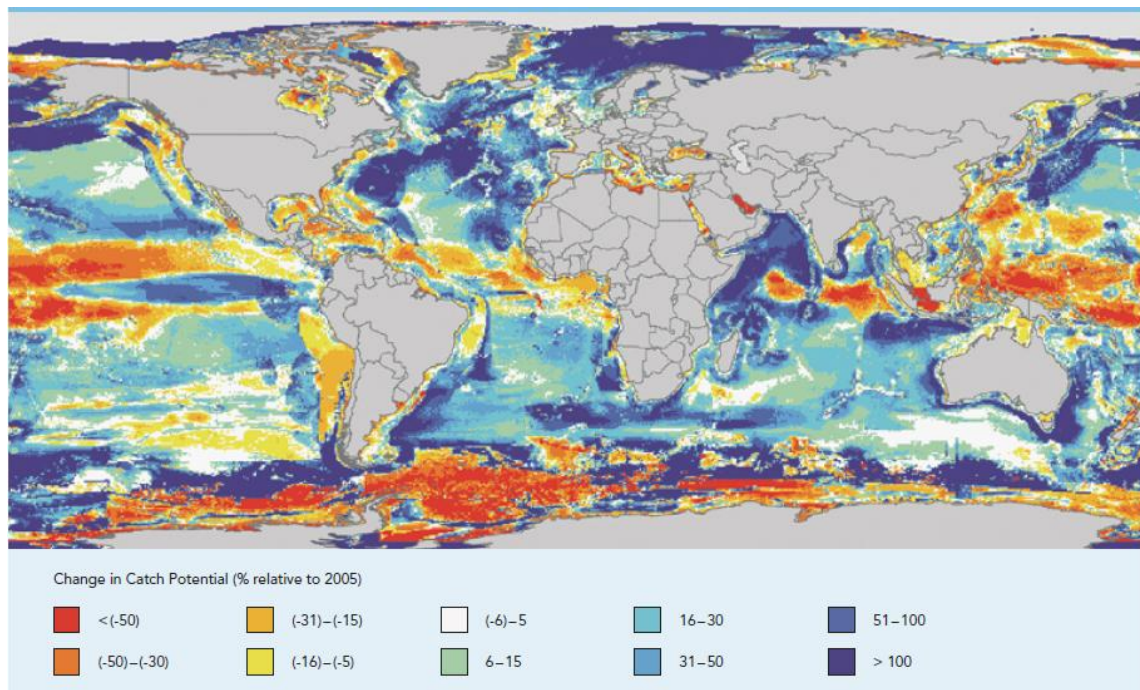


Image 3: Changes in catch potential as a result of climate change (PEW 2009)

### Other effects

Increased frequency of extreme weather events will affect the safety of fishers, damage homes, services and infrastructure, particularly in coastal areas (IPCC, 2007a) and will also damage many coastal ecosystems. Mangroves and reefs, which provided vital defence in many areas of the Indian Ocean following the Indonesian tsunami in 2004 and which protect small islands from wave damage during regular hurricanes and tropical storms, will be damaged by climate change, reducing their effectiveness as coastal defences (UNEP-WCMC, 2006). Increases in heavy rainfall events will increase flood risk, reduce water quality and threaten physical infrastructure.

Reduced dry season flow rates in South Asian rivers and most African river basins are expected to result in reduced fish yields due to impacts on spawning and larval dispersion (FAO, 2007).

### ***Impacts of climate change on aquaculture***

The impacts of climate change on aquaculture are more complex than those on terrestrial agriculture owing to the much wider variety of species produced (Brander, 2007) but different to fisheries because of the greater level of control possible over the production environment.

Greater control can be exerted over the production environment (e.g., by providing food, controlling breeding and disease etc.), and over environmental conditions (e.g., by controlling water flows, temperature, water quality etc.), thus reducing dependence on ecosystem services. However many small-scale fish farmers in developing countries practise a low-input, low-output form of aquaculture depending heavily on ecosystem services and naturally available feed to support their fish. Rice-fish systems in south-east Asia often depend upon wild fish entering paddy fields (Haroon and Pittman, 1996; Rothuis, 1998; Das, 2002); reduced wild stocks will affect farmers who rely on catching fish in their paddy fields for part of their food or income. Many forms of aquaculture still depend heavily on wild stocks for food and seed (FAO, 2008c). The future supply of fishmeal and oils from capture fisheries,

used as feed stock in aquaculture, is far from certain (Naylor *et al.*, 2000; Roessig *et al.*, 2004; Brander, 2007).

Changes in rainfall will cause a spectrum of changes in water availability ranging from droughts and shortages to floods and will reduce water quality, while salinization of groundwater supplies and the movement of saline water further upstream in rivers caused by rising sea levels will threaten inland freshwater aquaculture (IPCC, 2007a). Increased run-off bringing in nutrients from sewage or agricultural fertilizers may cause algal blooms which in turn lead to reduced levels of dissolved oxygen and ‘fish kills’ (Diersing, 2009). Rising temperatures similarly reduce levels of dissolved oxygen and increase metabolic rates of fish, leading to increases in fish deaths, declines in production or increases in feed requirements while also increasing the risk and spread of disease (FAO, 2008a).

Coastal aquaculture will be exposed to major economic losses from extreme weather events and red tides, the frequency and severity of which are likely to increase (Roessig *et al.*, 2004).

However, not all of the changes will be negative.

As sea levels rise, flooding of low lying areas and salinization of groundwater and soil will create ideal conditions for aquaculture in many areas (MAB, 2009), while simultaneously rendering them unsuitable for regular agriculture. There has been a suggestion that Bangladesh could turn from a “rice-bowl into a fish-pond” due to this and increases in other flooding (WorldFish Center, 2007a). Other benefits of rising water temperatures and sea levels include reduced cold water mortality of valuable fish and expansion of areas suitable for brackish or saltwater aquaculture such as shrimp and mudcrab (WorldFish Center, 2007b).

Likewise increasing investment in water storage infrastructure such as dams, on-farm ponds and irrigation systems to retain reduced levels of precipitation and buffer variability in supply will create many potential sites for aquaculture production (MAB, 2009).

In currently cooler areas, such as those at higher altitudes or in more northerly latitudes, rising temperatures may result in increased growth rates and food conversion efficiencies, longer growing seasons, reduced cold water mortality and expansion of areas suitable for aquaculture (Brander, 2007; IPCC, 2007a).

## **Region-specific impacts**

Ecosystems, and thus the communities that depend on the services they provide, are sensitive to regional and local changes, not the global averages mentioned above, which are only indicative of potential changes at local level; such changes are “highly spatially heterogeneous” (Walther *et al.*, 2002). Unfortunately those ecosystems and areas with the most potential for development of fisheries and aquaculture and where fisheries and aquaculture could have the biggest impact on poverty reduction and food security—Africa, South Asia and Latin America—are also those most threatened by climate change (See Annex) (IPCC, 2007a; Allison *et al.*, 2009; WorldFish Center, 2009a, 2009b).

### **Africa**

Due to dependence on fish protein in diets, limited alternative sources of food and employment, and small weak economies many African countries are highly vulnerable to the effects of climate change on fisheries and aquaculture, socially and economically as well as ecologically (WorldFish Center, 2009b). Inland fisheries will be strongly affected by changes in rainfall and increased temperatures; some such changes are already evident. Coral damage, particularly in East Africa, will affect reef fisheries and could result in increased Ciguatera

poisoning (IPCC, 2007a). Low-lying coastal areas will suffer the effects of rising sea levels and damage to important coastal ecosystems such as mangroves.

**Example: Lake Chilwa, Malawi**

Lake Chilwa is just 3m deep on average and can dry out completely when rainfall is low. However in years of high rainfall it supplies up to 25% of Malawi's fish and employs 10,000 people (FAO, 2007). In lakes where stock levels are determined by highly variable water levels management for stock conservation has been argued to be irrelevant. If biomass levels are tied to climatic variation then controlling fishing effort only limits fishers' incomes. The most important measure to maintain the fishery is to ensure the wetlands which serve as a refuge for fish when the lake dries out are kept in good condition (Allison *et al.*, 2007).

**Asia**

Much of Southeast Asia including Bangladesh and Vietnam is seriously threatened by rising sea levels and changes in freshwater availability due to changing snowmelt and precipitation (Cruz *et al.*, 2007). Changing flows and flood patterns will affect aquaculture production, wild stocks, which rely on flood waters to disperse seed and larvae, and rice-fish systems, which rely on flooding to stock paddy-fields with wild fish. Some 86% of the world's fishers and fish-farmers live in the Asia-Pacific region and the vast majority of the world's farmed fish is produced there (89% by quantity and 77% by value). It is also the origin of two-thirds of global inland capture production (FAO, 2009a).

However, there are indications that production of pelagic fish in the North West Indian Ocean might increase as a result of climate change. Reduced snow cover across Eurasia is thought to be responsible for an increase in the strength of the south-westerly monsoon winds over the Arabian Sea. Increased wind strength stirs up deep water and increases the upwelling of nutrients into surface waters where it supports increased phytoplankton (algae) production. Increases in phytoplankton production of 300% were recorded between 1997 and 2004. This increased availability of food at the base of the food web should boost pelagic production (FAO, 2007). However, increases in pelagic stocks may not be of benefit to small-scale fishers if they occur in deeper waters out of their reach. For example, fishers on the southern coast of Yemen, where IFAD is currently developing a new fisheries project, are reporting that tuna migrations are taking place at an increasing distance from the shore, possibly as a result of rising temperatures in the relatively enclosed Gulf of Aden.

**Example: Mekong Delta**

Around 40 million people who live in the Mekong Delta are active in fisheries to some extent and fish production provides 10% of the GDP of both Cambodia and Lao (Easterling *et al.*, 2007). Sea-level rise will allow salt water to move further inland and upstream during dry season (Cruz *et al.*, 2007). While this could increase opportunities for cultivation of aquatic species that are tolerant of brackish or salty water it threatens the established catfish aquaculture industry, which currently employs 150 000 people, produces 1 million tonnes of fish and is worth US\$1 billion per year. Unless saltwater-tolerant catfish strains can be developed the industry faces serious difficulties (MAB, 2009).

**Latin America and the Caribbean**

Increasing temperatures and increases in extreme weather events are expected to result in widespread loss of marine species and reduced availability and quality of freshwater (IPCC,

2007a) as well as damage to coral reefs and mangroves. In Ecuador rising sea levels threaten aquaculture operations and in other Pacific countries pelagic fisheries will be disturbed by a stronger El Nino and higher sea-surface temperatures (Magrin *et al.*, 2007).

### ***Small Island Developing States***

Worldwide, small island states are vulnerable to rising sea levels, increased extreme weather events, erosion of beaches, coral damage and reduced water availability, all of which threaten homes and infrastructure, lives and livelihoods. The World Bank (2005) highlights Tuvalu, Tonga and Kiribati as being particularly vulnerable to the effects of climate change.

## **What can be done to help fishers and fish farmers?**

The main focus of development efforts aimed at fishers and fish farmers in the developing world must be on helping them to build their capacity to adapt to climate change in ways that allow them to moderate potential damages, to take advantage of opportunities or to cope with consequences (IPCC, 2007a; Prowse *et al.*, 2009).

Despite suggestions that adaptation is limited to altering catch size and effort (Easterling *et al.*, 2007) there are in fact many options available, many of which actually benefit or provide an advantage to small-scale fishers and fish-farmers. These include direct adaptations to specific changes as well as actions that increase the resilience and adaptive capacity of communities and ecosystems, particularly by reducing other stresses such as social (poverty, inequality) and environmental (over-fishing, habitat destruction, pollution) stresses that can significantly increase vulnerability of communities and ecosystems to the impacts of climate change (Cheung *et al.*, 2009a; IPCC, 2007a; Walther *et al.*, 2002).

Many fishing communities are dependent on stocks that exhibit regular fluctuations and so have already developed considerable coping capacity (Easterling *et al.*, 2007). Development agencies should direct efforts to documenting and understanding existing adaptation mechanisms and, where these prove successful, supporting and strengthening them and applying them elsewhere. Examples of such mechanisms include diversification of livelihood systems, such as switching between farming and fishing in response to seasonal and inter-annual variation in fish availability, as is done in parts of Asia and Africa, and seasonal migration to locations where fish are available; and flexible institutional and management strategies, such as integration of land and sea tenure to control access to fisheries and flexible redistribution of fishing rights between neighbouring regions to buffer localized scarcities in Palau, Micronesia (Allison and Ellis, 2001). However, although traditional management systems may support sustainable livelihoods, they may also reinforce the social positions of those who oversee them, at the expense of less privileged members of the community (Neiland *et al.*, 2005) and thus may not meet the requirements of equitable development.

Fish products are extensively traded. European Union countries and the USA are major markets, and there is a growing awareness of sustainability issues in these countries. Certification and similar sustainability initiatives could contribute to moves towards more efficient and sustainable systems. This should go beyond a simple 'carbon labelling' approach.

This should be applied to both fisheries and aquaculture, with a focus on market-led mechanisms that are affordable to developing countries; at present affordable options are rather limited.

## Fisheries

More research is needed into impacts of climate change at the levels of individual species and local fisheries and fishing communities, and investment is needed in the development of policies that will help reduce vulnerabilities and encourage people to take the actions needed to adapt to changed circumstances. People also need to be empowered to take those actions through increased access to appropriate financial services and opportunities for training.

At the policy level, there will need to be increased cross-boundary cooperation and flexibility of regional fishing agreements to cope with shifting stocks, as well as integration of fisheries and aquaculture into other national policies on climate change, food security, water management, poverty reduction, coastal zone management etc. to reduce conflicts over resource use and ensure coherence of adaptation activities. Greater co-management and decentralization of management to fishing communities themselves will help to increase flexibility in implementation of policies, together with a greater sense of ownership and improved compliance, making management more effective and reducing costs of enforcing top-down regulations. Management of fisheries and aquaculture will need to focus on maintaining the integrity of ecosystems, taking into account complex linkages and relationships between species and their wider ecosystems. This will require going beyond simply controlling catch levels of commercial important species. Marine Protected Areas, including permanent closures, could play a very important role, based on evidence to date of the dramatic positive impact they can have on fish stocks within and around them (World Bank, 2005).

At a more practical level, technology needs to be developed, adapted or implemented to reduce wastage and increase the value added to catches to balance the impact of decreasing catches on food security and livelihoods. Improved storage such as refrigeration and post-harvest handling and processing can reduce losses due to deterioration of fish quality. High-value export markets require high standards of food safety and hygiene, but accessing such markets can significantly increase incomes.

Fleet capacities will need to be adjusted to prevent overfishing. This may also require incentives to switch to smaller-scale operations using sustainable fishing gear and techniques, at least in areas accessible to small boats, as small-scale fisheries make a greater contribution to the local economy by providing more jobs at sea and on-shore, supplying fish to local markets and spending a lower share of earnings on fuel than large commercial/industrial fishing operations. Industrial fleets employ few locals, focus on high value export markets and often fish is never landed in the country in whose waters it is caught.

Changes in fishing methods will require changes to the equipment used; support may be needed to ensure that appropriate gear can be procured, including provision of credit, and to provide training and extension to broaden the fishers' knowledge of fishing techniques. Support will be needed for research on new fishing grounds and to promote the consumption of underexploited species for which there is currently no market. This is an important part of increasing the adaptive capacity of the fishing communities themselves.

Mechanisms will need to be provided to protect fishing communities from some of the immediate impacts of climate change, including the increasing incidence of red tides and ciguatera outbreaks and extreme weather events. Capacity to monitor the environment and provide early warning of threats needs to be enhanced. For example, fishers in the Bay of Bengal receive weather forecasts and warnings via mobile phone, reducing the number of vessels caught at sea by typhoons (FAO, 2007). Access to emergency funds and appropriate insurance products would also reduce vulnerability of the livelihoods of small-scale fishers and fish farmers to loss of income and assets resulting from extreme weather events.

## Aquaculture

There are numerous opportunities for adaptation in aquaculture. Primary among these are to take advantage of newly created aquaculture opportunities on flooded or salinized land and in reservoirs and ponds created to store water and integrating aquaculture with agriculture.

The construction of water storage and irrigation infrastructure may interfere with wild fisheries but introducing aquaculture or artificial stocking can provide livelihoods for local communities and boost food security. In Pakistan and India irrigation systems are already a valuable source of fish, but in India alone there are 40 000 km<sup>2</sup> of artificial reservoirs where fish production could still be increased (FAO, 2004). In Pakistan, flood control compartments are naturally stocked with wild fish during floods and careful management could turn these water bodies into a productive resource. The WorldFish Center received the World Food Prize in 2005 for a project that converted a million seasonally flooded ditches and pools to fish production in Bangladesh (WorldFish Center, 2007a). Groundwater pumped to irrigate crops can be fed through aquaculture systems first before applying to crops. Water from fish ponds can also be used to irrigate crops directly or crops can be grown around the pond where plants receive water by from seepage.

There is potential to increase the practice of rice-fish culture in Asia, Africa and elsewhere to increase rice yields and reduce the need for artificial fertilizers and pesticides (fish excreta fertilizes the field and fish consume pests like the rice stem borer). Waterfowl can also be integrated to increase productivity further. It is possible to integrate pond fish culture into mixed crop-livestock systems re-using waste materials productively and increasing food production and incomes.

Many aquaculture systems depend on declining wild stocks of fish for seed, and seed production facilities will need to be developed to offset the declines in wild populations. Declines in the availability of wild fish as sources of feed will require shift away from culture of carnivorous species. Measures should be put in place to culture species low in the food chain, such as seaweed and shellfish, which essentially sequester carbon (FAO, 2009b).

There is a need to move towards mariculture to mitigate the impact of climate change on freshwater hydrology. Similarly, with increasing saline intrusions, brackish water aquaculture should be broadened in scope as in many countries it has meant only shrimp farming. Research will be needed to develop new strains of aquaculture species that are tolerant of lower water quality and higher levels of salinity to cope with changes driven by climate change.

## Direct support to freshwater, coastal and marine ecosystems

Mangroves provide vital coastal defence and support local fish stocks by providing food, shelter and habitat (UNEP-WCMC, 2006). They are also very effective at absorbing excess nutrients from wastewater, sequestering carbon and provide fuelwood, building material and fodder for animals. However, due to overexploitation, extreme weather and unsustainable aquaculture development 35% of the world's mangroves have been lost over the last 20 years, rising to 80% in some areas (TEEB, 2008). The conservation, rehabilitation and afforestation of mangroves are important means of both adapting to and mitigating the effects of climate change. This can involve raising community awareness of their importance, reducing stress from other environmental threats, preventing overexploitation of mangroves for animal fodder or firewood and planting new mangroves artificially using collected seeds and fertilizer. The effects of mangrove planting and rehabilitation on the marine environment and fisheries are analogous to agricultural activities that improve soil fertility, increase supply of fodder for livestock and increase herd sizes.



Efforts will need to be directed at preserving the wetland ‘hinterland’ of African inland fisheries and deep sections of shallow lakes as refuges for fish when water levels fall. With the exception of large, deep lakes, changes in climate, rainfall in particular, are the main cause of stock changes in these fisheries, not fishing effort. In such cases reductions in fishing effort have little effect on stocks and serve only to reduce the incomes of fishers (Allison *et al.*, 2007).

## **Summary and conclusions**

Climate change will have significant impacts on fisheries and aquaculture. At low latitudes these are likely to be largely negative for fisheries, damaging important ecosystems such as coral reefs and mangroves and causing reductions in fish stocks due to rising water temperatures and reduced primary production. This could have significant effects on food security and employment in areas dependent on fisheries that are particularly vulnerable to the impacts of climate change; these include reef fisheries, fisheries in shallow lakes or wetlands and fisheries in other enclosed or semi-enclosed bodies of water. However, some areas may experience localized increases in fish stocks due to in-migration of species from other areas and rising primary production. Brackish and saltwater aquaculture could benefit from rising sea levels and freshwater aquaculture in cooler regions could benefit from increased feed efficiency and reduced cold water mortality, though reductions in availability of wild fish for feed and seed, increased spread of disease and reduced water quality pose threats.

Responses to these changes must centre on boosting adaptive capacity and resilience both of communities and the ecosystems on which they depend. The heavy dependency of small-scale fishers and fish-farmers in developing countries on ecosystem services must be recognized and measures taken to increase the health of these ecosystems by reducing other stresses such as over-exploitation and pollution. Communities themselves must be strengthened through provision of services such as insurance and weather warnings to reduce risk, support for participatory natural resource management and sustainable fishing operations, and assistance in post-harvest processing and preservation to maximize value-added and employment and minimize waste from both fisheries and aquaculture.

Adaptation in the fisheries sector need not be restricted to altering catch size and effort (Easterling *et al.* 2007). Numerous options are available, many focusing on building adaptive capacity and resilience, and many also contributing to additional goals of improved fisheries management and poverty reduction, improving the livelihoods of those poor rural people most at risk from the effects of climate change.

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## References

- Allison, E.H. and Ellis, F. (2001) The livelihoods approach and management of small-scale fisheries. *Marine Policy* 25, 377–388.
- Allison, E.H., Andrew, N.L. and Oliver, J. (2007) Enhancing the resilience of inland fisheries and aquaculture systems to climate change. *Journal of Semi-Arid Tropical Agricultural Research* 4(1). Available at: <http://www.icrisat.org/Journal/SpecialProject/sp15.pdf>. Date accessed: 6 December 2010.
- Allison, E.H., Perry, A.L., Badjeck, M.-C. et al. (2009) Vulnerability of national economies to the impacts of climate change on fisheries. *Fish and Fisheries* 10(2), 173–196.
- Brander, K.M. (2007) Global fish production and climate change. *Proceedings of the National Academy of Sciences* 104(50), 19704–19714.
- Cheung, W.W.L., Lam, V.W.Y., Sarmiento, J. L., Kearney, K., Watson, R., Zeller, D. and Pauly, D. (2009a) Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Global Change Biology* 16, 24–35. Available online: <http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2486.2009.01995.x/full>
- Cheung, W.W.L., Lam, V.W.Y., Sarmiento, J.L., Kearney, K., Watson, R. and Pauly, D. (2009b) Projecting global marine biodiversity impacts under climate change scenarios. *Fish and Fisheries* 10, 235–251.
- Cheung, W.W.L., Lam, V.W.Y., Sarmiento, J. L., Kearney, K., Watson, R., Zeller, D. and Pauly, D. (2010) Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Global Change Biology* 16, 24–35.
- Cruz, R.V., Harasawa, M., Lal, S. et al. (2007) Asia. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, eds. Cambridge University Press, Cambridge, UK, pp. 471–506. Available at: <http://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-chapter10.pdf>. Date accessed: 6 December 2010.
- Das, D.N. (2002) Fish farming in rice environments of north eastern India. *Aquaculture Asia*, 7(2): 43–47.
- Diersing, N. (2009) *Phytoplankton Blooms: The Basics*. Florida Keys National Marine Sanctuary, Key West, Florida, USA, 2 pp. Available at: <http://floridakeys.noaa.gov/pdfs/wqpb.pdf>. Date accessed: 6 December 2010.
- Dulvy, N. and Allison, E. (2009) A place at the table? *Nature Reports Climate Change* 3, 68–70.
- Eakin, M.C., Kleypas, J. and Hoegh-Guldberg, O. (2008) Global climate change and coral reefs: rising temperatures, acidification and the need for resilient reefs. In: *Status of Coral Reefs of the World: 2008* (C. Wilkinson, ed.). Global Coral Reef Monitoring Network and Reef and Rainforest Research Centre, Townsville, Australia, pp. 29–40. Available at: <http://www.reefbase.org/download/download.aspx?type=1&docid=13311>. Date accessed: 6 December 2010.
- Easterling, W.E., Aggarwal, P.K., Batima, P. et al. (2007) Food, fibre and forest products. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, eds.). Cambridge University Press, Cambridge, UK, pp. 273–313. Available at: <http://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-chapter5.pdf>. Date accessed: 6 December 2010.
- Epstein, P.R. (2000) Is global warming harmful to health? *Scientific American*, August 2000, 50–57.
- FAO (2004) Fisheries in irrigation systems of arid Asia. *FAO Fisheries Technical Paper* No. 430. FAO, Rome, Italy, 150 pp. Available at: <ftp://ftp.fao.org/docrep/fao/007/y5082e/y5082e00.pdf>. Date accessed: 6 December 2010.
- FAO (2005) Nutritional elements of fish [web page]. Fisheries and Aquaculture Department, FAO, Rome, Italy. Available at: <http://www.fao.org/fishery/topic/12319/en>. Date accessed: 6 December 2010.

- FAO (2007) Building adaptive capacity to climate change: policies to sustain livelihoods and fisheries. *New Directions in Fisheries – A Series of Policy Briefs on Development Issues* No. 8. FAO Rome, Italy, 16 pp. Available at: <ftp://ftp.fao.org/docrep/fao/010/a1115e/a1115e00.pdf>. Date accessed: 6 December 2010.
- FAO (2008a) Climate change implications for fisheries and aquaculture. In: *The State of Fisheries and Aquaculture 2008*. FAO, Rome, Italy, pp. 87–91.
- FAO (2008b) *Climate change for fisheries and aquaculture. Technical background document from the Expert Consultation, 7 to 9 April 2008, FAO, Rome*. Paper presented at ‘Climate Change, Energy and Food’, High-level Conference on Food Security: The challenges of climate change and bioenergy, 3–5 June 2008. Rome, Italy. Available at: <ftp://ftp.fao.org/docrep/fao/meeting/013/ai787e.pdf>. Date accessed: 6 December 2010.
- FAO (2008c) *Options for decision makers*. Workshop on Climate Change and Fisheries and Aquaculture, FAO Headquarters, Rome, 7–9 April 2008. FAO, Rome, Italy, 5 pp. Available at: [http://www.fao.org/fileadmin/user\\_upload/foodclimate/presentations/fish/OptionsEM7.pdf](http://www.fao.org/fileadmin/user_upload/foodclimate/presentations/fish/OptionsEM7.pdf). Date accessed: 6 December 2010.
- FAO (2009a) *The State of World Fisheries and Aquaculture 2008*. FAO, Rome, Italy, 176 pp.
- FAO (2009b) Climate change implications for fisheries and aquaculture: overview of current scientific knowledge (K. Cochrane, C. De Young, D. Soto and T. Bahri, eds.). *FAO Fisheries and Aquaculture Technical Paper* No. 530. FAO, Rome, Italy, 212 pp.
- Hamilton, C. (2009) *Is it too late to prevent catastrophic climate change?* Lecture to a meeting of the Royal Society of the Arts, Sydney, 21 October 2009. 19 pp. Available at: [http://www.clivehamilton.net.au/cms/media/documents/articles/rsa\\_lecture.pdf](http://www.clivehamilton.net.au/cms/media/documents/articles/rsa_lecture.pdf). Date accessed: 6 December 2010.
- Haroon, A.K.Y. and Pittman, K.A. (1996) Rice-fish culture: feeding, growth and yield of two size classes of *Puntius gonionotus* Bleeker and *Oreochromis* spp. in Bangladesh. *Aquaculture* 154(3–4), 261–281.
- Hoegh-Guldberg, O., Mumby, P.J., Hooten, A.J. et al. (2007). Coral reefs under rapid climate change and ocean acidification. *Science* 318 (5857), 1737–1742.
- IFAD (2007) *IFAD Strategic Framework 2007–2010*. IFAD, Rome, Italy, 35 pp. Available at: [http://www.ifad.org/sf/strategic\\_e.pdf](http://www.ifad.org/sf/strategic_e.pdf). Date accessed: 6 December 2010.
- IFAD (2008) *Climate Change: A Development Challenge*. IFAD, Rome, Italy, 4 pp. Available: [http://www.ifad.org/climate/factsheet/climate\\_e\\_web.pdf](http://www.ifad.org/climate/factsheet/climate_e_web.pdf). Date accessed: 6 December 2010.
- IPCC (2007a) *Climate Change 2007: Synthesis Report – Contribution of Working Groups I, II, and III to the Fourth Intergovernmental Panel on Climate Change*. Core Writing Team: R.K. Pauchauri and A. Reisinger, eds. IPCC, Geneva, Switzerland, 8 pp.
- IPCC (2007b) Summary for policymakers. In: *Climate Change 2007: The Physical Science Basis. Contribution of the Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (S. Solomon, D. Qin, M. Manning et al., eds.). Cambridge University Press, Cambridge, UK, 22 pp. Available at: <http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-spm.pdf>. Date accessed: 6 December 2010.
- MAB (Multi-Agency Brief) (2009). *Fisheries and Aquaculture in a Changing Climate*. FAO, Rome, Italy, 6 pp. Available at: [ftp://ftp.fao.org/FI/brochure/climate\\_change/policy\\_brief.pdf](ftp://ftp.fao.org/FI/brochure/climate_change/policy_brief.pdf). Date accessed: 6 December 2010.
- Magrin, G., Gay García, C., Cruz Choque, D. et al. (2007) Latin America. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, eds.). Cambridge University Press, Cambridge, UK. Available at: <http://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-chapter13.pdf>. Date accessed: 6 December 2010.
- Naylor, R.L., Goldburg, R.J., Primavera, J.H. et al. (2000). Effect of aquaculture on world fish supplies. *Nature* 405, 1017–1024.
- Naylor, R.L., Hardy, R.W., Bureau, D.P. et al. (2009) Feeding aquaculture in an era of finite resources. *Proceedings of the National Academy of Sciences* 106, 15103–15110.
- Neiland, A. E., Madakan, S. P. and Béné, C. 2005. Traditional management systems, poverty and change in the arid zone fisheries of northern Nigeria. *Journal of Agrarian Change* 5, 117–148.

- Nellemann, C., Hain, S. and Alder, J., eds. (2008). *In Dead Water: Merging of climate change with pollution, over-harvest, and infestations in the world's fishing grounds*. UNEP, Grid-Arendal, Norway, 63 pp. Available at: [http://www.unep.org/pdf/InDeadWater\\_LR.pdf](http://www.unep.org/pdf/InDeadWater_LR.pdf). Date accessed: 6 December 2010.
- Nicholls, R.J., Wong, P.P., Burkett, V.R. et al. (2007) Coastal systems and low-lying areas. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, eds.). Cambridge University Press, Cambridge, UK, pp. 315–356. Available at: <http://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-chapter6.pdf>. Date accessed: 6 December 2010.
- Paquotte, P. and Lem, A. (2008) Seafood markets and trade: A global perspective and an overview of EU Mediterranean countries. *Options Méditerranéennes, Series B* 62, 43–55.
- PEW. (2009) Redistribution of Fish Catch by Climate Change: A Summary of a New Scientific Analysis: Cheung, W.W.L., Lam, V.W.Y., Sarmiento, J. L., Kearney, K., Watson, R., Zeller, D. and Pauly, D. 2009.
- Prein, M. and Ahmed, M. (2000) Integration of aquaculture into smallholder farming systems for improved food security and household nutrition. *Food and Nutrition Bulletin* 21(4), 466–471.
- Prowse, M., Grist, N. and Sourang, C. (2009) Closing the gap between climate adaptation and poverty reduction frameworks. *Project Briefing* No. 21. Overseas Development Institute, London, UK, 4 pp. Available at: <http://www.odi.org.uk/resources/download/3290.pdf>. Date accessed: 6 December 2010.
- Roessig, J.M., Woodley, C.M., Cech, J.J. and Hansen, L.J. (2004) Effects of global climate change on marine and estuarine fishes and fisheries. *Reviews in Fish Biology and Fisheries* 14, 251–275.
- Rosenzweig, C., Casassa, G., Karoly, D.J. et al. (2007) Assessment of observed changes and responses in natural and managed systems. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, eds.). Cambridge University Press, Cambridge, UK, pp. 79–131. Available at: <http://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-chapter1.pdf>. Date accessed: 6 December 2010.
- Rothuis, A. (1998) *Rice-fish culture in the Mekong delta, Vietnam: constraint analysis and adaptive research*. Doctoral Thesis, Katholieke Universiteit Leuven, Leuven, Belgium, 127 pp.
- Stern, N. 2007. *The Economics of Climate Change. The Stern Review*. Cambridge University Press, Cambridge, UK, 712 pp.
- TEEB (2008). *The Economics of Ecosystems and Biodiversity: An interim report*. UNEP, Bonn, Germany, 66 pp. Available at: <http://www.teebweb.org/InformationMaterial/TEEBInterimReport/tabid/1278/language/en-US/Default.aspx>. Date accessed: 6 December 2010.
- UNEP. 2008. *In Dead Water: Merging of Climate Change with pollution, Over-Harvest, and Infestations in the World's Fishing Grounds*. UNEP: Grid-Arendal, Norway. Available online: [[http://www.unep.org/pdf/InDeadWater\\_LR.pdf](http://www.unep.org/pdf/InDeadWater_LR.pdf)].
- UNEP/GRID-Arendal. 2009. Fish protein world consumption. UNEP/GRID-Arendal Maps and Graphics Library. Available online: [<http://maps.grida.no/go/graphic/fish-protein-world-consumption>]
- UNEP-WCMC (2006) *In the Front Line: Shoreline protection and other ecosystem services from mangroves and coral reefs*. UNEP-WCMC, Cambridge, UK, 33 pp. Available at: <http://data.iucn.org/dbtw-wpd/edocs/2006-025.pdf>. Date accessed: 6 December 2010.
- Vergara, W., Deeb, A.M., Mira-Salama, D. and Toba, N. (2009) The consequences of climate induced coral loss in the Caribbean by 2050–80. In: *Environment Matters 2008*. The World Bank, Washington, DC, USA, pp. 20–22. Available at: <http://siteresources.worldbank.org/EXTENVMAT/Resources/EnvironmentMatters2008-a.pdf>. Date accessed: 6 December 2010.
- Walther, G., Post, E. Convey, P. et al. (2002) Ecological responses to recent climate change. *Nature* 416, 389–395.
- World Bank (2005) *Turning the Tide. Saving fish and fishers: Building sustainable and equitable fisheries governance*. The World Bank, Washington, DC, USA, 20 pp. Available at: [www.seaweb.org/resources/documents/reports\\_turningtide.pdf](http://www.seaweb.org/resources/documents/reports_turningtide.pdf). Date accessed: 6 December 2010.
- World Bank (2010) *World Development Report 2010: Development and Climate Change*. The World Bank, Washington, DC, USA, 424 pp.

- WorldFish Center (2007a) Fisheries and aquaculture can provide solutions to cope with climate change. *Issues Brief* No.1701. WorldFish Center, Penang, Malaysia, 4 pp. Available at: <http://www.worldfishcenter.org/v2/files/CC-ThreatToFisheries1701.pdf>. Date accessed: 6 December 2010.
- WorldFish Center (2007b) The threat to fisheries and aquaculture from climate change. *Policy Brief*. WorldFish Center, Penang, Malaysia, 8 pp. Available at: [http://www.worldfishcenter.org/resource\\_centre/ClimateChange2.pdf](http://www.worldfishcenter.org/resource_centre/ClimateChange2.pdf). Date accessed: 6 December 2010.
- WorldFish Center (2009a) Climate change: Research to meet the challenges facing fisheries and aquaculture. *Issues Brief* No. 1915. WorldFish Center, Penang, Malaysia, 6 pp. Available at: [http://www.worldfishcenter.org/resource\\_centre/WF\\_2167.pdf](http://www.worldfishcenter.org/resource_centre/WF_2167.pdf). Date accessed: 6 December 2010.
- WorldFish Center (2009b) Don't let fish slip through the climate change net [online]. Available at: <http://www.worldfishcenter.org/wfcms/HQ/article.aspx?ID=684>. Date accessed: 6 December 2010.