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Climate Change and its Impact on Fisheries: A Review

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Abstract

Climate change will have significant impacts on fisheries and aquaculture. 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 ground water.

Keywords: Fisheries; Climate Change; Aquaculture; Temperature.

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

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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; Stern, 2007).

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). 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.

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_2 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 1100 km (IPCC, 2007a). Changes in the abundance, productivity, community composition, distribution and migration of freshwater aquatic species are all being detected.

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. 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).

The most pessimistic scenario 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, 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 (WCA)	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.

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 (World Fish 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 (World Fish 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).

Threats

The principal threats to future fisheries production identified here are expected to act progressively (i.e., a linear response) and to interact with each other. However, marine ecosystems can also respond to changes in physical or biological forcing in a nonlinear way, e.g., when a threshold value is exceeded and a major change in species composition, production, and dynamics takes place. We know that such nonlinear responses occur but do not yet understand how or under what conditions. This is a key limitation in our ability to forecast future states of marine ecosystems.

Fishing activity: Fishing is the greatest threat to future global fish production; however, the impacts of fishing and of climate change interact in a number of ways, and they cannot be treated as separate issues. Fishing causes changes in the distribution, demography, and stock structure of individual species and direct or indirect changes in fish communities and marine ecosystems. These changes have consequences for other ecosystem services (such as nutrient cycling and recreational use) and for sustainability, resilience and ability to adapt to climate change, and other pressures. Future sustainable fisheries depend on effective management of fishing activity, which in turn requires an understanding of the effects of climate change on the productivity and distribution of exploited stocks. Management must take into account the interactive effects of fishing, climate, and other pressures.

Fishing is size-selective and causes changes in the size and age structure of populations, which results in greater variability in annual recruitment in exploited populations. The truncation of age structure and loss of geographic substructure within populations makes them more sensitive to climate fluctuations. To sustain the resilience of fish populations, in particular when they are confronted by additional pressures such as climate change, their age and geographic structure must be preserved rather than relying only on management of their biomass. We are currently fishing most stocks at levels that expose them to a high risk of collapse, given the trends in climate and the uncertainty over impacts.

Fishing is one of a number of human pressures that have resulted in a global decline in biodiversity. This raises concerns over the role biodiversity plays in maintaining ecosystem services and, in particular, resilience to climate change. A recent meta-analysis concluded that the oceans' capacity to provide food, maintain water quality, and recover from perturbation has been impaired through loss of biodiversity, but other studies of the relationship between biodiversity and ecosystem functioning and services produce a more nuanced picture.

Direct and indirect effects of climate change on distribution, productivity, and extinction. Climate change has both direct and indirect impacts on fish stocks that are exploited commercially. Direct effects act on physiology and behaviour and alter growth, development, reproductive capacity, mortality, and distribution. Indirect effects alter the productivity, structure, and composition of the ecosystems on which fish depend for food and shelter. The effects of increasing temperature on marine and freshwater ecosystems are already evident, with rapid poleward shifts in distributions of fish and plankton in regions such as the North East Atlantic, where temperature change has been rapid. Further changes in distribution and productivity are expected due to continuing warming and freshening of the Arctic. Some of the changes are expected to have positive consequences for fish production, but in other cases reproductive capacity is reduced and stocks become vulnerable to levels of fishing that had previously been sustainable. Local extinctions are occurring at the edges of current ranges, particularly in freshwater and diadromous species such as salmon and sturgeon.

Threats to inland fisheries and aquaculture: Many inland fisheries are threatened by alterations to water regimes that, in extreme cases, cause whole lakes (e.g., Lake Chad) and waterways to disappear. Climate change has direct effects, through reduced precipitation and greater evaporation, and indirect effects when more water is used for irrigation to offset reduced precipitation. Threats to aquaculture arise from

- Stress due to increased temperature and oxygen demand and decreased, pH,
- Uncertain future water supply,
- Extreme weather events,
- Increased frequency of diseases and toxic events,
- Sea level rise and conflict of interest with coastal defences, and
- An uncertain future supply of fishmeal and oils from capture fisheries.

Aquaculture poses some additional threats to capture fisheries, and the development of aquaculture could affect the resilience of capture fisheries in the face of climate change. There will also be some positive effects due to increased growth rates and food conversion efficiencies, longer growing season, range expansion, and the use of new areas as a result of decrease in ice cover.

Economic impacts: A key factor concerning future economic impacts is the need to identify which countries and regions are most vulnerable. Modeling studies have assessed country vulnerability on the basis of exposure of its fisheries to climate change, high dependence on fisheries production, and low capacity to respond. The studies show that climate will have the greatest economic impact on the fisheries sectors of central and northern Asian countries, the Western Sahel, and coastal tropical regions of South America, as well as on some small and medium sized island states. Indirect economic impacts will depend on the extent to which local economies are able to adapt to new conditions in terms of labor and capital mobility. Change in natural fisheries production is often compounded by decreased harvest capacity and reduced access to markets. Global fish production is forecast to increase more slowly than demand to 2020, and the proportion of production coming from aquaculture is forecast to increase. Therefore, zero growth in capture fisheries production will not threaten total supply unduly, but a decline could affect global fish consumption.

Evidence of climate impacts: Climate change affects the survival, growth, reproduction, and distribution of individuals within a species, but impacts can also be shown at the level of populations, communities, or entire ecosystems. The following examples of observed climate impacts are intended to illustrate some of the main processes involved, their complexity, and their interactions. The climate-related drivers include temperature, salinity, wind fields, oxygen, pH, and the density structure of the water column. The examples range in scale from experimental studies on individual fish, through a combination of experimental and field studies, to modelling and observation of whole ecosystems and large sea areas.

Metabolic stress and its effects: Changes in the distribution of common eelpout (Zoarces viviparus) in the southern North Sea have been related to thermally limited oxygen delivery during summer hot spells, using a combination of experimental and field work to identify the physiological effects and consequences for mortality. Salmon in the Fraser River, Canada, suffered enhanced mortality when summer temperatures exceeded the levels previously recorded in a 60-year time series over a period of weeks in the summer of 2004. These examples show that the impacts of climate change can occur during short periods within a year and should, therefore, be ascribed to changes in the frequency and intensity of extreme events (floods, droughts, heat waves, hurricanes), as well as to changes in the mean values.

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 interannual 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 neighboring 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.

Future Fish Production

The quantity of future fish production depends on changes in NPP and on what proportion is transferred through the marine ecosystem to human consumption. Because there are considerable uncertainties about both of these factors, very low confidence can be placed in current predictions of future fish production. Regional and local forecasts may be more reliable than the global forecast because of special factors (such as loss of ice cover in high latitudes, which will allow greater light penetration). Some recent observation-based studies found that NPP has been declining, particularly in low latitudes, because of increased warming of the surface layers, which increases stratification and reduces nutrient mixing from depth. The scientific base is improving rapidly, as is evident from the very recent dating of key publications cited here, but we are some way from achieving a reliable consensus.

The examples of observed climate impacts cited above show changes in distribution and abundance of particular species, but because species are often replaced by functionally similar species, the net effect on trophic structure and fish production may be small. It is generally difficult to predict the changes in trophic structure and composition of ecosystems, therefore one simplifying assumption is that such functional replacement always occurs and that fish production is proportional to NPP. A second possible approach is to study the impacts of climate on fish communities rather than at the individual-species level. The rising proportion of aquaculture in global fisheries production will increasingly determine the trophic structure of fisheries; however, aquaculture is likely to remain dependent on capture fisheries for its food supply.

Summary and Conclusion

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 smallscale 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 valueadded 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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