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FORESIGHT PROJECT ON GLOBAL FOOD AND FARMING FUTURES

Potential impacts of climate change on marine wild capture fisheries: an update

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SUMMARY

This paper provides a brief update on the potential impacts of climate change on marine ecosystems and marine wild capture fisheries based on the scientific literature published since 2007. Current models predict shifts in fish distributions of 45–60 km per decade, with 0·80 of species moving poleward. With a high CO_2 emissions scenario, little overall change in the global maximum potential fisheries catch is projected (± 1%), although with high spatial variability: decreases of 40% are projected for the tropics, with increases of 30–70% for higher latitudes. Tropical nations appear to be most vulnerable to the impacts of climate change on fisheries production. Coupled atmosphere–ocean–fish production–human society models are beginning to be developed for specific market systems. Results suggest that how society responds can have as large or larger an effect as the strength of the climate impact. Good observations of the impacts of climate change exist for high latitude, coral reef and North Atlantic systems. Management strategies are being developed to address climate change and fisheries, including risk and vulnerability assessment frameworks, pro-active planning with stakeholders regarding potential impacts and responses and examining existing regulations to identify gaps created by altered species distributions (e.g. unregulated fishing in newly ice-free areas). Overall, fisheries governance systems are needed which are flexible and can quickly adapt to changing ecological and human societal conditions. Significant knowledge gaps include a comprehensive and co-ordinated global network of observations to help distinguish climate change from variability, and increased detail in the structure and processes of models. Necessary next steps include reducing the uncertainties of climate impacts models at present, understanding the synergistic effects of multiple stressors and the inclusion of humans into coupled models and socio-economic analyses, in particular at regional and local scales. In the intermediate term, developing nations in tropical regions are likely to be most negatively impacted, whereas developed nations at higher latitudes are most likely to benefit. In the longer term, overall marine food security will depend on the impacts of climate change on marine primary production, for which the present projections are highly uncertain. Adoption of an integrated social–ecological approach that improves the adaptive capacities of ecological and human social systems will help to sustain food security from marine wild capture fisheries.

INTRODUCTION

Marine wild capture fisheries are crucial to the food and livelihood security of over 0·20 of the human population. The FAO reported that wild capture fisheries and aquaculture supplied about 110 million tonnes of food fish to humans in 2006, of which 0·53 was from the wild capture fisheries sector (FAO 2009). Fish provide almost 3 billion people with 0·15 of their *per capita* animal protein, and fish as a protein source is particularly important in the developing world. The worldwide *per capita* annual supply of fish is 16·7 kg

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(FAO 2009). Combined, the fisheries and aquaculture sectors typically contribute 0·005–0·025 to national GDP but may be greater than 0·07 in some countries, similar to the contribution of agriculture (Garcia & Rosenberg 2010). The FAO estimates that, in 2006, over 44 million people were directly involved in the production of fish from the wild capture and aquaculture sectors. Globally, 170 million people may be employed in the primary fish production and secondary processing and marketing sectors, although most fishers and fish farmers conduct small-scale artisanal activities in coastal and inland waters (FAO 2009).

The importance of fish to human food security and the burgeoning human population have placed marine fish populations under considerable stress. Whether wild marine fisheries will be able to continue to meet the needs of an expected additional 2 billion people by 2050 is unclear (Garcia & Rosenberg 2010). Direct pressures on marine ecosystems occur from biophysical and human factors and their interactions, including climate variability, ocean acidification, internal ecosystem dynamics such as predator–prey relationships and disease, fishing, habitat degradation, contaminants and introductions of exotic species. Processes acting within human societies such as demographic changes, economic and market changes, technological innovations, legal and policy changes and shifting societal values can have indirect impacts on marine ecosystems (Perry *et al.* 2010*a*). Compared to the levels of potential maximum sustainable yield, 0·80 of global fisheries resources are estimated to be fully exploited, over-exploited, depleted or recovering (FAO 2009). Garcia & Rosenberg (2010) reported that 0·30 of fishing areas globally are still increasing, 0·30 are stagnant and 0·40 are experiencing decreasing production. The challenges of climate change are occurring in addition to, and in interaction with, these existing stresses (Perry *et al.* in press). Furthermore, many of the international policy goals for marine ecosystems, such as maximizing production to ensure food supply and conserving biological diversity (which are opposing goals; Brunner *et al.* 2008; Brander in press) are made more difficult with the uncertainties of climate changes.

This paper provides a brief update on the scientific literature published since 2007 of the potential impacts of climate change on marine ecosystems, focusing on marine wild capture fisheries and the implications for fisheries management to ensure the security of future marine food supplies. It also identifies significant knowledge gaps and proposes required future work.

MARINE ECOSYSTEMS, FISHERIES AND CLIMATE CHANGE

Over the last few years, several studies have discussed the potential impacts of climate change on marine ecosystems and marine wild capture fisheries. The IPCC Fourth Assessment Report (Parry *et al.* 2007) concluded that climate change was affecting marine ecosystems and the production of fish, and was likely to confound the impacts of natural variation on fishing activities and to complicate management efforts. These changes were occurring because of altered food web dynamics, decreased abundances of benthic habitat-forming species, shifting species distributions and a greater incidence of fish diseases (Parry *et al.* 2007; Hoegh-Guldberg & Bruno 2010). However, there are also likely to be significant regional variations to these global patterns (Table 1). For example, whereas increased vertical stability is likely to reduce nutrient inputs to large areas of the ocean, at higher latitudes this increased stability should also increase the residence times of plankton within the well-lit euphotic zone, thereby increasing their productivity.

Barange & Perry (2009) provided a detailed overview of scientific knowledge on the physical and ecological impacts of climate change on marine and inland capture fisheries and aquaculture based on the literature up to 2007. Warming of sea waters will have direct effects on the distributions and abundances of marine populations, with consequent changes in the production from fisheries. Distributions will shift poleward, and seasonal migrations are likely to occur earlier. Changes in fish abundances are expected, with populations at the polar extents of their ranges likely to increase in abundance, whereas those at their equatorial extents will decrease. Warmer temperatures will also increase growth rates although, in practice, these may be limited by the availability of suitable food. For example, changes in the species composition of marine zooplankton in the European North Sea have been suggested as an important contributing factor to declines in Atlantic cod (*Gadus morhua*) abundances in that area (Beaugrand *et al.* 2008). Changes in the timing of important ecological processes have been observed, for example changes in the plankton community structure in the European North Sea in which dinoflagellate blooms are peaking earlier as a result of warming whereas the larger diatom species show no consistent pattern of change.

Recent advances in modelling studies

Recently, there has been considerable progress in estimating the potential impacts of climate change on marine ecosystems, in particular with respect to modelling. Several approaches are now in use in order to forecast the effects of climate change on fish and fisheries (Hollowed *et al.* 2010). These include global static models, global dynamic models, dynamic downscaling approaches and statistical downscaling approaches. Hollowed *et al.* (2010) noted that statistical time-series analyses can describe previous patterns of variability but may be less useful for forward projections. Cheung *et al.* (2008, 2009, 2010) have made

Table 1. *Climate-related threats and potential consequences to marine ecosystems based on spatial scale. Modified from Brierley & Kingsford (2009)*

Coastal		
Salt marshes; mangroves; estuaries	Sea level rise	Habitat loss, altered productivity
	Rising temperature	Changing growth rates, increased desiccation at low tides
	Increasing storm frequency	Physical damage; salinity changes
Rocky substrates		
Intertidal	Sea-level rise	Altered zonation
	Rising temperatures	Increased desiccation at low tide
	Increasing storm frequency	Increased exposure
Kelp forests	Rising temperatures	Changes in growth and distribution
Coral reefs	Rising temperatures	Coral bleaching, distribution changes
	Increasing acidity	Reduced calcification
	Sea-level rise	Drowned reefs and reduced fishing
	Altered circulation	Disrupted larval transport and connectivity
Oceanic systems		
Pelagic	Rising temperatures	Changes in species distributions, timing of peak production, reduced fish production
	Rising atmospheric CO_2	Increased primary production
	Increasing acidity	Reduced calcification
	Altered circulation and upwelling	Changes in nutrient inputs and primary production
	Decreasing oxygen concentrations	Expanding anoxic zones
Polar	Rising temperatures	Sea ice loss, increased primary production, species distribution changes
	Ice reduction	Habitat loss, circulation changes, species composition changes
Deep sea	Rising temperatures	Increased stratification and decreased nutrient inputs, species distribution and composition shifts
	Increasing acidity	Reduced calcification
	Decreasing oxygen	Increasing anoxic zones

significant quantitative advances on projecting the impacts of climate change on distributions of fish populations, commercial fish and invertebrate biodiversity, and fisheries catch potential using a statistical bioclimatic envelope approach (based on the ranges of temperature and other physical conditions within which species occur combined with trophic energetics and allometric scaling of metabolism; Cheung *et al.* 2008). Using high (IPCC A1B), medium (IPCC B1) and low (stable, 2000) emissions scenarios, they projected range shifts of 45–60 km per decade, with 0·80 of species moving towards the poles. By 2050, average shifts were 600 km for pelagic species and 220 km for demersal (bottom fish) species (Cheung *et al.* 2009). The global average species extinction rate was 0·03, with the Arctic and Southern Ocean experiencing the highest (5·5 and 2 times the global average, respectively) and the equatorial region the lowest (0·5 times the global average). Cheung *et al.* (2009) noted this is lower than the predicted extinction rates of 0·15–0·37 for terrestrial systems, concluding that climate change is likely to result in numerous local extinctions of fish populations in sub-polar, tropical and semi-enclosed marine regions, and that species invasion will be most intense in polar regions. When projecting the implications of these results for the potential fisheries catch in ten-year averages from 2005 to 2055, Cheung *et al.* (2010) found little overall change in global maximum catch potential (± 1%) but considerable change in the spatial distribution of this potential catch. Under the high-emissions scenario, catch potential in higher-latitude regions increased on average by 30–70% whereas it decreased by up to 40% in the tropics (e.g. Fig. 1). The Indo-Pacific was projected to be most highly impacted, with up to a 50% decline in ten-year average maximum fisheries catch potential by 2055. Other regions with projected large losses were Indonesia, the continental United States, Chile and China. The largest increases in catch potential were projected to occur off Norway, Greenland, Alaska and eastern Russia. Under the low-emissions scenario, however, the pattern of changes was less clear, being about 0·60 of the results from the high-emissions scenario.

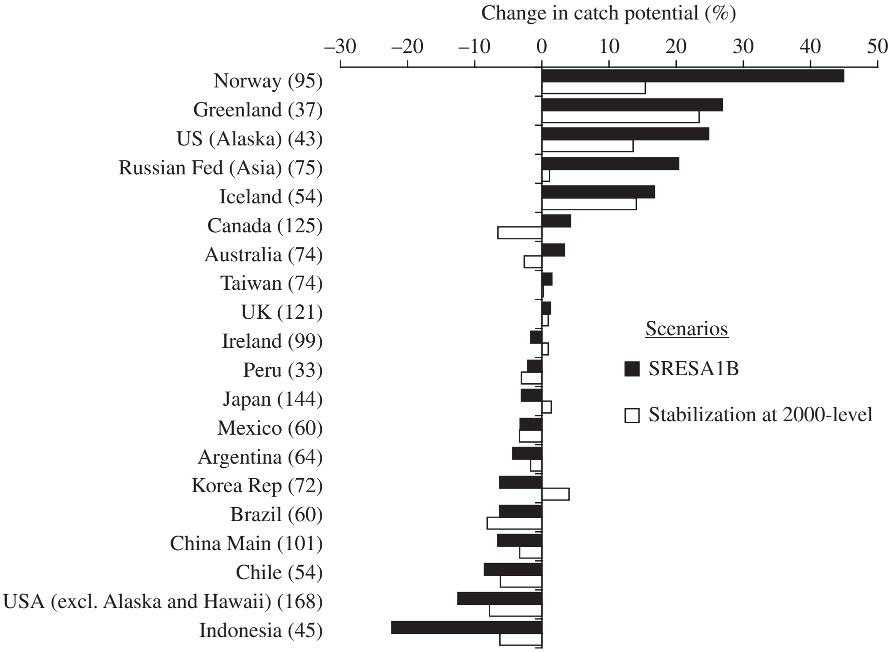

Fig. 1. Model-based projected changes in ten-year averaged maximum catch potential from 2005 to 2055 by the 20 exclusive economic zone regions with the highest catch in the 2000s. The numbers in parentheses represent the numbers of exploited species included in the analysis. Reprinted from Cheung *et al.* (2010) with permission of Wiley-Blackwell Publishing.

Models of climate change impacts to ocean primary production have had variable results, with some projecting slight decreases in global average production (e.g. Cox *et al.* 2000) and others slight increases (e.g. 0·7–8·1%; Sarmiento *et al.* 2004), although with large spatial variability. For the western North Pacific Ocean, results from a 3D primary production model using a more complex food web and full coupling of the biology and the physics project a slight decrease in annual average chlorophyll biomass due to increased vertical stratification, but, more importantly for fish, a shift towards earlier timing and a change in the dominant phytoplankton species (from large diatoms to smaller forms) of the spring bloom (Hashioka & Yamanaka 2007).

Simulation models have now progressed to the stage such that they can be coupled directly with atmospheric models of climate change to project impacts on fish populations. Brown *et al.* (2010) used the common marine food web model Ecopath with Ecosim (EwE) linked with an ocean general circulation model (CSIRO Mark 3.5 coupled atmosphere–ocean general circulation model) and a nutrient–phytoplankton–zooplankton lower trophic level model to evaluate the impacts of climate change on primary production and fisheries around Australia. Under a standard climate change scenario (IPCC A2), they projected increases in primary production, increases in fisheries catch and value and increases in the biomass of threatened marine species such as turtles and sharks. Brown *et al.* (2010) also projected little change in species composition using this model. However, model formulations that included more complex predator and competition interactions reversed the expected responses from some species resulting in declines in catches and in abundances of some threatened species even with background increases in primary production.

The United Kingdom QUEST_FISH program (Barange *et al.* in press *a*) is developing coupled physical to fish to people models to project the implications of global change on marine ecosystems. They couple global circulation models to high-resolution physical–biological models of 20 large marine ecosystems, and then estimate size-based fish production from primary production and temperature using macro-ecological theory (e.g. Jennings *et al.* 2008). This approach permits the assessment of future climate changes combined with non-climate influences such as global fish commodity markets. Initial results are indicating that the sustainability of the global fishmeal market and its supporting fisheries depends as much (or more) on how society responds to climate impacts as on the strength of the climate effect (Merino *et al.* 2010*a*).

Table 2. *Predicted impacts of climate change on populations and communities of coral reef systems, and the level of uncertainty associated with these predictions (high: predications are well supported by observations; moderate: predictions have some empirical support but are not conclusive; low: predictions are speculative and lack good supporting evidence). Modified from Munday* et al. *(2008)*

Impact	Drivers	Certainty
Reduction in local diversity and species composition changes	Loss of coral cover; erosion of reef complexity	High
Geographic range shifts	Increased ocean temperatures	High
Reduced pelagic duration	Increased ocean temperatures	High
Life history modifications	Increased ocean temperatures	Moderate–High
Shift of breeding season	Increased ocean temperatures	Moderate
Reproductive decline	Increased ocean temperatures	Moderate
Increased recruitment variability	Increased ocean temperatures and/or changes in productivity and circulation	Moderate
Reduced productivity	Increased ocean temperatures and/or changes in productivity and circulation	Low
Reduced connectivity	Increased ocean temperatures and habitat loss	Low
Reduced performance	Ocean acidification	Low

Recent advances in observational studies

Observational evidence continues to accumulate that suggests the impacts of climate change are occuring now and are not just theoretical future concerns, although distinguishing these impacts from climate variability and the effects of direct human stresses such as fishing can be difficult (e.g. Rouyer *et al.* 2008; Last *et al.* in press). Many of these observed changes are helping in verifying the projections of climate change models. Some of the most evident climate-related changes are occurring in polar regions. Sea ice is particularly sensitive to climate change, with predictions that the Arctic Ocean may be ice free in summer by 2030 (Brierley & Kingsford 2009), yet sea ice is the single most important physical feature structuring the marine ecosystems in these regions. Schofield *et al.* (2010) described how rapid environmental change in the West Antarctic Peninsula region over the past few decades has coincided with shifts in the marine food web from plankton to apex predators, significantly altering marine ecosystem structure and function. Physical changes include increases in mid-winter surface air temperatures of 6 °C (five times faster than the global average) over the past 50 years, 0·87 of the glaciers in this region are in retreat, and the loss of perennial sea ice. Biological changes include a 12% decrease in the magnitude of phytoplankton blooms over the past 30 years, a net decrease in primary production and changes in species composition towards smaller-celled organisms. As a result, the keystone species Antarctic krill (*Euphausia superba*) is being replaced in this region by soft-bodied tunicates as the important zooplankton grazers, which has caused changes in top predators. Abundances of the ice-dependent Adélie penguin (*Pygoscelis adeliae*) have declined by 90%, whereas more northerly ice-intolerant penguin species have invaded the area and are increasing in abundance. These changes can be clearly related to climate change since fishing does not play a role in this particular regional ecosystem.

Climate change is also clearly impacting on coral reef systems. Mass coral bleaching and resulting mortalities due to increasing temperatures are already reducing the density and diversity of coral reef fishes and other organisms (Hoegh-Guldberg *et al.* 2007). Coral bleaching occurs as temperatures exceed 1 °C above the long-term summer maximum for extended periods (Hoegh-Guldberg *et al.* 2009). Munday *et al.* (2008) suggested that such bleaching will have rapid impacts on the diversity and species composition of coral reef fish communities. At present, however, there is little evidence that coral bleaching had has much impact on coral reef fisheries, perhaps because these fisheries do not target the smaller and specialized coral-dependent species that are more vulnerable to environmental change (Munday *et al.* 2008; Pratchett *et al.* 2008). Climate change is likely to have additional impacts on the trophic linkages, recruitment dynamics and population connectivity of coral reef fishes (Munday *et al.* 2008; Table 2).

For the North-eastern Atlantic, Rijnsdorp *et al.* (2009) concluded that global warming is principally responsible for large-scale shifts in the distribution and abundances of fish species in this region. Changes in the distributions of demersal species have generally been smaller than changes in the distributions of pelagic species. Rijnsdorp *et al.* (2009) suggested that climate-related changes in recruitment success, in particular increased survival of the early life stages, and improvements to the nursery habitats for juvenile fishes, were key factors in these changes. A deepening

Table 3. *Summary of observed and future predicted changes to marine fisheries in the waters around the British Isles (from Pinnegar* et al. *2010)*

What is happening now

- Locations for high catches of traditional bottom fishes such as cod, haddock, plaice and sole have shifted over the past 80–90 years. Climate change is implicated as a factor, along with fishing and habitat modifications.
- Shifting distributions of fish are impacting the effectiveness of some fishery closed areas and the allocation of fish resources among neighbouring countries.
- New fisheries have developed for warmer-water species such as seabass, red mullet, anchovy and squid as these species have increased in abundance in UK waters.

What could happen in the future

- With climate change, UK waters are expected to have slightly greater fishery yields (+1–2% compared to present) by 2050, although regional variations are likely.
- Models suggest that cod stocks in the North Sea may decline, whereas those in the Celtic and Irish Seas may disappear, by 2100.
- Early estimates of the socio-economic impacts of climate change on UK fisheries suggests little overall effect (because fishing is a small proportion of the total UK economy), although effects in specific areas such as Scotland and Southwest England (where fishing is more important) may be significant.
- Ocean acidification may be a significant threat to UK shellfish industries.

of the distribution of the bottom fish community in the European North Sea as bottom temperatures warmed has also been observed (Dulvy *et al.* 2008), indicating that distribution shifts will occur in three dimensions. Hiddink & Ter Hofstede (2008) examined changes in the diversity of fish species in the North Sea over the past 22 years and found that increases in the richness of species were related to increasing water temperatures, and that much of this increase was due to smaller-sized species mostly of southerly origin. Pinnegar *et al.* (2010) reviewed the potential impacts of climate change to marine fisheries around the British Isles (Table 3) and concluded that fishing locations for traditional commercial species are changing, which is affecting the effectiveness of location-based management measures. In addition, new fisheries are being developed for warm-water species which now occur regularly in UK waters. Potential future changes not only include slightly higher (1–2%) fishery yields by 2050, but also the disappearance of some traditional fishery stocks by the end of the century.

A PICES Scientific Report edited by Beamish (2008) examined whether climate trends affect the production of species in the major fisheries of the North Pacific and found that the specific impacts depended on the life history of each species. It concluded that, although the mechanisms linking climate trends to fisheries production in this region are still poorly understood, the amount of prey available to first feeding young was likely to be a common constraint. As the Bering Sea has warmed and sea ice has retreated, there have been shifts in species distributions as well as overall increases in total biomass, species richness and average trophic level (Mueter & Litzow 2008). However, fish species did not all shift distributions at the same rates. This caused traditional fish communities to be pulled apart and to be reorganized into new communities (Mueter & Litzow 2008), potentially affecting fisheries and ecosystem productivity.

There is observational evidence that the production of plankton, which forms the base of marine food webs leading to commercial fisheries, has been changing globally. Boyce *et al.* (2010), using data on ocean transparency and chlorophyll biomass since 1899, reported declines of phytoplankton biomass in eight out of ten ocean regions, at an estimated rate of about 1% of the global median per year. The largest rates of decline were in the South and Equatorial Atlantic and in the Southern Ocean. Increasing biomass was observed in the northern and southern Indian Ocean. Boyce *et al.* (2010) concluded that these long-term declining trends were related to increasing sea surface temperatures. Using a 9-year time series of remotely sensed ocean colour data, Polovina *et al.* (2008) found that the world's least productive waters (mostly associated with open ocean gyres) have expanded by 15% from 1998 to 2006, consistent with increasing sea temperatures but at rates greater than projected by model studies. O'Connor *et al.* (2009) tested experimentally the effects of warmer temperatures on a simplified marine food web (consisting of phytoplankton and zooplankton). As temperatures were increased, it was found that grazing by zooplankton increased at faster rates than increases in the primary productivity of the phytoplankton, with the net result that standing phytoplankton biomass was reduced. The end result was a decline of the overall biomass in their experimental system. They concluded that even small changes in water temperature can cause significant shifts in marine food web structure and productivity. In addition, Morán *et al.* (2010) found that warmer ocean temperatures lead to smaller phytoplankton cells, further altering the structure of marine ecosystems. Richardson (2008) suggested that global warming may have greater impacts on marine than terrestrial ecosystems because temperature can have important influences on the abundance, size composition, diversity and trophic efficiency of the zooplankton. Impacts of global warming on zooplankton have been observed as poleward shifts in distributions and earlier timing of life history events such as spawning, leading to changes in abundance and community structure. It was concluded that range shifts of zooplankton are among the fastest and largest of any marine or terrestrial group.

The potential impact of ocean acidification on marine systems, both on its own and in combination with other stressors such as warming temperatures, is a rapidly progressing research topic (Doney *et al.* 2009). Huge unknowns remain, largely due to the lack of basic knowledge of biological and chemical responses of marine organisms to low pH. Organisms with calcium carbonate shells or skeletons will certainly be negatively impacted. Cooley & Doney (2009) provided a study of the potential impacts of ocean acidification on fisheries, in particular those based on molluscs, in the United States and suggested that a reduction of 0·1–0·2 pH units over the next 50 years would result in harvest declines of 6–25% in mollusc fisheries, for an estimated loss of several billion US dollars. It was concluded that damage to marine habitats and resources due to ocean acidification would cause substantial declines in fisheries revenues and jobs, and have other indirect economic costs related to ecosystem impacts on fish species which are predators of these invertebrate species. In the UK, Pinnegar *et al.* (2010) noted that four of the ten most valuable marine fisheries are those for calcifying invertebrates (*Nephrops*, scallops, crabs and lobsters), which contribute 0·44 of the total value from fisheries. Evidently, there is the potential for significant economic harm to fisheries and marine food security due to ocean acidification.

MANAGEMENT AND SOCIETAL IMPLICATIONS

Models are beginning to be developed which project the impacts of global warming from marine ecosystems to fisheries production and their consequences for human societies. These are, however, ‘early days’ for these approaches, with many uncertainties over how information is transformed within human communities and how human behaviour responds to changing pressures (Hollowed *et al.* 2010). Allison *et al.* (2009) assessed the vulnerability of national economies to the potential impacts of global warming on fisheries using an approach in which vulnerability was based on the exposure to the physical effects of global warming, the sensitivity (dependence) of the national economy on fisheries and the extent to which the nation had the adaptive capacity to mitigate the potential impacts. It was observed that many of the most vulnerable countries were also among the least developed and with a high dependence on fish in local diets. These included four countries in West and Central Africa, Peru and Columbia in north-western South America, and four countries in tropical Asia. It is noteworthy that most of these countries are in the equatorial region, a region which the modelling studies of Cheung *et al.* (2009, 2010) predicted will be impacted significantly and negatively by the effects of global warming on fish diversity and fisheries catch potential. Merino *et al.* (2010*a*, 2010*b*) modelled the marine production–human consumption system of small pelagic fisheries and fishmeal markets under climate variability and change. It was concluded that regional fish stocks were able to recover from climate fluctuations unless these occurred at the same time as increasing fishing pressure due to expansions of international markets. When the model system was forced with a climate change scenario, the results suggested that the sustainability of small pelagic fish populations depended more on how society responded to the climate impacts than on the magnitude of the climate changes (Barange *et al.* in press *b*).

A number of responses and adaptation options are available for human societies to respond to the impacts of climate change on marine ecosystems and fisheries production (Daw *et al.* 2009; Badjeck *et al.* 2010). These include changing fisheries operations, switching target species, alternative fishing occupations, short-term bridging strategies and ultimately the abandonment of fishing. McIlgorm *et al.* (2010) noted that fishery governance will need to deal with uncertainty in both the ecological system and in the human social system. It was suggested that adaptive governance systems will need to include more flexible fishery management approaches (which are able to respond more rapidly to changing conditions), schemes for adjusting fishing capacity to new situations, catch limitations and development of alternative livelihoods for fishers. Grafton (2010) explored the problem of when, and how, marine capture fisheries should adapt to climate changes and proposed that a risk and vulnerability assessment and management decision-making framework be developed prior to the actual need to adapt. Such a framework would include an assessment of current and potential future vulnerabilities, engage stakeholders and simulate a variety of response options to different future conditions. Without such a decision framework in place before major changes occur, Grafton (2010) noted that current actions risk increasing vulnerabilities or being inadequate to the challenges of climate change and recognized two complementary and interacting strategies: developing measures that increase the resilience and adaptive capacities of marine ecological and human social systems before significant impacts occur, and adaptive management actions to quickly respond to unexpected changes when they are observed to occur. The economics of adapting fisheries to climate change has been considered by a number of recent activities (e.g. Hannesson *et al.* 2006; Hannesson 2007), most recently by the Organisation for Economic Cooperation and Development at a workshop in June 2010 (Workshop on the Economics of Adapting Fisheries to Climate Change; www.oecd.org). A report on the potential costs of adapting to a 2 °C warmer world by 2050, prepared for the World Bank (World Bank 2009), estimated global losses in landed catch value of US$10–31 billion by 2050, with countries in East Asia and the Pacific being the most severely impacted. Losses for developing countries globally ranged from US$7 to US$19 billion, whereas losses for developed countries ranged from US$2 to US$8 billion. Change in Europe was estimated to range from a loss of US$1 billion to a slight gain.

Specific examples of management strategies to address issues of climate change and fisheries are beginning to appear in the scientific literature. Higgason & Brown (2009) presented a framework that includes workshops with stakeholders to discuss the potential local impacts of climate change, research plans to address key uncertainties and an approach to adaptively manage changes as they occur (Fig. 2); the application of this framework to the Gulf of the Farallones National Marine Sanctuary in California was presented. Stram & Evans (2009) described how the United States North Pacific Fisheries Management Council is developing risk-averse management approaches in advance of increasing uncertainty due to climate change. Pro-active measures taken by the council have included closing US arctic waters to all commercial fishing pending further research, assessing whether changes in fish distributions might allow for unregulated fishing in ‘new’ locations, and adopting measures to control the expansion of the trawl fishing fleet into newly ice-free areas. In addition, adaptive management measures are being developed for those species for which the links between climate variables and fish distributions have been identified.

KNOWLEDGE GAPS AND NEXT STEPS

The impact of climate change on marine ecosystems, fisheries and food security is a rapidly progressing field of inquiry, and great progress has been made over the past few years, in particular with respect to modelling. An international symposium on The Effects of Climate Change on Fish and Fisheries was held in Sendai, Japan, in April 2010 to discuss recent advances and current work on this topic. A preliminary summary of the key outcomes from the meeting is provided by Hollowed *et al.* (2010; Table 4). Two key outcomes from this symposium are highlighted: the need for long-term and co-ordinated ocean monitoring to observe the impacts of climate changes, and further improvements to modelling capabilities.

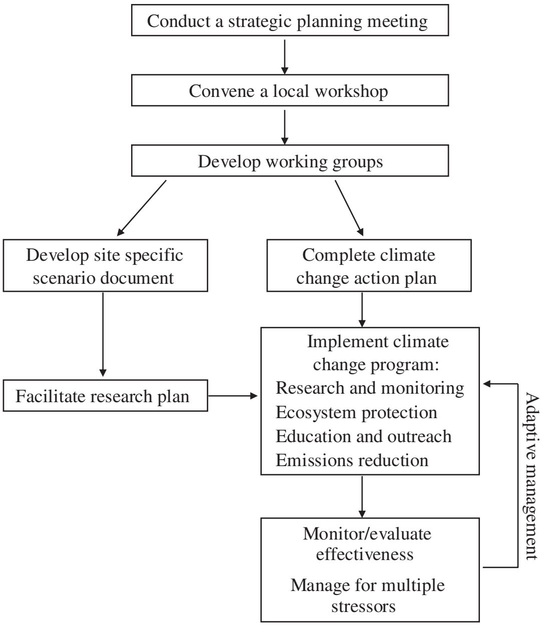

Fig. 2. Process to manage the effects of climate change on a local ecosystem, as developed for the Gulf of the Farallones National Marine Sanctuary, California. Redrawn from Higgason & Brown (2009), by permission of Oxford University Press.

A co-ordinated approach to observational studies is needed to separate the impacts of climate change from those of climate variability. With the latter, there is an expectation that conditions will eventually return to ‘normal’, whereas with the former, ‘normal’ may have to be redefined. The response strategies of human communities may be very different between these two situations (Perry *et al.* 2010*a*). A strategy for an observational system to detect climate change impacts in the West Antarctic Peninsula region would involve a nested multi-platform approach, including deployment of oceanographic sensors on marine animals (Schofield *et al.* 2010). The goals of such a system would be to quantify the atmosphere and ocean heat budgets, to understand how the deep ocean interacts with the Antarctic shelf region, and how these affect the regional climate, ice dynamics and marine ecology (Schofield *et al.* 2010). Beaugrand *et al.* (2008) pointed out that some regions of the ocean may be more important than others and have greater leverage on the impacts of climate change and identified a critical thermal boundary in the North Atlantic (between 9 and 10 °C which coincides with the transition zone between two large marine biomes), at which small

Table 4. *Summary of preliminary key outcomes from the Symposium on Effects of Climate Change on Fish and Fisheries, held 26–29 April 2010 in Sendai, Japan. Modified after Hollowed* et al. *(2010)*

1 Need for long-term ocean monitoring and on-going observation programmes.
2 Networks of shelf-seas ecosystem models are now available to examine structural uncertainties within these models.
3 Uncertainties of global ocean models relating to parameter uncertainty, structural uncertainty and scenario uncertainty are being investigated.
4 Five approaches are being used in order to predict the effects of climate change on fish and fisheries: (a) conceptual predictions; (b) laboratory studies; (c) statistical downscaling from global to regional scales; (d) dynamic downscaling to regional scales; and (e) whole earth system models.
5 Field and experimental studies are needed to evaluate species environmental tolerances and capacities to adapt, and for tracking species responses to long-term ecosystem changes as they occur.
6 Models coupling marine social and economic responses with ecosystem changes are needed to evaluate management strategies, but few exist.
7 Issues of food security and conservation are contradictory and new approaches to satisfy growing demands for marine resources may be needed.
8 Communication among scientists and stakeholders are necessary to develop meaningful scenarios of human responses to climate change impacts on marine ecosystems.

changes in temperature can produce large ecosystem shifts across several trophic levels, including Atlantic cod (*Gadus morhua*). Such locations are obvious sites for enhanced monitoring, and other high-leverage locations need to be identified. These global observational systems then need to be connected to a network with an efficient data distribution system so that comparative analyses can be done to separate climate change from variability (e.g. IOC 2009).

Although modelling the impacts of climate change on marine ecosystems and fisheries has made significant advances, several important challenges remain. Brander (2009) suggested the application of five criteria to judge the quality of predictions of climate change impacts: (1) do they provide additional information beyond that derived from first principles; (2) are their predictions testable; (3) are they credible and provide confidence levels and uncertainties relating to confounding factors; (4) are they capable of predicting past changes; and (5) are they based on knowledge of physical, physiological and ecological structures, processes and limits? For example, the bioclimatic envelope approach to climate impacts projections has been criticized as being too simple, and that physiological responses to stress in nature are more complex. Instead, a systems-based approach is recommended to integrate the effects of environmental and physiological variability on the ecological responses of marine organisms (Helmuth 2009). As noted by Brown *et al.* (2010), including more realistic species interactions such as predation and competition can significantly alter the projections of ecosystem models. Feedback effects, such as how changes in demographic characteristics, mortality rates and allele frequencies affect growth rates, organism size and resilience of the entire population to climate change (Brierley & Kingsford 2009), and the impacts of multiple stressors on marine systems have generally not yet been included in climate impacts models. Substantial research is needed on the direct and synergistic impacts of ocean acidification on fisheries production. In addition, most of these are not undisturbed populations and systems, and many have been fished for a long time. The activity of fishing, in particular industrial-scale fishing over the past 60 years, changes the characteristics of marine populations, communities and ecosystems (Planque *et al.* 2010) so that they no longer have the same adaptive capacities to climate variability and change and may respond more rapidly than in the past (Perry *et al.* 2010*b*). Genner *et al.* (2010) examined the long-term (1911–2007) variability of a bottom fish assemblage in the western English Channel, a region experiencing both commercial fisheries and wide (2 °C) interannual temperature changes; it was found that abundances of smaller-sized species followed the changes in temperature, suggesting they would likely respond quickly to climate changes. In contrast, the larger-sized species declined in both abundance and mean body size, as expected with sustained size-based overharvesting. Lindegren *et al.* (2010) provided an example of the type of regional-scale modelling that is needed to assess the combined impacts of climate change and fishing on marine food webs, and the consequences for management actions. The results obtained for Atlantic cod in the Baltic Sea show how exploitation will need to be adjusted to achieve sustainable management with different climate change scenarios.

Urgent problems that need to be addressed regarding the impacts of climate change to marine wild capture fisheries include reducing the (presently large) uncertainties in climate change impacts models, understanding the synergistic effects of multiple stressors beyond changes in temperature and fishing, and inclusion of humans with improved realism as both drivers and recipients of changes in marine ecosystems. Stock *et al.* (in press) reviewed the application of IPCC-type climate models to living marine resources, and concluded that uncertainties in these models, relating to coarse resolution and complexities of marine ecosystem responses, can limit the robustness and precision of the projections from such models; analyses of multi-model ensembles, bias corrections and statistical and dynamic downscaling to smaller spatial scales to resolve some of these limitations were recommended. Regional models are better able to incorporate smaller-scale features that control primary production, and can also include other characteristics such as changes in phenology and species (size) composition of organisms at the base of the food web. Other stressors may also become apparent at regional scales, such as low oxygen (Weston *et al.* (2008) provide an example for the North Sea), and these need to be included along with changes in temperature, salinity, pH and fishing. Assessments of the socio-economic impacts of climate change on marine capture fisheries should develop the vulnerability approach adopted by the IPCC (e.g. Allison *et al.* 2009; Johnson & Welch 2010). This approach considers vulnerability as a function of exposure, sensitivity and adaptive capacity of the socio-economic system to climate changes. Such an approach also needs to be applied at regional and local spatial scales to get at local motivations and responses to change (e.g. Brookfield *et al.* 2005). The ultimate problem is with the limits of predictability itself. If marine systems do develop 'no-analogue' communities as a result of shifting species distributions at different rates and other impacts, then understanding of, and the inferences from, previous conditions may not apply (Williams & Jackson 2007).

CONCLUSIONS

It is highly probable that the impacts of climate change will be significant for marine ecosystems, the production of food from these systems and human food security. Marine ecosystems are already under stress and food production from wild capture fisheries may have peaked. The impacts of climate change will be in addition to these existing stressors, with the potential for significant negative effects in particular to developing nations in tropical regions (declining fish biodiversity, shifts of species distributions polewards, declining fisheries catch potentials, national economies vulnerable to fluctuations in fisheries supplies). Ironically, it appears to be the more northerly (and developed) nations which are likely to benefit from climate change, at least initially. Long-term consequences of climate change to capture fisheries production are highly uncertain and depend on what happens to marine primary production, the projections for which at present are highly variable. The results of such uncertainty will be increasing surprises and unexpected events, beyond the prediction capabilities of current models. Such events require a well-tuned observational system so that they can be recognized early, and an adaptive governance system which is able to respond quickly. These situations support calls for fully integrating people into the models, observational systems and governance frameworks addressing the impacts of climate change on marine ecosystems and food security, i.e. for embracing a coupled marine social–ecological systems approach (Perry *et al.* in press). Such a system would be well positioned to develop resilience and build adaptive capacity in both the marine ecological and human social systems to address the uncertainties of climate change and to sustain the security of marine food supplies.

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