BACKGROUND STUDY PAPER NO. 55

May 2011

منظمة الأغذية والزراعة للأمم المتحدة

联合国粮食及农业组织

Food and Agriculture Organization of the United Nations

Organisation des Nations Unies pour l'alimentation et l'agriculture

Продовольственная и сельскохозяйственная организация Объединенных Наций

Organización de las Naciones Unidas para la Agricultura y la Alimentación

COMMISSION ON GENETIC RESOURCES FOR FOOD AND AGRICULTURE

CLIMATE CHANGE AND AQUATIC GENETIC RESOURCES FOR FOOD AND AGRICULTURE: STATE OF KNOWLEDGE, RISKS AND OPPORTUNITIES

by

Roger Pullin and Patrick White

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I. ABOUT THIS PUBLICATION

At its Twelfth Regular Session in 2009, the Commission on Genetic Resources for Food and Agriculture recognized the need to address climate change in its Multi-Year Programme of Work. The Commission requested FAO to prepare scoping studies on climate change and genetic resources for food and agriculture for consideration at its next session.

This Background Study Paper is the scoping study for the aquatic genetic resources that underpin and provide for the future of aquaculture, culture-based and capture fisheries. It gives overviews of available knowledge regarding present and expected climate change impacts on aquatic environments and their genetic resources, as well as assessments of the ongoing and potential roles of aquatic genetic resources for adaptation to and mitigation of climate change, with recommendations for further work, partnerships and priority actions to facilitate the Commission's future work.

This paper covers all aquatic genetic resources for aquaculture, culture-based fisheries and capture fisheries, including those for the production of aquatic plants (microalgae, macroalgae and freshwater macrophytes; for human food and for industrial purposes) and fish (finfish and aquatic invertebrates; for human food and for industrial and ornamental purposes). It emphasizes the current roles and potentials of aquatic genetic resources for adaptation to and mitigation of climate change. Aquatic ecosystems are the world's largest carbon sinks.

This paper complements other Commission publications on aquatic genetic resources, climate change and biotechnology, especially Background Study Papers 34 and 37 (CGRFA, 2007a and b), 41, 45 and 49 (CGFRA, 2009 a,b and c) and other related FAO publications including, *inter alia*: Sharp (2003); FAO (2003a; 2005a; 2005b; 2007a; 2007b; 2008a; 2008b; 2008c; 2010a; 2010b; 2010c; and 2011); Ruane and Sonnino (2006); Bartley *et al*. (2007a and b); Bondad-Reantaso *et al*. (2008); and Soto *et al*., (2008). A major FAO review on the implications of climate change for fisheries and aquaculture (Cochrane *et al*., 2009) and a summary of climate change implications for fisheries and aquaculture, published in the latest review of the state of world fisheries and aquaculture (FAO, 2010a), illustrate further many of the points made here.

Aquaculture and fisheries currently provide about 50 percent each of the world's supply of about 100 million tonnes of food fish and fish products, worth about US$78.8 billion and employing over 135 million people. Aquaculture is the source of 46 percent of the world's supply of food fish (FAO 2010a). Food fish and fish products provide essential nutrition to 3 billion people and supply at least 50 percent of dietary animal protein and minerals to 400 million people in the least developed countries. Fish are globally important as providers of micronutrients and of the lipids that are essential for human brain development and function. Aquaculture and capture fisheries for ornamental fish provide important livelihood opportunities for the rural and urban poor, mainly in tropical developing countries. Seaweed farming produces over 15 million tonnes of aquatic products annually, worth over US$7 billion. Farmed and wild-harvested fish (finfish and aquatic invertebrates) and aquatic plants (seaweeds and freshwater macrophytes) are vital contributors to world food security, especially for provision of animal protein, micronutrients and essential lipids, as well as providing livelihoods for the producers, processors and sellers of food, ornamental, sport and bait fish.

Aquaculture and fisheries depend upon goods and services from a wide range of ecosystems. The Commission is pursuing internalization of the ecosystem approach for biodiversity management in agriculture, forestry and fisheries, in order to review contributions of biodiversity to achievement of the Millennium Development Goals and prepare *The State of the World's Biodiversity for Food and Agriculture.* Aquatic genetic resources are part of biodiversity, comprising currently and potentially farmed and fished aquatic species and their supportive ecosystems. Together with the Background Study Papers prepared in parallel for plant, animal, forest, microorganism and invertebrate genetic resources, this Background Study Paper can contribute to cross-sectoral and ecosystem-based approaches for realizing the potentials of genetic resources for food and agriculture to meet the challenges of climate change.

Climate change interacts with many anthropogenic factors to shift the biodiversity, physical and productivity baselines of food and agriculture ecosystems. In the present context, the most important of those factors are degradation and losses of aquatic habitats and overharvesting of aquatic organisms. From the seventeenth century to the present, there have caused massive changes to aquatic ecosystems and their biota (Jackson, 2001). Climate change will exacerbate the consequent major shifts in the locations and productivity of aquaculture and fisheries.

The authors wish to thank the staff of the FAO Fisheries Library for their invaluable help in searching and obtaining material for the preparation of this publication.

II. EXECUTIVE SUMMARY

2.1 Scope: the importance of aquatic genetic resources in general and in the context of climate change

This Background Study Paper follows the climate change terminology and definitions of the UN Framework Convention on Climate Change, but considers mitigation from the broader perspective of improving aquatic ecosystems, such as watersheds and coastal zones, and reappraising some cross-sectoral, integrated production systems, on the assumption that these interventions will definitely, or possibly, reduce greenhouse gas emissions.

Aquatic genetic resources underpin all current world production of aquatic plants (micro- and macroalgae and freshwater macrophytes) and aquatic animals (finfish and aquatic invertebrates; termed collectively as fish) and provide for their future production in the face of ecological change, including climate change (short-term climate fluctuations and long-term trends such as sea level rise, warming, ocean acidification and reduced or increased availability of freshwater).

The world’s supply of aquatic produce and its related benefits (food security, nutrition and livelihoods) derive in approximately equal measure from the farming of progressively domesticated aquatic organisms (aquaculture) and the hunting of aquatic wildlife (capture fisheries), with further contributions from so-called culture-based fisheries, akin to fish ranching. Inland and coastal fisheries and aquaculture share, and derive ecosystem goods and services from, the same ecosystems that provide for – and are being changed by – the terrestrial food and agriculture sectors.

In the context of climate change, aquatic ecosystems and their biota account for the largest carbon and nitrogen fluxes on the planet and act as its largest carbon sinks. This is particularly well summarized as a diagram of the terrestrial and aquatic components of the world’s carbon cycle by FAO (2010a). In addition to the continuous rain of calcifying microorganisms (such as foraminiferans and coccolithophores) to the ocean floor, the calcium carbonate in the skeletal structures of marine invertebrates, particularly echinoderms, and the carbonates precipitated in marine fish intestines make huge contributions to global carbon storage.

Ocean acidification merits particular emphasis because it could limit the distribution, productivity, health and survival of marine organisms that build calcareous skeletal structures: including not only farmed and fished species and many of their food organisms, but also the species upon which entire ecosystems and biological communities depend (such as reef-building corals) and the global populations of marine microorganisms, invertebrates and finfish that contribute their calcium carbonate to oceanic carbon sinks.

The main taxa that are impacted by, and that have roles in adaptation to and mitigation of, climate change comprise the following: microalgae and other aquatic microorganisms; macroalgae and sea grasses; freshwater macrophytes; mangroves; crustaceans; molluscs; other aquatic invertebrates; finfish; and Marine Genetic Resources in Areas Beyond National Jurisdiction.

2.2 Climate change challenges for aquatic organisms, ecosystems, aquaculture and fisheries

Most fish obtain oxygen from their surrounding water and are unable to regulate their body temperatures. Dissolved oxygen varies markedly with water temperature and quality. Water temperature and water quality limit the breathing of fish and determine the rates of their body functions and behaviour, including: appetite, growth, reproduction and immune response. Climate change therefore poses challenges for the health and survival of aquatic organisms, for the functioning of aquatic ecosystems and for the productivity and sustainability of aquaculture and fisheries.

More widely fluctuating water temperatures, together with changed precipitation patterns, sea-level rise, changed wind patterns and oceanic currents, and changes in the location, frequency and severity of storms, will make some aquaculture and fisheries operations more risky and sometimes impossible in affected areas, while opening up some new possibilities in others. Some fish that live in cold freshwaters, and cannot move away as these are warmed, often with reduced water space, will be eliminated, mainly by lack of oxygen and intolerable temperatures. Conversely, many marine fish typical of warm waters are already increasing their ranges poleward.

This paper reviews these challenges for freshwaters, brackishwaters and marine waters, with special mention of vulnerable aquatic ecosystems: coral reefs; sea grass beds; mangroves and other coastal forests; agricultural wetlands; and flooded forests. Specific challenges to aquaculture (seed supply, ponds, cages and pens, rafts and ropes, tidal flat culture, integrated farming systems, and integrated multitrophic level systems) and to fisheries (culture-based, inland, coastal and open sea, marine pelagic, marine demersal, fisheries for highly migratory fish, and deep-sea fisheries) are also reviewed. Regional implications are summarized for Africa, Asia, Europe, Latin America/Caribbean, North America and Oceania.

In broad terms, aquaculture and fisheries will have to place increased reliance on species, stocks and strains that can live and perform adequately in a wide range of environments, with less predictable, changing and changed climates. For ecological and economic reasons, this will favour the use of fish that feed at lower trophic levels (herbivores and detritivores) and that have relatively short production cycles. In warmer waters of variable quality, air-breathing species will have increased potential, especially in aquaculture.

2.3 Aquatic genetic resources and adaptation to climate change

Most adaptation by aquatic organisms, wild and farmed, to the stressors of climate change is being accomplished through natural selection to their changed and more changeable environments. The most important traits, which are highly interactive, include survival; fecundity; tolerance to lower water quality (in terms of available oxygen, acidification, increased or reduced salinity, increased turbidity and siltation, and increased levels of pollutants), resistance to diseases, parasites and toxic blooms; as well as, particularly for aquaculture, the commercial traits of fast growth and good feed conversion.

For aquaculture and culture-based fisheries, a wide range of biotechnologies can be applied to increase the fitness of farmed and fished populations in changing and changeable climates and environments: selective breeding (including marker-assisted selection); cross breeding and hybridization; chromosome set manipulations and monosex populations; and genomics, gene discovery and transgenesis. The potentials of all of these depend upon conservation (*in situ*, in open waters and on farms; and *ex situ*, *in vitro* as cryopreserved genetic material and *in vivo* as aquarium and other captive populations) of the widest possible genetic diversity for targeted traits, in species of current and potential future importance.

2.4 Aquatic genetic resources and mitigation of climate change

Responsible aquaculture and fisheries, in concert with agriculture, forestry and other sectors that rely on shared ecosystem goods and services, must be pursued from the perspective that aquatic biodiversity, from genetic resources to entire ecosystems, especially the oceans and all wetlands, have immense current importance and future potential for mitigation of climate change. Sustaining their current roles and exploring their future potentials also depend upon the conservation of wide aquatic genetic diversity.

Cross-sectoral interventions to mitigate and also provide adaptation to climate change include the following: improvement of watersheds, to stabilize hydrological regimes and to increase aquatic and terrestrial vegetation; keeping wetlands wet, to reduce greenhouse gas emissions; maintaining freshwater connectivity; and defending and restoring damaged and threatened coastal areas, for example by replanting mangroves. Cross-sectoral interventions that might also contribute significantly to mitigation, but which need further research and trial development include: reappraisal of integrated agriculture-aquaculture-waste reuse systems, including the possibility that fish in wetland agro-ecosystems (e.g. wet ricelands) might reduce greenhouse gas emissions; redesigning reservoirs and managing natural lakes to minimize their greenhouse gas emissions, including appraisals of the roles and interactions of aquaculture and fisheries; extraction and capture of nutrients, particularly carbon, by using nutrient-rich aquaculture effluents for irrigation; and mass production and harvesting of micro- and/or macroalgae as feedstocks for clean biofuels.

2.5 Gaps - and partnerships to address them

Aquatic ecosystems are interconnected and aquatic genetic resources for food and agriculture are shared globally, sometimes with difficult transboundary issues. Fostering and maximizing the roles of aquatic genetic resources for adaptation to, and mitigation of, climate change require that many gaps be addressed progressively, especially those concerning information, knowledge, education and awareness, capacity building and the overall gaps in policy to which all of the above contribute. Meeting the challenges of climate change is a globally shared responsibility.

The keys to addressing these gaps are partnerships including, *inter alia*, the following types: global (such as FAO’s partnerships with the UN Framework Convention on Climate Change, the Convention on Biological Diversity, the Ramsar Convention on Wetlands, the Convention on International Trade in Endangered Species); regional, subregional and country; specific ecosystem (such as river basins and seas); governmental and non-governmental networks and consortia (such as those for regional aquaculture centres and information systems); and public–private.

2.6 Conclusions and recommendations

The paper notes the following recommendations from the Twenty-ninth Session, January 31 to February 4 2011, of the FAO Committee on Fisheries (COFI) concerning fisheries and aquaculture in changing climates and relevant to aquatic genetic resources:

“*(a) that Members should intensify their efforts to assess environmental and anthropogenic factors affecting aquatic ecosystems including changes in migratory patterns of fish species and other adverse impacts including ocean acidification, and should consider these in management approaches;*

(b) that FAO should continue to keep Members informed about the implications of climate change for fisheries and aquaculture, based on the best available scientific information and the needs of vulnerable nations and developing countries;

(c) that emphasis should be placed on the ecological and economic resilience of fisheries and aquaculture operations and the communities that depend upon them; and…

(e) taking note of the urgent need of many members for technical assistance, that FAO should continue and strengthen support to Members and especially developing countries,

> *particularly in relation to adaptation, including facilitating access of these countries to UN adaptation funds for fisheries and aquaculture* (FAO 2011).”

The paper’s general conclusions and recommendations call for better information systems; increased investment for research on aquatic biodiversity at all levels (gene, species/population and ecosystem); taking care of aquatic ecosystems and conservation of aquatic gene pools; wider inclusion of inland fisheries and aquaculture as partners in the multipurpose use of scarce freshwaters; consideration by FAO to add to its series of Technical Guidelines in support of its Code of Conduct for Responsible Fisheries a volume on “Meeting the Challenges of Climate Change”, including in that volume appropriate emphasis on responsible conduct to maximize the roles of aquatic genetic resources in adaptation to and mitigation of climate change; consideration by the Commission of how best to assign responsibilities for coverage of aquatic plant and aquatic microorganism genetic resources, as well as for the genetic resources of any aquatic vertebrates and invertebrates that are used for food and agriculture but not yet covered as aquatic genetic resources.

Specific and detailed sets of conclusions, recommendations and priority actions follow, concerning adaptation, mitigation, conservation, cross-sectoral collaboration and ecosystem approaches, biotechnology and biosecurity, education and awareness, and partnerships.

III. DEFINITIONS

3.1 Fish; aquaculture; culture-based fisheries; capture fisheries; aquatic genetic resources; *in situ* and *ex situ* conservation; biotechnology and biosecurity

Fish

In this paper, the term fish means all finfish (Pisces) and all aquatic invertebrates that are used by humans, directly or indirectly, including the following: corals, crustaceans, echinoderms, molluscs, tunicates and minor phyla. The term finfish is used when referring only to Pisces. The term shellfish is avoided, because it can be used and understood in various ways, either including or omitting different crustaceans, molluscs and other aquatic animals, and is therefore not a consistent descriptor for categories of farmed and fished aquatic invertebrates.

Aquaculture

Aquaculture is the farming of aquatic organism, at any scale from household to large commercial operations. Farmed aquatic organisms include microorganisms, plants, invertebrates and finfish. Aquaculture operations are typically split into those for seed supply (from the harvesting of wild seed or from hatcheries and nurseries) and for “growout” to market size in production systems, i.e. ponds, pens, cages, tanks and raceways, rafts and ropes, integrated farming systems such as rice–fish farming, and self-contained recirculation systems. In the capture-based aquaculture of species such as tunas, yellowtails and some groupers, wild juvenile or subadult fish are captured and held for fattening. Aquaculture and related research involve the farming of over 300 species of fish, about 50 species of microalgae and invertebrates as food organisms in fish hatcheries, about 20 species of seaweeds, and over 30 species of freshwater macrophytes. Domestication of new candidate aquatic species for aquaculture is ongoing and can be rapid, once captive breeding has been achieved.

Culture-based fisheries

Culture-based fisheries are the aquatic equivalent of terrestrial ranching and are usually undertaken by communities, government organizations or corporations. Waters such as lakes, reservoirs, rivers used by migratory fish, lagoons, semi-enclosed bays, coastal tidal areas, artificial reefs, and other coastal waters, are stocked with fish seed: usually from hatcheries, but sometimes harvested from the wild. With or without such stocking, the ecosystems that support culture-based fisheries are sometimes modified by increasing food sources and refuges for fish; for example, in brush park fisheries.

In their use of, and impacts on, aquatic genetic resources, culture-based fisheries overlap with aquaculture. In culture-based fisheries, the genetic diversity of the stocked fish is determined by hatchery managers or by collectors of wild seed. The stocked fish almost invariably interact with wild populations and sometimes interbreed with wild conspecifics. This has led to much criticism of hatchery-based stocking, especially where insufficient attention has been paid to its potential genetic impacts on wild fish and their habitats. These issues are discussed in a large literature (e.g. Bartley, 1996; Tringali and Bert, 1998), from which the overall conclusion is that the ecosystem risks, including genetic implications of every culture-based fishery, must be assessed as a specific case. Guidelines are given by FAO (2008b), treating the genetics of culture-based fisheries as part of aquaculture.

Capture fisheries for wild aquatic organisms

In this Background Study Paper, the term fisheries means all capture fisheries, including the relatively small minority that are culture-based. Most capture fisheries, whether undertaken by individual fishers or large commercial enterprises, harvest wild organisms. Their targets include aquatic plants and fish, from the following natural and artificial aquatic ecosystems: freshwaters (lakes, reservoirs, streams and rivers, in watersheds and across floodplains, and associated with agricultural wetlands such as rice lands and dambos); brackishwaters (estuaries, lagoons, other inland and coastal saline waters); and marine waters (intertidal zones, shallow seas, large marine ecosystems, and the deep sea and its reefs). The world’s food, industrial (fishmeal and fish oil) and ornamental capture fisheries target over 4 000 species and sometimes harvest other species as by-catch. Sport fishing targets over 1 000 species and uses hundreds of other species as bait, some of which are farmed.

***Aquatic genetic resources and their conservation,* in situ *and* ex situ**

Aquatic genetic resources for food and agriculture comprise the genetic material (as populations, individuals, gametes, DNA and alleles) of all aquatic plants and fish that provide food and related goods and services to humans, or that have potential to do so. The genetic resources of farmed aquatic amphibians, reptiles and birds are considered to be animal genetic resources, not aquatic genetic resources. Nevertheless, some production and value statistics for farmed amphibians (frogs) and farmed reptiles (crocodiles and turtles) are included with farmed fish statistics, at national level and by FAO. For statistical purposes, FAO uses the International Standard Statistical Classification of Aquatic Animals and Plants (ISSCAAP) species groups. Wild aquatic reptiles (crocodiles, snakes and turtles) and mammals (e.g. dolphins, dugongs and whales) are charismatic species of high cultural significance and high value in ecotourism, but are not regarded as aquatic genetic resources for food and agriculture.

Information about aquatic genetic resources at species level is available in databases such as FishBase (www.fishbase.org) and Sealifebase (www.sealifebase.org), which contain thousands of growth, reproduction, environmental tolerance and other relevant records and analyses. Aquamaps (www.aquamaps.org) are beginning to provide known and predicted global distributions of aquatic species, by half-degree grid cells, based upon known occurrence data and six predictors: bottom depth; temperature; salinity; primary production; sea ice concentration; and distance to land. These and other global aquatic biological databases and tools strive to keep pace with the rapidly changing taxonomy and nomenclature of aquatic organisms.

Many aquatic genetic resources have yet to be characterized adequately in terms of intraspecific genetic variation. This means that much of the *in situ* conservation of aquatic genetic resources, including populations in marine and other aquatic protected areas, lacks documentation below species level and sometimes below biological community and ecosystem functional group levels. Some of the aquatic genetic resources that are of high importance for meeting the challenges of climate change are described as species or as functional groups in food webs: for example, by trophic levels as grazers, filter feeders, detritivores and top predators in Ecopath (www.ecopath.org); or based on their respiratory organs, water quality and preferred habitats, such as “white”, “grey” and “black” water riverine fishes (Dudgeon, 2000).

Only a small minority of aquatic genetic resources is presently characterized as genetically distinct populations (e.g. location- and season-specific stocks, strains) and as genetically manipulated forms, complete genomes and alleles. Even at the species level, as Thorpe *et al*. (2000) pointed out for marine invertebrates, populations that were formerly described as a single species can turn out to be distinct, cryptic species. Such scenarios are now being clarified by global sharing of genetic data; e.g. by the fish components of the Bar Code of Life project (www.fishbol.org). Pullin (2000) reviewed management and conservation units for aquatic genetic resources, following the approach of Wood and Holtby (1998), which is based on defining populations in terms of their reproductive isolation and gene flow.

The domestication of most aquatic organisms used in aquaculture, culture-based fisheries and related research lags far behind the domestication of food plants, livestock and forest trees, but is now proceeding very rapidly (Duarte *et al*., 2007). Bilio (2008) cited FAO (2008a) statistics for aquaculture and capture fisheries species as comprising 1 174 finfish, 174 crustaceans, 155 molluscs, 321 other invertebrates and 31 plants. The same author applied his own criteria for domestication, based upon successful and continuous controlled reproduction in captivity, to estimate the following numbers of domesticated species in aquaculture, compared with total numbers of farmed species in brackets: finfish, 42 (272); crustaceans, 13 (44); and molluscs, 10 (73). Benzie *et al*. (in press) provide a comprehensive overview of the diversity and status of aquatic genetic resources for aquaculture.

About 10 fish species are used as standard models in toxicology. Aquatic microorganisms are cultured commercially. Some are under study for use as probiotics, in fish feeds or in aquaculture systems. Marine Genetic Resources in Areas Beyond National Jurisdiction (MGRs in ABNJ) include organisms that are associated with thermal vents.

Table 1 summarizes the main types of aquatic genetic resources upon which aquaculture and fisheries currently depend. This picture will change with increasing applications of biotechnology. Farmed fish, as well fish used in culture-based and capture fisheries and all related research, include wild types, selectively bred strains, natural and artificial hybrids, polyploids, monosex populations and transgenes.

Table 1. Main (and subsidiary) aquatic genetic resources for aquaculture (seed supply and growout) and for capture fisheries (culture-based and wild harvests): C = captive bred, but not yet domesticated; D= domesticated; W = wild or feral populations (modified from Science Council Secretariat 2005).

PRODUCTION SYSTEM	GENETIC RESOURCES
AQUACULTURE: Seed supply (broodstock, hatcheries, nurseries)	C and D (W)
AQUACULTURE: Growout in ponds, cages, pens, tanks and raceways (includes fattening of wild fish, such as eels and tuna)	C, D and W
AQUACULTURE: Growout using poles, ropes and net bags (for molluscs)	C and W (D)
AQUACULTURE: integrated farming systems (e.g. rice-fish):	C, D and W
CULTURE-BASED FISHERIES: stocked waters (natural and artificial)	C and W (D)
CULTURE-BASED FISHERIES: no stocking; only habitat modification (e.g. artificial reefs, brush parks)	W and (C)
ALL OTHER CAPTURE FISHERIES: (bait, food, industrial, ornamental and most sport species)	W

Aquatic genetic resources for food and agriculture comprise not only those for the farmed and fished populations, but also those for a wide range of live food organisms: cyanobacteria and other microorganisms, microalgae, protozoans, rotifers, Artemia, copepods, cladocerans, molluscan larvae and tubifex, as well as the industrial and low-value trash fish and species that are fished to provide fishmeal, fish oil and wet feeds. Moreover, the productivity and resilience of the aquatic ecosystems that host aquaculture and fisheries depend upon many species of aquatic microorganisms in the water column and in detrital food webs, including autotrophic and heterotrophic microorganisms, particularly cyanobacteria and fungi; microalgae and protozoans (Moriarty and Pullin 1987). Aquatic genetic resources underpin the productivity, sustainability and adaptability of all aquaculture, culture-based and capture fisheries, as well the essential services that are performed by aquatic ecosystems for ecotourism, recreation, sport fishing and waste treatment. *In situ* conservation of aquatic genetic resources, on farms and as wild and feral populations, and *ex situ* conservation of aquatic genetic resources, as aquarium and research populations and in gene banks as cryopreserved sperm, embryos and tissue DNA, are therefore of immense importance for maximizing the availability of aquatic genetic diversity to meet the challenges of climate change.

For plant and animal (livestock) genetic resources, the term *in situ* refers mostly to individuals and populations on farms. The term *in situ* can be used in the same sense for farmed aquatic organisms, but for much of aquaculture and for almost all fisheries, *in situ* aquatic genetic resources still comprise wild and feral populations, in open waters and wetlands. Wild type fish provide much of the genetic material for breeding programmes in aquaculture and related genetic improvement research. They also underpin the sustainability and resilience of the fish populations that are targeted by capture fisheries. *Ex situ* conservation of aquatic genetic resources, as cryopreserved spermatozoa, embryos and DNA, and/or as captive breeding populations, will become increasingly important as *in situ* conservation faces threats, including changes through climate change to aquatic protected areas.

In aquaculture, culture-based and other capture fisheries, it is important to consider the effects of climate change and the roles of aquatic genetic resources at all stages of production cycles. In aquaculture and culture-based fisheries, breeding programmes and the hatchery and nursery operations that provide “seed” (e.g. plant cuttings, eggs, larvae, postlarvae, fry and fingerlings) are usually undertaken as different enterprises, in different environments from the main production (‘growout’) environments. In addition to whatever artificial selection, hybridization or genetic manipulations are applied to farmed aquatic organisms, natural selection to hatchery, nursery) and growout environments is always ongoing. This can be particularly important for fish species that produce millions of fertilized eggs per mating, among which there can be high natural mortalities at early life history stages. In the present context, it is important to consider the potential role of aquatic genetic resources as climate change impacts seed supply and growout in aquaculture, seed supply and open-water production in enhanced fisheries, natural recruitment to capture fisheries and the functioning of aquatic ecosystems.

Biotechnology and biosecurity

Biotechnology is defined here following the Convention on Biological Diversity’s broad definition, as: any technological application that uses biological systems, living organisms, or derivatives thereof, to make or modify products or processes for specific use. Aquaculture and culture-based fisheries use a wide diversity of captive-bred and fully or partially domesticated populations that are all genetically different from wild types. Farmed fish include interspecific hybrids, some of which are fertile, as well as a wide range of selectively bred, polyploid and monosex populations. Genetically modified fish in the narrow sense (i.e. transgenes) have been developed in research establishments. All biotechnological applications in fish breeding, including traditional selective breeding, cause genetic alterations of the targeted fish. FAO (2008b) suggested that the term genetically modified fish be used only when genetic material has been altered through gene and cell technologies, e.g. development of transgenic fish. The domestication of farmed aquatic organisms, their genetic improvement for aquaculture, and all technological applications in aquaculture and capture fisheries and conservation of aquatic genetic resources are all regarded here as biotechnology.

Biosecurity means safeguarding humans, biodiversity and the environment against risks and adverse impacts from diverse biological threats including biotechnology. The biosecurity aspects of aquatic genetic resources for food and agriculture are broadly similar to those for plant, animal and forest genetic resources, with which they are periodically reviewed by FAO (e.g. Ruane and Sonnino, 2006). However, the importance of wild genetic resources and of safeguarding them against loss and alteration by genetic and other impacts of the products of biotechnology is much greater in aquaculture and fisheries resources than in agriculture and forestry.

3.2 Climate change; short-term climate fluctuations; long-term climate change; adaptation; adaptive capacity; mitigation; and vulnerability

The term climate change refers here to the combination of short-term climate fluctuations, some of which can be seen as short-term trends, and long-term trends, because both are occurring together. Short-term climate fluctuations (including extreme events) are defined as seasonal patterns and oscillations, such as the El Niño-La Niña Southern Oscillation (ENSO), as well as variable temperature patterns, heavy precipitation patterns (associated with cyclones, hurricanes, typhoons and monsoons) and severe storms.

Short-term climate fluctuations are seen as those having increasing frequency and amplitudes, while what were formerly regarded as normal patterns become less frequent, and the near-term climate becomes more and more unpredictable. Extreme weather events are increasing in frequency and severity and occurring in wider areas (IPCC, 2001). Extreme weather is defined with reference to the recorded historical distribution of a climatic event. Long-term climate change is defined as gradual climate change over decadal-scale timescales, including: sea-level rise; oceanic currents; gradual warming; acidification of open waters; and changes in the availability of freshwater. The long-term climate change scenarios considered here are based on those developed by the Intergovernmental Panel on Climate Change (IPCC), as well as on the general circulation models (GCMs) that are in common use. (IPCC 2001; IPCC 2007a, b and c).

Adaptation to climate change is defined here following the United Nations Framework Convention on Climate Change (UNFCCC; www.unfccc.int) definition as: "*Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities*". Adaptation to climate change can be achieved by aquatic farmers and fishers adjusting their operations, as well as by applications of scientific and technological advances, through governmental and other interventions. Adaptive capacity means the ability of a system to adjust to climate change (including climate variability and extremes), to moderate potential damages, to take advantage of opportunities, or to cope with the consequences. (IPCC, 2001).

The UNFCCC defined mitigation of climate change as: *"a human intervention to reduce the sources or enhance the sinks of greenhouse gases. Examples include expanding forests and other "sinks" to remove greater amounts of carbon dioxide from the atmosphere."* Those elements of mitigation are accepted and used here, but mitigation is defined here more broadly than specific human interventions to reduce greenhouse gases. As defined here, mitigation includes interventions than can mitigate climate change in other ways, such as improving and stabilizing watersheds and coastal zones.

Vulnerability is defined here, following its UNFCCC definition, as: *"The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity*." This refers not only to the vulnerability of the system, but also to that of the people who are dependent on the system for their food, livelihood and any other goods and services.

3.3 Regions and subregions

This paper follows the Statistics Division of the United Nations Secretariat and the International Organization for Standardization (ISO) definitions and terminology for regions and subregions (see: http://unstats.un.org/unsd/methods/m49/m49regin.htm), in preference to any of the alternatives that are available for aquatic ecosystems, such as FAO Fisheries Areas (see www.fao.org) and Large Marine Ecosystems (see www.seaaroundus.org). However, examples of climate change impacts and adaptations in specific waters are included throughout.

Regions (and sub-regions) are defined here as follows:

- Africa (Central, East, North, Southern and West)
- Latin America/Caribbean (Central America, South America and the Caribbean)
- Northern America
- Asia (Central, Eastern, Southern, South-Eastern and Western)
- Europe (Eastern, Northern, Southern and Western)
- Oceania (Australia and New Zealand, Melanesia, Micronesia, Polynesia)

IV. BROAD IMPLICATIONS OF CLIMATE CHANGE FOR AQUACULTURE AND FISHERIES

For the whole aquatic sector

No food and agriculture sector has ever been able to cope entirely with the unpredictability of climate and with the temporary or permanent changes to the physical environment that can be brought about by extreme climatic events. Genetic resources can contribute to meeting such challenges, but cannot eliminate the risks of temporary or permanent failure that climatic uncertainty and climate change will always pose for agriculture, aquaculture, fisheries and forestry.

Most aquatic organisms are poikilotherms, meaning that they are unable to regulate their body temperatures. Some fish are able to move to locations that are more suitable when conditions become unfavourable, provided that there is connectivity in the watercourses or water bodies that are open to them. Fish that live in isolated waterbodies or watercourses, such as lakes and mountain streams must adapt to climate change *in situ*, or become increasingly stressed and ultimately extinct. Some fish move vast distances along migration routes, for which connectivity must also be assured if they are to adapt and survive. Other fish are capable of only limited movements or are sessile: for example, bivalve and gastropod molluscs and intertidal finfish. Many fish depend upon stable biological communities around them. These can be based on keystone species such as corals, kelp, mangroves and sea grass. If such keystone species are unable to adapt to climate change, the whole community will undergo major changes or be lost.

Cochrane *et al*. (2009) reviewed at length the implications of climate change for aquaculture and fisheries. In common with all other sectors of food and agriculture, aquaculture and fisheries are supply chains, from ecosystems though harvests, postharvest handling and processing, to markets and consumers. In the interactive governance approach to fish supply, fish chains were defined and discussed by Thorpe *et al*. (2005) as “systems to be governed”. Climate uncertainties and climate change affect every link in these chains, though the largest impacts and needs for adaptation and mitigation are in the ecosystems that produce the fish, i.e. farms, open waters used for fisheries, and all waters used for *in situ* conservation of aquatic genetic resources.

As climate change proceeds, some aquatic farmers, fisheries managers, as well as conservationists of *in situ* aquatic genetic resources, will face increasingly the prospect of deterioration in the health and economic viability of their resources and of increasing mortalities in production and breeding operations. This is happening because of lethal and sublethal physical changes in the aquatic environment and related changes in the prevalence of harmful organisms and climate-related events. The most important ongoing and anticipated changes are higher or lower water temperatures concurrent with lower or higher dissolved oxygen and higher or lower metabolism; disruption of ocean currents; higher or lower salinity, caused by saline intrusion or heavy precipitation; higher turbidity, caused heavy precipitation; lower water depth and flow, during droughts; increased challenges from diseases, parasites, predators and alien species; increased prevalence of toxic blooms; and increased acidification of marine waters, with lower availability of minerals for building skeletal structures. The physical and biotic changes listed above can pose risks to all life-history stages in their particular environments, with any major losses then jeopardizing whole populations and genetic diversity. This applies particularly to highly migratory species, such as salmon and sturgeons.

In general, the most severe effects of these changes will be felt by aquatic populations in restrictive circumstances: for example, farmed fish in ponds, pens, cages and raceways; wild or stocked fish in shallow lakes and reservoirs, streams and rivers in conditions of low flow and stagnation, as well as in shallow coastal waters, with special habitat features and communities, such as those of coral reefs and sea grass beds, that even motile organisms will not leave; wild populations conserved *in situ* in aquatic protected areas and nature reserves, especially those that lack refuges from extreme conditions, for example, the feeder streams of drying lakes; and, in general, by all species that are habitat specialists rather than generalists (Munday, 2004).

With climate change, some aquatic hatcheries and farms will have to relocate or change to raising populations that have been bred for their new, climate-changed environments or different species that will perform better there. Culture-based and capture fisheries will become either more or less viable with climate change. Some will have to be relocated to wherever the fish can not only survive but also prosper. In all cases, the availability of suitable aquatic genetic resources will determine success or failure. Fisheries managers have fewer options and must rely largely on natural selection within wild populations, so that waters become populated with more tolerant survivors. Restocking with wild or hatchery-reared fish having appropriate environmental tolerance is possible, but can have large and irreversible genetic impacts on surviving wild populations. Conservationists of wild *in situ* aquatic populations can only monitor the extents to which those populations cope with changed aquatic environments and, where it seems necessary for the purposes of conserving important genetic resources that can no longer remain available there, resort to moving them to other *in situ* sites and/or to *ex situ* collections and gene banks.

For aquaculture

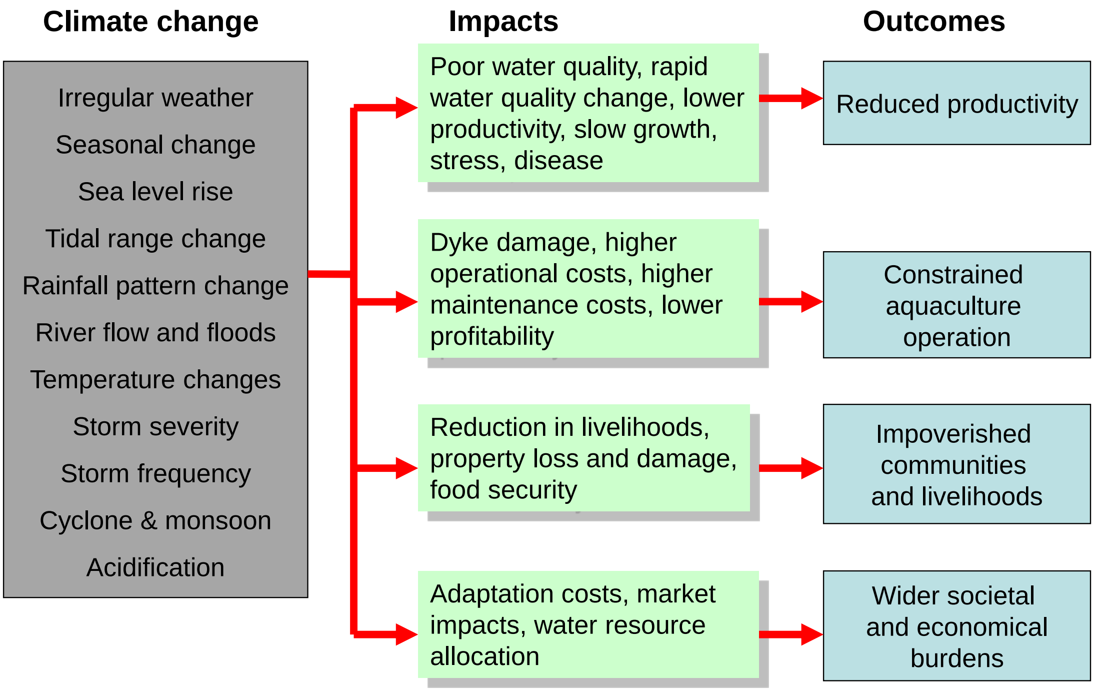
The impacts of climate change on aquaculture could be positive or negative, arising from direct and indirect impacts on the farmed organisms and on the natural resources that aquaculture requires, especially water, land, seed, feed and energy. As fisheries provide significant feed and seed inputs for aquaculture, the impacts of climate change on them will also, in turn, affect the productivity and profitability of aquaculture systems. Handisyde *et al*. (2006) and De Silva and Soto (2009) reviewed the likely impacts of climate change on world aquaculture, including indirect impacts such as price fluctuations of competitive capture fisheries produce and impacts on the availability of fishmeal and fish oil.

For aquaculture there will be some negative and some positive impacts from climate change. Climate change will increase physiological stress in some farmed fish. This will not only affect productivity, but will also increase vulnerability to diseases and, in turn, impose higher risks and reduce returns to farmers. Interactions of fisheries and aquaculture subsectors could create other impacts. For example, extreme weather events could result in escapes of farmed fish and contribute to reductions in genetic diversity of wild populations, affecting biodiversity more widely. These impacts will be combined with other factors that affect adaptive capabilities, including: increased pressure from ever larger human populations on natural resources; political, institutional and management rigidity that negatively impacts the adaptive strategies of aquaculture-dependent communities; deficiencies in monitoring and early-warning systems or in emergency and risk planning; and other non-climate factors such as poverty, inequality, food insecurity, conflict and disease. Positive impacts can also emerge where climate change permits new species to be farmed and new markets developed. Higher temperatures will increase growth rates and productivity in some aquaculture systems and will allow some species to be farmed in new areas. These opportunities are not yet well understood. A community's ability to benefit will depend also on its adaptive capacity. Table 2 and Figure 1 summarize the main negative impacts and outcomes of climate change for aquaculture.

Table 2. Main impacts and outcomes of climatic change for aquaculture

Change	**Impacts and outcomes**
Short-term heat/cold extremes	Hypoxia, heat and disease challenges kill fish and reduce productivity
Long-term warming	Reduced water quality, broodstock and seed availability and disease challenges force changes in farm locations; some fish grow faster, with better feed conversion and increase productivity
Sea-level rise	Coastal land is lost and eroded, damaging coastal ponds; salt water intrudes and forces relocation of freshwater farms, but increases brackishwater and marine farming areas
Ocean circulation	Variable supplies of fishmeal, fish oil and some low value/trash fish, sometimes increasing fish feed costs; availability of some wild seed is reduced
Acidification	Calcareous shell formation is compromised, especially for molluscs; water quality and plankton populations change, threatening fish health and potentially threatening reproductive processes of aquatic species
Precipitation	Predictability of water supply is reduced; flooding and droughts increase, compromising water supply and water quality, damaging farms, allowing fish escapes and killing fish; increased agricultural run-off can restrict safe harvesting from coastal aquaculture (e.g. oysters)
Severe storms; storm surges	Severe storms and storm surges increase in frequency and strength and in wider areas; farms are damaged with fish escapes and fish kills

Figure 1. Climate change: anticipated impacts and outcomes for aquaculture



Adapted from Allison *et al.* (2009).

For fisheries

Fisheries, including culture-based ones, are fundamentally different from almost all other food production systems with respect to the impacts and outcomes of climate change. Climate change has both direct and indirect impacts on commercial and subsistence fish stocks. Its direct effects include physiological and behavioural changes at molecular, cellular, whole organism and population levels, altering growth rates, development, reproductive capacity, mortality, distribution and migrations. Species interactions and the structure and functions of aquatic biological communities are also changed directly by climate. The indirect effects of climate change on fisheries relate mainly to changes in the productivity, structure and composition of the ecosystems upon which the fish depend for food, oxygen, shelter and other services. The inland, coastal and marine ecosystems that support fisheries are all highly sensitive to climate change; for example, the Intergovernmental Panel on Climate Change (IPCC, 2007) noted the loss of coastal wetlands, coral bleaching and changes in the distribution and timing of fresh water flows, and acknowledged the uncertain effects of acidification of oceanic waters. It is important to recognize that all of these effects act along with fishing pressure (Pörtner and Peck, 2010). The magnitude and direction of climate change-specific stressors will vary from one fisheries ecosystem to another. For most fisheries, climate change is acting on scenarios of long histories of overfishing and ecosystem degradation, which continue. As fish stocks and numbers of effective breeders and spawning grounds decline, fish genetic resources can be caught in a downward spiral with the possibility of Allee effects. In this context, Gregory and Jones (2010) explained Allee effects as reductions in fitness as populations get smaller and fewer eggs are fertilized, and used the collapse of Newfoundland cod stocks as an example, citing Anderson and Rose (2001).

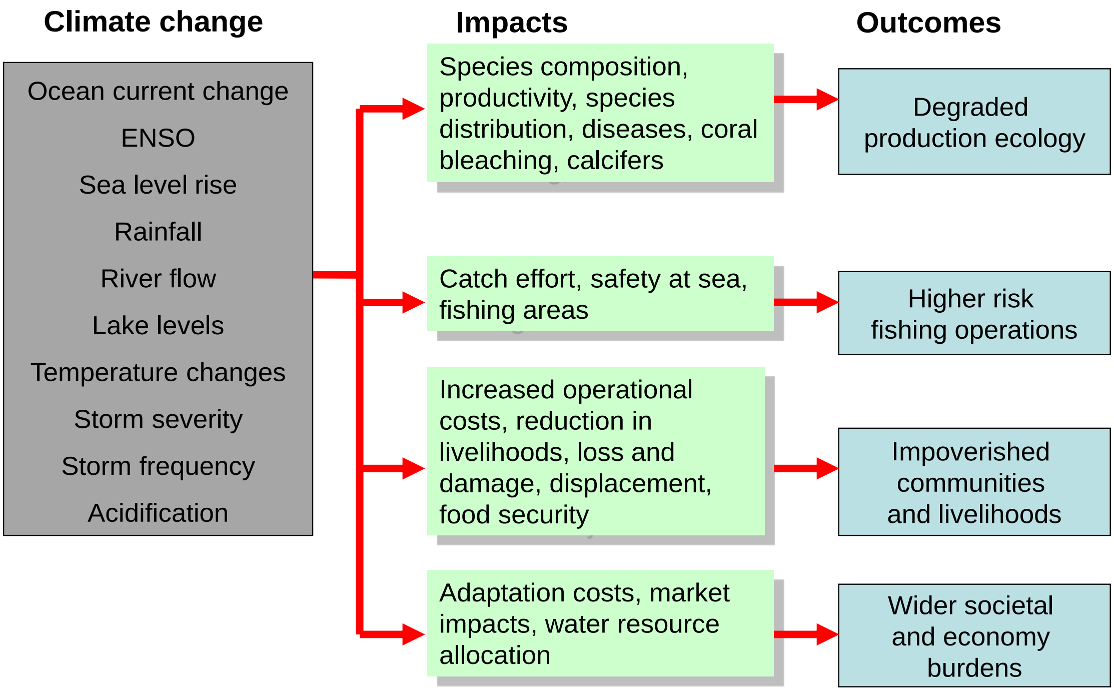
Cheung *et al*. (2009) projected changes in global catch potential for 1 066 species of exploited marine fish and invertebrates from 2005 to 2055 under climate change scenarios. Climate change might lead to large-scale redistribution of global catch potential, with an average of 30–70 percent increase in high-latitude regions and a drop of up to 40 percent in the tropics. Moreover, maximum catch potential could decline considerably in the southward margins of semi-enclosed seas, while increasing at the poleward tips of continental shelf margins. Such changes are expected to be most apparent in the Pacific Ocean. The Exclusive Economic Zones (EEZs) that are likely to have the highest increases in catch potential by 2055 include those of Norway, Greenland, the United States of America (Alaska) and the Russian Federation (Asian waters). The EEZs that face the biggest losses in catch potential include Indonesia, the United States of America (excluding Alaska and Hawaii), Chile and China. Climate change will exert great pressures on fisheries-dependent communities. Table 3 and Figure 2 summarize the main impacts and processes of climate change for capture fisheries.

Table 3. Main impacts and outcomes of climatic change for fisheries

Indirect, ecological changes	**Impacts and outcomes**
Warmer waters	Ranges and seasonal abundance of fish and plankton change; algal blooms increase; corals are bleached and die; some disease challenges are widened; spawning seasons, migrations and sex ratios of some fish change; some invasive species are favoured
Acidification	Calcareous structures are weakened in molluscs, crustaceans, corals, echinoderms and some phytoplankton, larger effects are expected in estuarine zones with less buffer potential
Sea-level rise	Coastal fish breeding and nursery habitats, such as mangroves and coral reefs, change in distribution, reduced or lost
Ocean circulation	Ecosystem productivities and fish recruitment change

Precipitation	Inland water levels and flows fluctuate unpredictably; with extreme droughts and floods
Direct changes for fishing and fishers	**Impacts and outcomes**
Sea-level rise	Harbours, landing facilities and homes are damaged or lost
Severe storms	Harbours, landing facilities and homes are damaged or lost; more fishing days are lost; accidents increase
Precipitation	Inland fishing operations are compromised by droughts, floods and unpredictability of wet and dry seasons, with reduction and loss of livelihoods and food security

Figure 2. Climate change: anticipated impacts and outcomes for fisheries



Adapted from Allison *et al*. (2009)

Climate change will have negative or positive impacts for different fisheries and will open up some new fishing areas; for example, as ice sheets melt. Some fish stocks that cannot move away from adverse conditions may face extinction, but others will be able to move, facilitating increased catches in other areas.

V. CLIMATE CHANGE CHALLENGES FOR AQUATIC GENETIC RESOURCES

5.1 Three major climate change challenges: warming, acidification and elevated dissolved nutrients (N, P)

Aquatic genetic resources for food and agriculture comprise microalgae and other microorganisms, macroalgae and freshwater macrophytes, crustaceans, molluscs, other aquatic invertebrates, finfish and marine representatives from of all of those taxa among MGRs in ABNJ. With increasing human populations, dissolved nutrients (N, P) in aquatic ecosystems will increase as temperatures also increase. Table 4 summarizes the probable outcomes of warming, acidification and elevated N and P for all, after which more detail is given concerning impacts of short-term climate fluctuations and long-term climate change.

Table 4. Probable outcomes of climate change [warming, acidification and elevated dissolved nutrients (N, P)] on aquatic genetic resources for food and agriculture from major taxa

Taxa	Warming	Acidification	Elevated N, P
Microalgae	With increased nutrients, algal blooms are enhanced; oxygen is periodically depleted; but productivity higher in the food web could increase	Calcite formation is reduced; e.g. in coccolithophores	Eutrophication and harmful algal blooms, including red tides, are enhanced with lethal and sublethal effects on aquatic organisms
Macroalgae; freshwater macrophytes	Enhanced biomasses, with increased nutrients; periodic oxygen depletion due to die-offs; thermal stratification is increased	Coralline algae are reduced and more susceptible to diseases and grazing	Eutrophication and biomasses increase
Crustaceans	Gametes are less viable in decapods and barnacles and disease problems increase reducing some populations	Food sources are reduced; larval development and building skeletal structures may be compromised; recruitment is lowered	Eutrophication and harmful algal blooms are increased, with periodic oxygen depletion; e.g., on nursery grounds
Molluscs	Disease problems and irradiation stress increase	Shell formation is compromised and recruitment lowered	Water toxicity and harmful algal blooms increase
Other aquatic invertebrates: e.g. corals, echinoderms	Corals are bleached and suffer increased viral attacks; sea urchin gametes are less viable and fertilization is reduced	Calcareous skeletal structures are compromised	Water toxicity and harmful algal blooms increase; lower light reduces photosynthesis in coral symbionts
Finfish	Distributions and migrations are altered, with poleward shifts in some species; water column mixing and available oxygen decrease; some disease problems increase	Distributions and migrations are altered in pH-sensitive species	Water toxicity and harmful algal blooms increase

5.2 Short-term climate fluctuations

Seasonal patterns

Most studies of climate change impacts have focused on changes in mean climate conditions, but global climate change is bringing changes in seasonal patterns, sometimes with extreme events. The projected changes in extreme weather and climate events in the twenty-first century include more frequent heat waves, less frequent cold spells (barring so-called singular events), greater intensity of heavy rainfall events, more frequent mid-continental summer droughts, and greater intensity of tropical cyclones. In the tropical Pacific, more intense ENSO events are expected.

The ENSO is a quasi-periodic climate pattern, characterized by warming or cooling of the tropical eastern Pacific: known as El Niño and La Niña respectively. El Niño and La Niña are usually accompanied, respectively, by high and low air atmospheric pressure in the western Pacific (Trenberth *et al*., 2007). During non-El Niño years, east to west trade winds above the Pacific push water heated by the tropical sun westward. The surface water becomes progressively warmer because of its longer exposure to solar heating. From time to time, the trade winds weaken and warmer water flows back eastward across the Pacific to South America. During an El Niño, there is a failure in the upwelling of deep cold water and an increase in near-surface water temperature, which causes a decline in biomass and total production of small pelagic fish, leading to altered food webs and a shortage of fishmeal and fish oil. During a La Niña there can be very severe flooding and abnormally low temperatures.

El Niño is a natural climate event, occurring once every seven years on average. Droughts and floods occur in different parts of the world in association with El Niños and La Niñas. The ENSO has profound impacts on agriculture, fisheries, aquaculture, forests, precipitation, water resources, human health and society in general (IPCC, 2007). For comparison, the North Atlantic Oscillation (NAO) involves fluctuations in the difference of atmospheric pressure at sea level between Iceland and the Azores. The NAO controls the strength and direction of westerly winds and storm tracks across the North Atlantic. It is highly correlated with the Arctic oscillation, of which it forms part.

Overall, differential warming between land and oceans and between polar and tropical regions affect the intensity, frequency and seasonality of climate patterns (e.g. ENSO) and extreme weather events (e.g. floods, droughts and storms) and, hence, the stability of marine and freshwater resources adapted to or affected by them (FAO, 2008c). Understanding of natural climate variability at the time scales of seasons, years and decades has significantly increased. This is especially true for the ENSO and the NOA, which can now be simulated by coupled atmosphere–ocean general circulation models.

Extremes of warm temperature have increased in most regions, whereas the numbers of frost days and daily cold extremes have generally decreased (CGRFA, 2009a). There is a shift towards a warmer climate with an increase in extreme high temperatures and a reduction in extreme low temperatures. Abnormally hot days and nights and heat waves are very likely to become more frequent, with cold days and nights very likely to become much less frequent. The number of days with frost is very likely to decrease (USCCSP, 2008a). Winter and night minimum temperatures are increasing faster than summer and day maximum temperatures, respectively, reducing seasonal and diurnal temperature ranges. New record high night minimum temperatures are shortening the frost season in many mid-and high latitude regions (Leemans and van Vliet, 2004).

Precipitation

Observed changes in precipitation differ significantly among and within regions. Precipitation in temperate regions generally increased from 1900 to 2005, whereas the tropics showed a persistent decline of precipitation from the mid-1970s onwards (IPCC, 2007a). Annual precipitation trends for 1900 to 2000 show a contrasting picture between northern (10–40 percent wetter) and southern Europe (up to 20 percent drier). In most parts of Europe, changes have been greatest in winter. For example, winters in the United Kingdom have been getting wetter and summers have been getting drier (Pinnegar *et al*., 2006). Similar trends have been reported for other regions (Leemans and van Vliet, 2004).

The IPCC (2001) found a widespread increase in heavy rains in many regions where total precipitation had increased. In some regions, such as East Asia, however, increases in heavy rainfall were identified where the total precipitation has decreased or remained constant. This was attributed to a decrease in the frequency of precipitation (Leemans and van Vliet 2004). Extreme precipitation episodes have become more frequent and more intense in recent decades over most of North America and now account for a larger percentage of total precipitation. Heavy precipitation events averaged over North America have increased over the past 50 years, consistent with the observed increases in atmospheric water vapour, which have been associated with human-induced increases in greenhouse gases. Intense precipitation in the continental United States of America increased by 20 percent over the past century, while total precipitation increased by 7 percent. The rainy season is beginning about 10 days later than usual in Mexico, and North America in general has fewer, but more intense, heavy summer rain events (USCCSP, 2008a).

Elsewhere, reduced precipitation, coinciding with increased evaporation due to rising temperatures, has led to more areas experiencing droughts (CGRFA, 2009a). Evaporation and precipitation occur at different places, and whereas wet regions could receive even more rainfall as the planet warms, drier regions might experience more shortages of water, as evaporation accelerates (USCCSP, 2008a). For example, the Sahel has become drier over the past few decades, accelerating desertification and placing an even greater premium on scarce water supplies (USCCSP, 2008a). Higher air temperatures will increase evaporation and contribute to more frequent and severe droughts. For example, more severe droughts are likely in the southwestern United States of America and parts of Mexico, in part because precipitation during the winter rainy season is projected to decrease. Where increases in precipitation cannot keep pace with increased evaporation, droughts are also likely to become more severe. It is likely that droughts will continue to be exacerbated by earlier and possibly lower spring snowmelt, so that less water becomes available in late summer (USCCSP, 2008a).

During the 20th century, there was considerable decade-to-decade variability in the frequency of snowstorms; for example, in the United States of America, a decrease in the South and Lower Midwest and an increase in the Upper Midwest and Northeast. This represents a northward shift in snowstorms which, combined with higher temperature, is consistent with a decrease in snow cover over the United States of America. In northern Canada, there has been an observed increase in heavy snow events over the same time period. Changes in heavy snow events in southern Canada are dominated by decade-to-decade variability. The patterns of ice storms also vary (USCCSP, 2008a).

Projections for the twenty-first century suggest that global mean precipitation will increase, but more strong regional differences are expected. The general trends observed in the late twentieth century are projected to continue. Increases in precipitation at high latitudes are very likely, whereas low latitudes (especially subtropical regions) are likely to experience further declines of up to 20 percent by 2100 (IPCC, 2007). On average, precipitation is likely to be less frequent, but precipitation extremes are very likely to increase (USCCSP, 2008a). The extreme precipitation events and consequent floods and landslides that are currently causing loss of life and livelihoods worldwide are likely to continue.

Severe storms

Severe storms, especially in the topics, develop due to warm ocean surface temperatures, high humidity and persistent wind patterns With the warming of ocean surface waters, humidity increases. Hurricanes occur when sea surface temperatures exceed 26 ^{0}C. A warmer atmosphere results in more tropical storms, extreme heat waves, floods and droughts (USCCSP, 2008a). Between 1980 and 2006, the number of floods and cyclones quadrupled, from 60 to 240 in a year (OXFAM, 2007). There are, however, strong regional differences, with highest rates of increase in storms in the North Pacific, Indian and Southwest Pacific oceans. Since the 1960s, storms have also increased in mid-latitude regions, although in the late 1990s, their frequency went back to normal in the Northern Hemisphere (CGRFA, 2009a).

Atlantic tropical storm and hurricane destructive potential, as measured by the Power Dissipation Index (which combines storm intensity, duration and frequency) has increased substantially since the 1950s and 1960s, associated with warming Atlantic sea surface temperatures (see http://www.gfdl.noaa.gov/global-warming-and-hurricanes). Overall, there have been fluctuations in the numbers of tropical storms and hurricanes from decade to decade, with more uncertain data prior to the satellite era (which began in 1965). It is likely, however, that the annual numbers of tropical storms, hurricanes and major hurricanes in the North Atlantic have increased over the past 100 years, as Atlantic sea surface temperatures have increased (USCCSP 2008a) and are likely to increase further with climate change (USCCSP 2008a). Hurricanes have also become more destructive in both the Atlantic and the Pacific.

Overall, projections are for reduced total numbers of storms, but their intensity is expected to rise with regard to wind speed and precipitation (CGRFA, 2009a). There is also evidence for recent increases in extreme wave height characteristics, associated with more frequent and more intense hurricanes. Hurricane intensity has shown some increasing tendency in the western north Pacific since 1980. It has decreased since 1980 in the eastern Pacific. However, coastal station observations show that rainfall from hurricanes has nearly doubled since 1950, in part due to the slower movement of storms (USCCSP, 2008a).

Increased sea surface temperatures create environments favourable for tropical cyclones, particularly in more northern latitudes. In Europe, there seems to be little sign of long-term changes in storm intensity and frequency, but inter-decadal variations are pronounced, recent analyses of changes in severe local weather provide evidence for widespread systematic long-term changes, and Western Europe could be affected by a larger number of remnants of tropical cyclones (Semmler *et al.*, 2006).

Temperature

The 12 years from 1995 to 2006 included eleven of the warmest since records began (CGRFA, 2009a; USCCSP, 2008a). Temperatures have increased the most during two periods: from about 1910 to 1945; and since 1976. Most of this warming has occurred on land, which tracks temperature change faster than large water bodies, although the oceans have also warmed significantly in the last 50 years, especially in the upper 300 m. The Baltic and North Seas and the western Mediterranean have shown a warming of about 0.5 ^{0}C over the past 15 years. Sea surface temperatures in the North Atlantic have been rising since the mid-1980s, with rapid increases of surface air temperature in much of Europe (Leemans and van Vliet, 2004).

In some areas, temperature rise has been greater than global average; for example, northwest Russian Federation and the Iberian Peninsula have warmed by 0.95 ^{0}C since 1900. Over the past 100 years, the numbers of cold and frost days have decreased in most parts of Europe, whereas the number of days with temperatures above 25 ^{0}C and heat waves have increased considerably (Leemans and van Vliet, 2004). Increasing sea temperatures cause movements of plankton, fish and other species in poleward directions. Further changes in fish migration routes and in the productivity of fish stocks are expected with continuing warming, leading to possible local loss of fish species (Brander, 2007). At the same time, range shifts through changing temperatures might also favour the extension of invasive species into new marine ecosystems, posing additional threats to biodiversity (Brander, 2007). Rising sea temperatures cause coral bleaching and reduce reef structures and reef fish diversity.

Higher water temperatures have been reported in lakes in response to warmer conditions, and changes in the physical and chemical characteristics of lake water have brought changes in phytoplankton dynamics and primary productivity. Increased water temperature and longer ice-free seasons influence the thermal stratification and hydrodynamics of lakes. In warmer years, surface water temperatures are higher, evaporative water loss increases, summer stratification occurs earlier in the season, and thermoclines become shallower (Bates *et al.*, 2008). Increased stratification reduces water movement across the thermocline, inhibiting the upwelling and mixing that provide essential nutrients to the food web. There have been decreases in nutrients in the surface water, and corresponding increases in deep-water concentrations, in European and East

African lakes because of reduced upwelling due to greater thermal stability (Bates *et al.*, 2008).

Winds

Changes in winds and currents alter aquatic environments in terms of salinity, temperature, mixing and upwelling. Easterly trade winds have generally increased during the past 50 years across the Atlantic, Southern Indian and Northern Pacific oceans. The acceleration of trade winds in the Southern Hemisphere, since 1980, corresponds with increased evaporation and salinity.

5.3 Long-term climate change

Sea level rise

Sea level change is difficult to measure, but there is a clear trend of sea level rise. Sea level was relatively constant during the last 2 000 years, but sea level rise began to accelerate in the twentieth century. From 1961 to 2003, global mean Sea level rose by an average of 1–1.8 mm per year, with a clear acceleration from 1993 to 2003 (CGRFA, 2009a). The major causes are thermal expansion of surface waters and the melting of glaciers and snow, on land and at the Greenland ice cap (Leemans and van Vliet, 2004; CGRFA, 2009a; USCCSP, 2008b). Relative to the period 1961–2003, estimates of the contributions from thermal expansion and from glaciers and ice sheets indicate that increases in both of these sources contributed to the acceleration in global sea level rise that characterized the 1992-2003 period (Bindoff *et al.*, 2007). Regional differences in sea level rise arise not only from changes in land height, but from local differences in ocean thermal capacity and the patterns of winds and currents. Over the past 50 years, sea levels have risen faster across the subtropical belt, particularly in the northern Pacific and in the Caribbean (Hoegh-Guldberg, 1999).

Paleorecords demonstrate a strong inverse relation between atmospheric carbon dioxide (CO_2) and global ice volume. Sea level rise associated with the melting of the ice sheets at the end of the last Ice Age, between 10 000 and 20 000 years ago, averaged 10–20 mm per year with large “melt water fluxes” exceeding sea level rise of 50 mm per year and lasting several centuries clearly demonstrating the potential for ice sheets to cause rapid and large Sea level changes (USCCSP, 2008b). Current observations show that the Greenland Ice Sheet is losing mass and that this has very likely been accelerating since the mid-1990s. The Greenland landmass has been rising at high elevations because of the increase in snowfall that is consistent with high-latitude warming, but this gain is more than offset by an accelerating loss, with rapidly thinning and accelerating outlet glaciers accounting for a large component of this loss. Antarctica showed a net loss of about 80 gigatonnes of ice per year in the mid-1990s, increasing to almost 130 gigatonnes per year in the mid-2000s. It is unclear whether this very high rate of loss reflects a general trend or short-term fluctuation. It could indicate an even faster sea level rise to come (CGRFA, 2009a). Based on IPCC (2007b), sea level is projected to rise 28 ± 10 cm to 42 ± 16 cm by 2100, with thermal expansion accounting for 70–75 percent of this rise. It is possible that these estimates are conservative.

Population densities in coastal regions and on islands are about three times higher than the global average, with approximately 23 percent of the world’s population living within 100 km of the coast and < 100 m above sea level (Nicholls *et al.*, 2007). Therefore, even a small sea level rise will have significant societal and economic impacts through coastal erosion, increased susceptibility to storm surges and resulting flooding, ground water contamination by salt intrusion, loss of coastal wetlands and other issues. In Europe, the areas most at risk include the Dutch and German coastlines, some Mediterranean deltas, and Baltic coastal zones (Watson *et al.*, 2000).

In Latin America, sea level rise will impact particularly low-lying coasts, in countries such as those of the Central American isthmus, Venezuela (Bolivarian Republic of), Argentina and

Uruguay (Watson *et al*., 2000). Higher rates of erosion and coastal land loss are expected in many small islands as a consequence of sea level rise. Low-lying island states and atolls will experience increased seawater flooding and saline intrusion as direct consequences of sea level rise. For example, a 1.0 m rise in sea level would put at risk as much as 80 percent and 12.5 percent of total land, respectively, in the Majuro Atoll, Marshall Islands and Kiribati (Watson *et al*., 2000).

Oceanic currents

Climate change impacts on global current regimes and circulation are matters of considerable debate, with little firm information. Over the past 50 years, ocean current trends have been most pronounced along the Equator, with increased eastward currents across the Indian and Pacific Oceans, while the Atlantic experienced increased westward currents. The westward North Equatorial Current of the Pacific has increased, consistent with the observed change in wind (Hoegh-Guldberg, 1999). Temperature variations have been documented in Southern Ocean and deeper circulation waters, as well as in the Gulf Stream of the North Atlantic and in the North Pacific (CGRFA, 2009a). The southward flows of East Australian Currents have strengthened, pushing warmer and saltier water 350 km further south as compared to 60 years ago. On the other hand, the southward flow of Leeuwin Current near the western coast of Australia has slightly weakened since the 1970s (Hoegh-Guldberg, 1999). For local ocean currents, uncertainties in projections are high, but the expected growth of strong wind and heavy precipitation events might influence local current regimes. During the twenty-first century, the Atlantic Ocean Meridional Overturning Circulation (MOC) is very likely to slow down, though estimates range from virtually no change to a reduction of up to 50 percent by 2100 (CGRFA 2009a). On a global scale, evidence is growing that climate change could cause a slow-down of thermohaline circulation. Even slight changes of MOC could impact marine ecosystem productivity, ocean chemistry and fisheries (MacKenzie *et al*., 2007, Nellemann *et al*., 2008). Changes in oceanic currents are likely change cause shifts of bioregional zones in the oceans, changing some fish migration routes and altering the dispersal of pelagic eggs and larvae (Brander, 2007).

Warming

Earth surface temperatures over the last 100 years have shown a clear upward trend, with a total temperature increase of 0.76 °C since 1899. Since the late nineteenth century, the global average sea surface temperature has increased by 0.6 °C, consistent with the increase in global air temperature. The second half of the last century showed a warming rate of 0.10 °C to 0.16 °C per decade, almost twice as high as the average warming rate for the whole century. Global projections for the years to 2100 show large variations (IPCC, 2007). The most optimistic expect temperatures to rise by 1.1 ^{0}C to 2.9 ^{0}C. Under non-mitigation scenarios, they are expected to rise from 2.4 ^{0}C to as much as 6.4 ^{0}C (IPCC, 2007b).

Polar regions are showing the most rapid responses to climate change. As a result of a strong ice–ocean influence, small changes in temperature, salinity and ice cover may trigger large and sudden changes in regional climate with potential downstream feedbacks to the climate of the rest of the world. A warming Arctic Ocean may lead to further releases of the methane from hydrates and permafrost. The Southern Ocean plays a critical role in driving, modifying and regulating global climate change via the carbon cycle and through its impact on adjacent Antarctica. The Antarctic Peninsula has shown some of the most rapid rises in atmospheric and oceanic temperature in the world, with an associated retreat of the majority of glaciers.

In most environments, higher temperatures will result in increased aquatic productivity and growth rates of aquatic organisms, though there will be many complications for the timing of reproduction, the survival and health of different life-history stages, the assurance of food supplies, diseases, predators and migrations. Most predicted increases in temperature will be within acceptable ranges for farmed fish, but there will undoubtedly be some shifts in the natural ranges and farming ranges for some farmed fish. In terms of warming alone, climate change will impact positively on some aquaculture operations, provided that water, feed and other input requirements can be met and that other factors, such as disease, do not interfere. For example, McCauley and Beitinger (1992) suggested that the range of channel catfish (*Ictalurus punctatus*) would be extended northwards by 250 km for every 2 ^{0}C rise in mean annual temperature.

Ocean acidification and carbon sinks

When CO_2 dissolves in seawater, the concentration of bicarbonate ions (HCO_3) increases while the amount of carbonate ions ($CO_{3)}$ and pH of the surface ocean waters decrease. Changes in the pH of ocean surface waters over the past 650 000 years appear to have been cyclical and associated with the glacial periods, with the transition from low to high values occurring every 50 000 years. The only factor that balances out high CO_2 levels in the oceans is the alkaline flux from the weathering of silicate rocks, which happens on a time-scale of hundreds of thousands of years (Fernand and Brewer, 2008).

Before the Industrial Revolution, the pH of the ocean surface waters ranged from 8.0 to 8.3. Since then, ocean surface water pH has dropped by 0.1 pH units and now ranges from 7.9 to 8.2 (Caldeira and Wickett, 2003). From a historical perspective, the current levels of CO_2 are already high, and anthropogenic emissions are exacerbating this problem. Unless significant cuts in CO_2 emissions are realized in the next few decades, ocean surface water pH will fall another 0.14–0.35 pH units by 2100 (IPCC, 2007 Synthesis Report). The Royal Society (2005) forecast a decrease of 0.5 pH units by 2100, and noted that it will take more than 10 000 years for the ocean to return to its pre-1800 acidity level (ACECRC, 2008; Fernand and Brewer, 2008; Royal Society, 2005). Although studies into the impacts of high concentrations of CO_2 in the oceans are still in their infancy, there is some evidence that ocean carbon uptake is starting to decrease (Schuster and Watson, 2007).

Ocean acidification is a global phenomenon, but regional and seasonal differences, combined with the biological, chemical and physical factors, influence the uptake of CO_2 and result in variable acidification: from pH 7.3 inside deep estuaries to pH 8.6 in productive coastal plankton blooms and pH 9.5 in some tidal pools (Royal Society, 2005). Southern ocean surface waters will be particularly exposed to decreasing calcium carbonate saturation, although low-latitude regions will also be affected. The penetration of atmospheric CO_2 into the deep sea is expected to change seawater and benthic chemistry down to several thousands of metres (Royal Society, 2005; CGRFA, 2009a;). The oceans have an estimated daily uptake of 22 million tonnes of CO_2 (Royal Society, 2005; Feely *et al.*, 2008). The pre-industrial oceanic carbon reservoir has been estimated at about 38 000 gigatonnes, compared with about 700 gigatonnes in the atmosphere and somewhat less than 2 000 gigatonnes in the terrestrial biosphere.

Oceans act as an important carbon sink, absorbing 2 gigatonnes more CO_2 per year than they are releasing into the atmosphere. The oceans have absorbed 48 percent of all the CO_2 emitted since 1800 (Sabine *et al.*, 2004). Total biological production in the oceanic water column is thought to be around 0.6 and 1.8 gigatonnes of carbon per year (Royal Society, 2005). Anthropogenic carbon penetrates deep and intermediate depth waters, such as those of the North Atlantic, and the Southern Ocean. Anthropogenic CO_2 can be found in depths of up to 2 500 m in certain areas, although newer studies in the North Atlantic have revealed large changes in CO_2 concentrations in deep-water masses between 3 000 and 5 000 m, indicating that CO_2 might have penetrated some of those waters (Tanhua *et al.*. 2007). Depending on the location and ocean currents, CO_2 can be retained in deep waters for several hundred years (Chisholm, 2000; IPCC, 2005).

Calcifying organisms incorporate carbon directly from seawater into their skeletons in the form of inorganic minerals such as calcium carbonate. Their bodies contain substantial amounts of inorganic carbon as carbonates. When they die and sink, some of that inorganic carbon is remineralized, and much of it becomes buried in sediments, where it remains locked up indefinitely. There are two forms of $CaCO_3$ in the oceans and marine organisms: aragonite and calcite. Because the aragonite saturation horizon is always nearer the surface of the oceans than the calcite saturation horizon, organisms that build their shells with aragonitic calcium carbonate (e.g. corals and pteropods) are the more endangered by acidification. Calcifying organisms that produce the calcite form of $CaCO_3$ (e.g. coccolithophores and foraminiferans) are possibly less sensitive (Orr *et al*., 2005; Fabry *et al*., 2008).

Foraminiferans, coccolithophores and diatoms are major components of the “rain” of carbonaceous material to the ocean floor, but ocean acidification could compromise the incorporation by marine biota of carbon as calcium carbonate. Foraminiferans live in vast numbers in the oceans and are regarded, along with coccolithophores, as one of the biggest contributors to the flux of calcium carbonate from the sunlit surface waters to the ocean’s interior: the so-called “biological carbon pump”. Recent work by R. Glud and co-workers, reported by BBC (2011), suggests that deep ocean trenches are disproportionately important as receptors of that “rain” and as sites for its turnover by deep-sea bacteria. ScienceDaily (2010) reported M. Lebrato and co-workers’ estimates that echinoderms (starfish, sea urchins, brittle stars, sea cucumbers and sea lilies) incorporate more than 0.1 gigatonnes of calcium carbonate, exceeding the contributions of foraminiferans and coccolithophores. Wilson *et al*. (2009) reported that marine fish precipitate carbonates in their intestines and excrete them at high rates, contributing 3 to 15 percent of total oceanic carbonate production. These finfish carbonates are more soluble than others that are incorporated by marine biota, because they have higher magnesium content. Finfish carbonate production might increase with increasing CO2 levels (Wilson *et al*., 2009).

The main concern for the future is to what extents ocean acidification might compromise the roles of all these calcifiers as contributors to ocean carbon sinks. The effects of increased oceanic acidification due to a gradually rising uptake of anthropogenic carbon by the oceans are poorly documented. Declining pH will affect marine organisms with calcified shells, bones or skeletons (Brander, 2007). Dramatic impacts could follow from changes in low trophic levels of marine ecosystems. If vulnerable planktonic organisms, such as crustacean zooplankton, are affected by ocean acidification, marine food web relations might fundamentally change, which would impact higher trophic levels and might alter ecosystem composition (Nellemann *et al*., 2008).

Freshwater availability

Freshwater is a limited and precious resource. The majority of the Earth’s water resources are salt water (97.5 percent), with only 2.5 percent as freshwater, of which 70 percent is frozen in the polar ice caps and 30 percent is mostly present as soil moisture or lies in underground aquifers. Less than 1 percent of the world's freshwater, as found in lakes, rivers, reservoirs and as groundwater shallow enough to be tapped at affordable cost, is readily accessible for direct human uses.

Climate change will alter the hydrological cycle; in particular precipitation and evapotranspiration (Jung *et al*., 2010). The world’s rivers are fed with water from precipitation. Run-off results from the balance between precipitation, groundwater recharge, groundwater discharge and evaporation.

Some water slowly infiltrates the soil, flows as groundwater and re-emerges in spring. These storage processes often buffer water sources and determine water availability for human use, even when there is little precipitation (Leemans and van Vliet, 2004). Precipitation can be stored in winter as snow and ice and released during the melting season. For example, declining glaciers and snowfields in the Himalayas threaten water availability in the Gangetic floodplains, which are among the most vulnerable in the world to changes in climate (Leemans and van Vliet, 2004). Although temperature and precipitation have increased, river discharges show decreasing trends, especially during low-flow months when most of the water originates from snowmelt. This will become increasingly problematic over time, as there is less glacial mass to melt, and will have serious implications for food security.

Across Europe, annual river discharges have changed over the past few decades. In Eastern Europe, annual river discharge has increased, while in southern Europe it has significantly decreased. Some of these changes can be attributed to observed changes in precipitation.

The combined effects of projected changes in precipitation and temperature will in most cases amplify the changes in annual river discharge. Annual discharges are projected to decline strongly in southern and southeastern Europe, but to increase in almost all parts of northern and northeast Europe, with consequences for water availability (Leemans and van Vliet, 2004). The flows in many of the world's major rivers have decreased due to reduced precipitation, increased single-purpose abstraction, especially for irrigated agriculture, and construction of many new dams. Water availability is especially at risk across much of eastern and southern Africa.

VI. EXPECTED IMPACTS OF CLIMATE CHANGE ON AQUATIC ENVIRONMENTS AND VULNERABLE AQUATIC ECOSYSTEMS

6.1 Changes in aquatic environments and their implications

Climate change is having enormous impacts on aquatic environments. Long-term climate change will affect the physical, biological, and biogeochemical characteristics of inland waters, coasts and oceans, modifying ecosystems and the ways in which they function (Hoegh-Guldberg, 1999).

Climate change and the safety of aquatic produce

The safety of some aquatic produce for human consumption can be affected by short-term climate fluctuations and long-term climate change; particularly by higher temperatures in aquatic ecosystems and along post-harvest processing and marketing chains. Microbial spoilage of fish and problems such as histamine production become greater with increased ambient temperatures in post-harvest handling, processing and marketing (e.g. Chamberlain, 2001). In some tropical reef fisheries, ciguatera is a potential form of fish poisoning for consumers of large herbivorous fish. Ciguatoxins are produced by marine dinoflagellates, particularly *Gambierdiscus toxicus*. Hales *et al*. (1999) found strong positive correlations between ciguatera occurrences and warming of local waters during El Niño conditions and predicted that ciguatera poisoning might increase in such waters with climate change. Tucker (2000) reviewed off-flavour problems in fish – mainly from aquaculture, but also from some open-water fisheries – and found that off-flavours due to cyanobacterial blooms are most common in the warmest months, but that late spring warming of temperate waters, up to 15-25 °C, is correlated with their production of the off-flavour chemicals geosmin and 2-methylisoborneol. Off-flavours curtail the marketability of affected fish; but this is temporary and depuration is possible.

Harmful algal blooms pose wider and more serious problems for coastal aquaculture and fisheries, as reviewed by Maclean (1993). In general, and especially around the coasts of Asian countries from which industrial pollution and nutrient enrichment of waters from agricultural run-off have increased, red tides and other harmful algal blooms that kill fish or render them unsafe for human consumption have increased and are likely to increase further as surface waters get warmer and pollution gets worse. Macleod (2002) described increases in red tides reported in Chinese coastal waters: from 26 in the 1970s to 75 in the 1980s and 234 in the 1990s. Cai *et al*. (2006) found that weaker wind patterns and warmer surface waters predispose for more red tides in Chinese waters. Wu and Ma (2008) speculated that extended red tide periods in the South China Sea, between 1980 and 2004, might be due to higher water temperatures and lower water quality.

Climate change could favour some harmful microalgae and microbial pathogens and therefore could potentially enhance biotic pollution and the spread of aquatic diseases (Harvell *et al*., 1999; Ward and Lafferty, 2004). When toxic microalgae enter fish and human food chains, there can be serious health risks. Paralytic shellfish poisoning has been frequently reported from the Philippines, especially in many coastal embayments where finfish aquaculture and mussels are both present (Yap *et al*., 2004; Azanza *et al*., 2005, 2006). The toxic dinoflagellate *Pfiesteria* has been associated with mortality of finfish on the Atlantic coast of the United States of America (Burkholder *et al*., 1992) and can cause neurological damage to people who come into contact with it.

Some cyanobacteria, which are the principle feeds of some farmed and fished freshwater fish, can also produce potent toxins, but have not yet posed any significant hazards in the human food chain. This begs the question as to whether they will remain safe as feeds for fish consumed by humans as climate change proceeds. The main species of interest here are *Microcystis* spp., the blooms of which provide the main foods for fished populations of tilapia in many lakes (e.g. Lake George, Uganda) and for many farmed populations and culture-based fisheries of filter-feeding fish (carps and tilapias) throughout the tropics and subtropics. When Microcystis populations produce the toxin microcystin, the results can be lethal for fish and for livestock and humans drinking the affected waters; yet no reports of adverse effects on tilapias and other fish in tropical aquaculture or fisheries were found by Colman and Edwards (1987); see also discussion in Maclean (1993). Microcystins have been confirmed as a cause of some channel catfish mortalities (Zimba *et al*., 2001), but Beveridge *et al*. (1993) found that silver carp (*Hypophthalmichthys molitrix*) and Nile tilapia (*Oreochromis niloticus*), which are equipped as algal filter feeders, were able to sense toxic Microcystis strains and shut down their grazing. Recent investigations have shed light on the many interactive factors that can influence microcystin production by *Microcystis* spp., including genetic diversity among strains (e.g. Mazur-Marzec *et al*., 2010), combined effects of temperature and nutrient loading (especially P and N/P ratio) (e.g. Jacoby and Kann, 2007; Jiang *et al*., 2008: Pereira *et al*., 2008; Song *et al*., 2009; Xu *et al*., 2010), and interactions with other species including zooplankton (e.g. Jang *et al*., 2007; Akcaalan *et al*., 2009). Most problems with *Microcystis* toxins are reported from non-tropical waters. Climate change might reduce microcystin production overall, through warming waters, but might increase it in cooler waters. With so many interactive factors involved, no firm predictions are possible and a watching brief is needed.

Freshwaters

Freshwater habitats and fish populations are highly fragmented. In combination with other anthropogenic pressures, climate change has already caused faster biodiversity declines than in terrestrial or marine ecosystems over the past 30 years.

Approximately 20 percent of the world’s freshwater fish species have been listed as threatened, endangered or extinct (MEA, 2005a). However this has been mainly due to anthropogenic impacts and the role of climate change cannot be clearly identified.

Freshwater species in lotic and lentic systems are typically exposed to large changes in water temperatures and availability of dissolved oxygen. Rising water temperatures decrease dissolved oxygen. Fish spawning seasons will be affected by temperature rise. In lotic systems, changed precipitation patterns and increased evaporation can affect water regimes and alter water availability (Ficke, 2007). Although 70 percent of the world’s rivers are projected to experience increased water availability with climate change, the remaining 30 percent will be negatively affected. Fundamental changes in water regimes are likely to cause the loss of a significant share of species in those basins by 2100 (MEA, 2005b). Recent studies show that up to three quarters of local fish species in rivers with reduced water flow are threatened with extinction by 2070. Climate change plays a crucial role in reducing river discharge which, linked with increasing water abstraction and other anthropogenic pressures, particularly agriculture and energy generation, is expected to lead to even higher fish extinction rates (Xenopolous *et al*., 2005).

In lentic systems, whole habitats can be greatly reduced or can disappear because of lack of rains. Some large African lakes, such as Lake Chad and Lake Turkana have long histories of shrinkages and expansions. Some smaller lakes dry completely from time to time, sometimes removing for years the fisheries upon which local people have depended, as well as destroying biodiversity and genetic resources. Re-establishment of fish populations is sometimes possible only from very small surviving stocks in feeder streams or other refuges. Lake Chilwa, Malawi, is a good example of such “closed-basin” lakes. In good years, it supplies up to a quarter of Malawi’s food fish (Allison *et al*., 2007), but it dries out periodically. With rainfall declining over southern Africa in recent years, dry periods have become more frequent and fish yields are declining accordingly. In contrast, extreme floods can cause the temporary merging of previously separated waters and their biota, mixing together aquatic genetic resources. Climate change is likely to exacerbate these problems for rivers and lakes.

Brackishwaters

Climate change affects estuaries, lagoons and other brackishwaters in coastal zones via sea level rise, as well as extreme weather events, such as storms and hurricanes and increased precipitation affecting runoff. Estuarine environments are particularly affected by hurricanes and storms. These habitats can be damaged through direct wind or wave action and can be altered by unusual loadings of freshwater, nutrients, sediments and pollutants. The amount of rainfall and subsequent runoff vary tremendously between storms. Freshwater inputs during and after major storms, particularly hurricanes, determine the mortality among sessile brackishwater and marine organisms, as well as the displacement and mortality of mobile species. The mesohaline region of estuaries is generally the most impacted by runoff during such events. When runoff reduces the salinity in this region to less than 10 psu for more than a week, extensive mortality occurs among benthic organisms such as sponges, bryozoans, coelenterates, molluscs and tunicates, (Andrews 1973; Smock *et al*., 1994). Some species, particularly those with limited dispersal capacity, can be eliminated. Further, if stress from the dilution of salinity coincides with the breeding season of a particular organism, its fecundity and survival will be affected.

Aside from reducing the overall salinity regime, runoff adds inorganic nutrients, dissolved organic nutrients, and sediments to the estuary (Paerl *et al*., 1998). More than 50 percent of an annual nutrient loading to coastal waters can occur during a single, large runoff event. Runoff from tropical storms and hurricanes can load more than a year's worth of sediment into an estuary within several weeks (Gross *et al*., 1978). Sedimentation affects the benthic community directly by burying many benthic organisms so they cannot feed effectively. The sediments represent a large source of organic carbon and increase biochemical oxygen demand (BOD) during the warmer months. The initial anoxic or hypoxic conditions produced by storm runoff are often not the result of bacterial action on increased algal production, but rather the immediate metabolism of organic material in the sediment (De Casabianca *et al*., 1997).

Nitrogen and phosphorus in the runoff play a direct role in stimulating phytoplankton growth. In addition, most tropical storms occur in the warmer months, when phytoplankton populations are actively growing. Under these conditions, they take up inorganic N and P and grow more rapidly. The same applies during smaller storm events that contribute nutrients to estuaries. The phytoplankton biomass increase generally occurs within a week following nutrient input and lasts for a few weeks up to three months, depending on the extent of loading (Litaker and Tester, 2003). In estuaries where flushing rates are high, excess nutrients and cells may be transported out of the system, resulting in smaller blooms than are found in lagoon systems, which can retain nutrients more efficiently. Phytoplankton blooms contain large quantities of carbon and are the bases of aquatic food chains. Zooplankton grazing communities are generally the major consumers of this increased productivity. However, zooplankton biomass is often significantly decreased following major runoff events (Litaker and Tester, 2003). This further favours the development of phytoplankton blooms and subsequent bacterial, rather than zooplankton, use of the newly produced carbon (De Casabianca *et al*., 1997). Studies of salt wedge estuaries that have experienced runoff events and blooms during warmer months indicate that if both the carbon supply from sinking phytoplankton and temperatures are sufficiently high, extensive bacterial respiration will cause the lower salt wedge to become hypoxic or anoxic (Litaker and Tester, 2003). Transient hypoxic or anoxic events similarly occur in shallow estuaries when the primary production is sufficiently high that the BOD consumes all or most of the oxygen in the water column. Though hypoxia and anoxia tend to slow down remineralization of organic compounds in the benthos, significant amounts of ammonium and phosphate can be released (De Casabianca *et al*., 1997).

Increased productivity following runoff events can have both positive and negative effects on fisheries. On the positive side, the increased productivity can result in a rapid increase in the abundance of certain invertebrates. For example, shrimp harvests can increase substantially the year after large runoff events caused by tropical storms, possibly because of increased productivity and disruption of predatory fish populations (Flint, 1985). On the other hand, certain parts of the estuary, with fairly low flushing rates and high recycling rates, can experience nuisance algal blooms, especially when there is little wind, greatly reducing the recreational value of the estuary and supplying enough carbon for the bacterial community to create anoxia and related fish kills (De Casabianca *et al*., 1997). Large amounts of freshwater coming into the system from heavy precipitation such as that associated with severe storms, can often dilute dissolved toxic compounds below harmful levels. Given sufficient outflow from the estuary during the event, they can then be largely eliminated. In that respect, high runoff can cleanse an estuary. However, upstream sediments that are contaminated with heavy metals, pesticides, or other harmful chemicals, can be flushed to an estuary and retained there, with some entering the food chain (De Casabianca *et al*., 1997).

There is widespread concern that the reduction in the pH of marine waters is altering marine habitats severely, but little or no attention has been given to the biota of estuarine and coastal settings, ecosystems that are less pH buffered because of naturally reduced alkalinity (Miller *et al*., 2009).

Marine waters

Climate change affects all marine ecosystems and biodiversity. The direct drivers include ocean warming, sea level rise, increase in wave height and frequency, loss of sea ice, increased risk of diseases in marine biota and decreases in the pH and carbonate ion concentration of surface oceans. Climate change drivers impact marine ecosystems globally, with high cumulative impacts and with particular importance for offshore habitats. The different factors influence directly the physiology, behaviour, growth, reproductive capacity, mortality and distribution of fish. More frequent extreme weather events and rising sea levels will lead to degradation of coastal ecosystems, including siltation and algal coverage of corals (CGRFA, 2009a).

Rising temperatures are implicated as triggers for the fastest changes in many marine ecosystems worldwide, altering the ranges, distribution and abundance of marine organisms (e.g. Hughes *et al*., 2003; Worm *et al*., 2006; Hoegh-Guldberg *et al*., 2007). These ongoing changes are expected to produce diverse functional, structural and ecological responses among aquatic organisms (Beaugrand *et al*., 2002; *Harvell et al*,. 2002; Parmesan and Yohe, 2003; Fabry *et al*., 2008; Byrne *et al*., 2009). Increasing sea surface temperatures are observed in the upper layers of the North Atlantic and Nordic Seas, where the seas were found to be warmer and more saline in 2006 than the long-term average (Hughes and Holliday, 2007). The upper ocean to the west and north of the United Kingdom has become saltier since the 1970s, but trends within the shelf seas are less clear (Pinnegar *et al*., 2006). Ocean temperatures around Australia have warmed by 0.7 °C since 1910-1929, with southwest and southeastern waters warming fastest (Pinnegar *et al*., 2006).

Any changes in biological processes in surface ocean waters will also affect deeper waters. Marine organisms living far from sunlight rely mainly on the products created by marine life in the surface waters. Deep-sea ecosystems remain relatively unexplored and are expected to contain thousands of new species of microorganism, invertebrates and finfish, especially in association with thermal vents and seamounts. Smith (2007) mentioned the paucity of genetic studies on the latter, even for fish that are being harvested commercially. These ecosystems and communities are as complex and vulnerable as coral reefs, though their great depths afford them much more protection from the impacts of climate change. The main current threats that they face relate to destructive methods of extraction, especially trawling with heavy gears.

On a global scale, climate change could cause a slow-down of thermohaline circulation, which is the large-scale ocean circulation that is driven by global density gradients created by surface heat and freshwater fluxes and forces extensive mixing between the ocean basins, reducing differences between them. Although little is known about the critical thresholds for abrupt and fundamental changes of these circulation systems, slight changes could impact marine ecosystem productivity, ocean chemistry and cause shifts in ecosystem composition for fisheries (MacKenzie *et al*., 2007, Nelleman *et al*., 2008). Changes in oceanic currents with climate are likely to alter the migration routes of fish and the dispersal of pelagic eggs and larvae.

Phytoplankton biomass is widely regarded as an indicator of the marine growing season. Observations show that phytoplankton biomass has increased considerably over the past few decades in parts of the Northeast Atlantic and the North Sea. From the late 1940s to the 1980s, the majority of production was restricted to bloom periods in spring and autumn. However, production during the winter and summer seasons has also increased since the late 1980s. This has considerable impacts on overall biological production and the food web (Leemans and van Vliet, 2004). Seasonal population peaks of decapod larvae and other zooplankton over the period 1948 to 2000 mirrored those of phytoplankton. From the 1990s, the seasonal development of some decapod larvae occurred up to 4–5 weeks earlier than the long-term mean (Leemans and van Vliet, 2004).

Climate change is also altering the distribution and abundance of some commercial marine fish. Trawl data from Scottish research vessels over 75 years, clearly showed that catches of the warm water pelagic species anchovy (*Engraulis encrasicholus*) and sardine (*Sardina pilchardus*) increased suddenly after 1995 (Beare *et al*., 2004). All these increases correlate well with the increase in temperature since the end of the 1980s (Leemans and van Vliet, 2004). Finfish and invertebrate species from warmer waters are spreading into new areas in northern Europe and the United States of America (Leemans and van Vliet, 2004). Increasing sea temperatures are allowing movements of plankton, fish and other species towards the poles. Examples of such movements have been recorded for plankton in the Northeast Atlantic, as well as for a number of warm temperate and subtropical fish species moving along the continental slope to the west of Europe.

There is increasing evidence that every part of the food web in marine systems is undergoing significant change. Some zooplankton species have shown a northward shift of up to 1 000 km. These shifts have been taking place southwest of the British Isles since the early 1980s, and from the mid-1980s in the North Sea (Leemans and van Vliet, 2004). An invasion of warmer water species into the cold temperate areas of the Northeast Atlantic has been observed. Warm-temperate and temperate species have migrated northward by about 250 km per decade (Leemans and van Vliet, 2004). In contrast, the diversity of colder temperate, subArctic and Arctic marine species has decreased. Changes in fish migration routes and in the productivity of fish stocks are expected with continuing warming. Temperature increases will enable more species to invade and become established in formerly cold waters, competing with and possibly replacing some cold water species, some of which will have their ranges reduced.

Subpolar regions, the tropics and semi-enclosed seas are therefore likely to experience some local species extinctions, while Arctic and Southern Ocean ecosystems face intense incursions by new species (Cheung *et al*., 2009). Increasing water temperatures can also shift the balance in favour of either the host or pathogen, changing the frequency and distribution of aquatic diseases and parasites.

Ocean acidification is expected to have substantial direct and indirect effects on marine organisms and their habitats. Direct effects include the impact of increasing acidity on organisms that build calcareous skeletal structures. Indirect effects include changes in availability or composition of nutrients and food organisms (Royal Society, 2005) Ocean acidification impacts will probably be seen first in the Southern Ocean, which contains a disproportionate amount of oceanic inventory of anthropogenic $CO_{2,}$ compared with other, warmer, oceans. Biogeochemical models indicate that the Antarctic polar waters will be the first to experience carbonate ion concentrations so low that shell-forming organisms will no longer be able to precipitate aragonite (The Royal Society, 2005). Recent evidence suggests, however, that the largest pH reductions (of up to 185 percent, equivalent to 0.45 pH units) in this century will occur in the surface waters of the Arctic Ocean if greenhouse gas emissions continue along current trends (Steinacher *et al.*, 2009).

Such waters might no longer support calcifying species, such as bivalves and pteropods, which play a key role in Arctic marine food webs. Time series observations in the Iceland Sea between 1985 and 2008 displayed similar scenarios: a winter decrease in surface water pH of 0.0024 per year, which is 50 percent faster than observations from subtropical time series stations and a faster rate of change than that observed in the deep sea (Olafsson *et al.*, 2009). The Royal Society (2005), however, concluded that "*the increase of CO_2 in the surface oceans expected by 2100 is unlikely to have any significant direct effect on photosynthesis or growth of most microorganism in the oceans.*" Some types of phytoplankton are also likely to benefit, although laboratory studies on this are not conclusive**.** Moreover, sea grasses and some phytoplankton will benefit from higher pCO_2 in seawater.

Reviews on the capacity of marine ecosystems to provide food and maintain environmental quality for fish, and also recover from perturbations, offer a bleak outlook (Jackson *et al*., 2001; Worm *et al*., 2006; Hughes *et al*., 2007). However, other studies of the relationship between biodiversity, ecosystem functioning and services produce a more disturbing picture (Vitousek *et al*., 1997; Hoegh-Guldberg *et al*., 2007; Cochrane *et al*., 2009; Mooney *et al*., 2009). Climate change can, thus, adversely impact fisheries production through causing direct changes to the behaviour, growth, distribution, reproductive capacity and recruitment of fishes. It can also have indirect impacts, which may include changes to the ecosystem productivity, structure and composition on which the fish depend for food and habitat. 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 Northeast Atlantic, where temperature change has been rapid (Beaugrand *et al*., 2002; Perry *et al*., 2005). Further changes in distribution of marine fish and productivity are expected due to the following: continuing global temperature increases; addition of freshwater to the oceans from the melting of sea ice; and thermal expansion of the oceans (Hansen *et al*., 2006; Rahmstorf *et al*., 2007).

6.2 Vulnerable Aquatic Ecosystems

All aquatic ecosystems are subjected to combinations of anthropogenic stressors including pollutants, excess of nutrients (e.g. eutrophication) and altered habitat and hydrological regimes (e.g. Vinebrooke *et al*., 2004; Adams 2005; Cardoso *et al*., 2005, 2008). The following aquatic ecosystems are regarded as being particularly vulnerable to these stressors, as well as to climate change.

Coral reefs

Coral reefs are among the most diverse marine ecosystems. They provide food and shelter for hundreds of thousands of other species (Royal Society, 2005), including an estimated 25 percent of known marine fish species, accounting for between 9-12 percent of world fish landings (Royal Society, 2005; UNEP, 2010). Coral reefs cover an estimated 1.28 million square kilometres of the world's tropical and subtropical well-lit and shallow waters, characterized by low water-column turbidity. The world's coral reefs are documented in ReefBase (www.reefbase.org) and the biology of world's reef-associated fishes is covered extensively in FishBase (www.fishbase.org). Corals are found from the tropics and mid-latitudes to even high-latitude cold waters. In contrast to corals in cold waters, warm-water corals are symbiotic with microalgae termed zooxanthellae.

Coral reefs are affected by ocean acidification, increasing sea temperatures, increased precipitation patterns, strong waves and currents, extreme weather events and sea level rise. These impacts overlap with human-induced damages. They are among the clearest indicators of the ecological impacts of climate change. Higher sea temperatures are causing extensive coral bleaching events and mass mortalities (Goreau, 1990; ISRS, 1998; Hoegh-Guldberg, 1999; Hodgson, 1999). Coral bleaching is the loss of symbiotic zooxanthellae from reef-building corals. Mass bleaching events, which often cover thousands of square kilometres of coral reefs, are triggered by small temperature increases, 1 to 3 ^{0}C above mean maxima. The loss of living coral cover then reduces the abundance of many reef-dwelling species (Leemans and van Vliet, 2004; CGRFA, 2009a). The intensity and scale of observed bleaching events have increased since the 1960s, and major bleaching events in 1998, 2002 and 2005 have negatively affected entire reef systems. Reef regions around the world experience varying thermal regimes, with corals adapted to the temperature range present at their specific locations. The Western Indian Ocean and the Caribbean are slightly cooler than the other tropical ocean basins. Reefs that are conditioned to cooler temperatures tend to have lower thresholds for bleaching of about 30 ^{0}C. Western Pacific reefs generally have a higher bleaching threshold of around 30.5 ^{0}C. Peak warming events took place in the Western Indian Ocean and Northwestern Pacific in 1997–1998, off the north of Australia and in the Central Pacific during 2003-2004, and in the Caribbean in 2005. About half of the reefs affected by bleaching recovered subsequently (Hoegh-Guldberg, 1999). Staghorn coral (*Acropora cervicornis*) and Elkhorn coral (*Acropora palmata*) are now expanding their range northwards along the Florida Peninsula and into the northern Gulf of Mexico (Precht and Aronson, 2004). Corals in the Northern Hemisphere will spread northwards in response to the increases in temperature.

Ocean acidification is likely to impact coral growth and distribution significantly (Caldeira, 2007; Hoegh-Guldberg *et al*., 2007; Feely *et al*., 2009). If atmospheric CO_2 doubles or triples above present levels, reef-building corals could become rare, on tropical and subtropical reefs, by the middle of this century (IPCC, 2000) Over long timescales, reefs that are critical for the protection of coastlines across tropical and subtropical regions may start to disappear, as the rates of erosion start to exceed calcification rates (Burke, 2004). Ocean acidification and increased thermal stress are the likely causes of a more than10 percent reduction in the growth rates of massive Porites corals on the Great Barrier Reef (Hoegh-Guldberg, 1999).

Coral reefs have low tolerance to reduced salinity and high turbidity from run-off. Salinity trends over the past 50 years have varied significantly among coral reef systems. Some oceanic waters have become more brackish in South and Southeast Asia, the Northern Pacific and the Caribbean, where rainfall increased from 1979 to 2009. On the other hand, the ocean has become saltier in the Southern Hemisphere, which is likely related to decreased rainfall over Africa and the subtropical Pacific. Interconnections between salinity and hydrology also suggest that increased rainfall in Southeast Asia and the Amazon region generates river plumes that extend offshore into reef environments. Associated sediment loading and harmful nutrients have negative impacts on reef ecosystem health (Hoegh-Guldberg, 1999).

Waves and currents influence significantly the location and diversity of coral reefs. Some coral species are better suited than others to high-wave environments. In general, “massive” corals are less affected by wave action than “branching” corals. Slow-growing massive often form a higher fraction of the coral population in swell-exposed areas, low-swell locations. The strong waves generated during tropical cyclones can exceed normal conditions on all parts of the reef, overturning colonies, breaking coral branches and causing extensive reef damage. A build-up of rubble and excess sediment can also occur, reducing the availability of suitable substrate (Hoegh-Guldberg, 1999). Changes in currents can affect coral reefs through a reduction (or increase) in mixing between surface and deep waters (with follow-on effects of changes in nutrient levels) modified advection of waters (which can influence connectivity between reef systems, particularly in the open ocean) and potential changes in lagoon flushing rates (Hoegh-Guldberg, 1999).

Some tropical cyclones can benefit coral reefs by alleviating thermal stress. First, heat energy from surface waters is transferred into the atmosphere through evaporation. The amount of heat transferred is related to the intensity and extent of the tropical cyclone. Second, surface water temperatures are cooled via increased mixing of deeper waters, the magnitude of which depends on wind speeds and water temperature variations with depth. Third, the ocean surface is shaded by clouds, which allows further cooling of the water and reduces light stress (Hoegh-Guldberg, 1999). Sea level rise can provide corals with greater space to grow. While corals are growing, however, and have not yet fully occupied this new space, there is the potential for increased wave action, which can damage corals. Of greater potential importance for corals is increased sedimentation due to erosion from land areas that are newly exposed to seawater.

Sea grass beds

Sea grass beds are disappearing at an alarming rate. Their loss represents a twofold threat: reduction of fish feeding grounds and nurseries; and diminished protection of sandy coasts against erosion. Increasingly, sea grass beds are at high risk from coastal development pressures, including port expansions and land reclamation. These development impacts are occurring against a background of regional and global pressures on sea grass beds, associated with climate change.

Sea grass beds are found in very shallow tropical, subtropical and temperate waters, which are exposed to large temperature fluctuations, including extreme heat waves. Genetic diversity among and within populations of sea grasses and their associated biota (especially microorganism, epiphytes, and benthic and fossorial invertebrates and finfish) is likely to be crucial for the stability of sea grass communities challenged by extreme climatic events and long-term climate change. Reusch *et al*. (2005) found 126 genotypes in a Baltic population of the vegetatively reproducing eelgrass (*Zostera marina*) and studied six genotypes, as clones, in experimental plots on an eelgrass meadow in heat wave (ca. 25 ^{0}C.) conditions. The different genotypes varied in their responses: from a 3-fold increase in shoot density to inability to recover from a 50 percent loss in shoot density. Comparisons between one- and six-genotype eelgrass plots also showed that the latter supported higher abundance, though not higher diversity, of associated epifauna, including grazing and filter-feeding molluscs and crustaceans. The authors concluded that any loss in genotype diversity within a species such as eelgrass, upon which a whole, relatively species-poor ecosystem depends, could be as serious as the loss of species diversity in species-rich ecosystems.

Based on more than 215 studies and 1 800 observations dating back to 1879, sea grass beds have been disappearing at a rate of110 square-kilometres (42.4 square-miles) per year since 1980, due to direct impacts from coastal development and dredging activities and indirect impacts of declining water quality (Hughes *et al*., 2009; Waycott *et al*., 2009). Sea grass populations in Asia, North America and Europe are on a steady decline. In Africa, sea grass beds have declined at an alarming rate (Watson *et al*., 2000). The ecology and biological communities of the sea grass meadows of Florida Bay are being changed by rising temperatures, eutrophication, decreased primary productivity, reduced oxygen levels, excessive plant growth and decay, and reduced water quality (WWF, 2010).

Mangroves and other coastal forests

Mangrove ecosystems are typical formations found in coastal deposits of mud and silt throughout the tropics and some distance into the subtropical latitudes. Mangroves comprise about 70 species in 20 families (Primavera *et al*., 2004). Across Asia, average mangrove loss has exceeded 60 percent in recent decades (Primavera, 1995; 2005). The world total area of mangroves has decreased to less than 15 million ha. Thousands of hectares have been cleared for shrimp farming and other forms of coastal development (Watson *et al*., 2000). Mangrove ecosystems are of immense importance as coastal protection barriers and as spawning and nursery grounds for many finfish and invertebrate species.

With climate change added to anthropogenic stressors, mangrove and other coastal forests are expected to experience significant losses of biodiversity and ecosystem services (CGRFA, 2009a) Climate change will disrupt further the balance between fresh and salt waters in mangrove areas. Sea level rise will affect mangroves by eliminating or modifying their present habitats and creating new tidally inundated areas to which some mangrove species may shift (IPCC, 2001), though some mangroves will be reduced where they have limited scope for spreading inland. Pacific Island mangroves face substantial reductions (Gilman, 2008). Regeneration periods will be reduced and local extinctions of mangrove species might occur in Antigua and Barbuda as soon as 2030 (CGRFA 2009a). Expansions of mangroves into salt marsh habitats in southeast Australia and into freshwater wetlands in northern Australia are driven by sea level rise and by soil subsidence associated with reduced rainfall respectively (Hoeng-Guldberg, 1999; Watson *et al*., 2000).

Mangroves and other coastal forests are also affected by extreme weather events. Tropical storms and typhoons can cause severe physical damage. Mortality and damage occur from uprooting, stripping of leaves and limbs and salt spray damage. This periodic damage creates open space, but also removes peat deposits, and can bring poisonous anoxic sulphide-rich sediments to the surface. The sulphide released from the mud kills weakened trees and saplings. Despite the damage, the mangrove and other plant communities gradually respond with increased productivity after the storm and generally recover until the next storm produces similar damage. The immediate effect of storms is the degradation of habitats for mangrove-associated species.

Agricultural wetlands

Agriculture is often categorized broadly as rain-fed or irrigated, and is mostly situated close to reliable sources of freshwater and in, or adjacent to, wetlands. Much of inland aquaculture is situated in agricultural wetlands; for example, in the rice-lands and peri-urban swampy areas of Asia. These areas are vulnerable ecosystems, which are threatened by impacts from other sectors that impinge upon their land and water space and which pollute them with solid and liquid wastes. Erwin (2009) emphasized that freshwater wetlands, including marshes and swamps, are likely to suffer widespread stress through climate change, with some disappearing completely and others being changed significantly.

Agricultural wetlands, including those that are used for the farming of rice and other crops, often contain wild aquatic plants and fish that are harvested by the rural poor (Halwart and Bartley, 2005). Halwart (2008) reviewed the huge benefits in terms of nutrition and livelihoods that can accrue to rural communities from the very wide plant and animal diversity in aquatic rice-based ecosystems. Other multipurpose agricultural wetlands, such as the dambos of Africa, have high potential for aquaculture. Agricultural wetlands contain a wide diversity or wild, farmed and feral aquatic species, which perform ecosystem services for agriculture, aquaculture and inland fisheries, and supply a large range of human and animal foods and other products. The many benefits obtained from agricultural wetlands, including their roles as carbon sinks, are underpinned by aquatic genetic resources. The keys to sustaining these benefits are good water management and avoiding the use of chemicals that damage or kill aquatic organisms.

Some agricultural wetlands contain aquatic genetic resources of potential importance for the development of aquaculture. For example, wild tilapia populations from the Nile Delta have had immense importance in tilapia breeding programmes (e.g. Eknath *et al*. 1993) and black-chinned tilapia (*Sarotherodon melanotheron heudelotii*) from wetlands known as the Niayes of Thiaroye, in the suburbs of Dakar, Senegal, have been shown to grow faster than populations of the same species from other sources (Gilles *et al*., 1998). Drainage of marginal and peri-urban wetlands for more intensive agriculture or other land uses, and their pollution by agriculture, human settlements and industry, not only compromises their roles as carbon sinks, but can also threaten important aquatic genetic resources.

Flooded forests

Annually flooded forest areas on tropical freshwater floodplains are sensitive ecosystems that are vital for sustaining high terrestrial and aquatic biodiversity. Flooded forests are important feeding, spawning and nursery areas, as well as migratory pathways for fish targeted by inland fisheries. The extensive low forests of Amazonia and adjacent lands are submerged by up to 11m, with associated macrophytes forming a "floating lawn", and a highly diverse fish fauna. De Jesús and Kohler (2004) described the pressures on some of these ecosystems, especially the problems of overfishing, and pointed out that reliably long and deep floods provide for increased productivity and diversity. More fragmented flooded forest areas in other large basins, such as the lower Mekong, also support important inland fisheries that have similar dependence on adequate and predictable flooding. Dams, water abstraction and pollution are reducing the quantities and quality of waters reaching such areas. Short-term climate fluctuations and long-term climate change that threaten the timing and extent of floods will not only reduce inland fisheries catches in flooded forests, but will also impact adversely the life cycles of fish that make temporary use of them and then become exploitable resources in other areas of the floodplains. Climate change adds additional stress to the adverse effects of continued deforestation in the flooded rainforests, increasing biodiversity losses, reducing rainfall and runoff within and beyond basins, and affecting the global carbon cycle.

VII. CLIMATE CHANGE AND AQUATIC GENETIC RESOURCES

Microalgae and other aquatic microorganisms

Five species of microalgae and cyanobacteria are currently farmed for food and health products and microalgae are widely cultured as live feeds for use in fish hatcheries, with diverse species and strains maintained by a network of *ex situ* culture collections. Probiotics for use in aquaculture feeds and production systems have been under development since the late 1980s and are increasingly used to improve feed conversion, disease resistance and productivity. Anthony and Philip (2008) listed the following categories and numbers of probiotics tested for use in aquaculture: Gram-positive bacteria, 14; Gram-negative bacteria, 2; others (bacteria and yeast products, bacteriophages, yeasts and microalgae), 5. Mass culture of microalgae has high potential for the production of biofuels. Bacterial flocs are used as fish feeds in aquaculture, and bacteria are used as probiotics to enhance the detrital foodweb in fishponds and the health of farmed fish.

Phytoplankton productivity and blooms are the basis for aquatic food chains: the major means by which carbon is fixed by and in aquatic biota. As climate change proceeds, with significant warming of some surface waters, concurrent with their increased nutrient enrichment, the intensity of algal blooms in coastal and inland waters will increase. The pros and cons of algal blooms are complex. More phytoplankton means more food for zooplankton and, directly, for phytoplanktivorous fish, as well as more oxygen production.

Microalgae emit oxygen during photosynthesis, but become net consumers of oxygen at night and under heavy cloud cover, causing temporary hypoxia. Decomposition of collapsing phytoplankton blooms can cause severe hypoxia. Blooms also attenuate the light in the water column upon which other aquatic plants depend. Long-term climate change is likely to cause shifts in the habitat ranges of microalgae, interactive with increased nutrient runoff from coastal lands. Microalgae and other microorganism, in warmer and more acidified oceans, will further expand oxygen-depleted zones (Hofmann and Schellnhuber, 2009), with negative consequences for many marine organisms. Gaedke *et al*. (2010) pointed out that biotic effects, such as grazing, can confound predictions based on climatic factors, but also forecast that increased cloudiness during warmer winters in the Baltic region will retard phytoplankton growth. Wagner and Adrian (2009) predicted that climate change will increase cyanobacterial blooms in lakes.

Macroalgae

About 20 species of macroalgae (seaweeds) are farmed for extraction of chemicals (carrageenan, agar and alginates) or for direct human consumption (McHugh, 1987, 2003). FAO (2008a) reported that seaweed farming had undergone an average annual rate of growth of 8 percent from 1970 to a total production of 15.1 million tonnes in 2006, worth US$7.2 billion. The local farming and hand gathering of many minor species of seaweeds are under-reported at the national level. East Asia, especially China and Japan, and Southeast Asia, especially Indonesia and the Philippines, are by far the most important regions producing edible and industrial seaweeds, but seaweed farming has also been increasing elsewhere, for example, in the United Republic of Tanzania (Rice *et al*., 2006). Crustose coralline algae help to stabilize coral reefs, make significant sediment contributions to these systems and are important food sources for finfish and invertebrates (Littler and Littler, 1984; Chisholm, 2000; Guinotte and Fabry, 2008).

Climate change could have negative impacts on the farming of some commercial macroalgae. Changes in salinity and increase in temperature range could enhance opportunistic species with short generation times as well as increasing pathogen transmission. High water temperatures combined with lowered salinity are factors linked to outbreaks of epiphytic filamentous algae (EFA) and “ice-ice” disease, which may reduce production of *Kappaphycus* (Ask, 1999; Daszak *et al*., 2000). Some macroalgae, such as *Hizikia fusiforme*, can increase their uptake of nitrate in the presence of high CO_2 and outcompete other seaweeds (Zou, 2005).

Seaweed farms are usually seeded through vegetative propagation. Many farm populations are wild types, but domestication and genetic improvement programmes have long histories for some important commercial species; for example, to develop cultivars of *Porphyra* spp. in East Asia. A strain of *Porphyra yezoenesis*, selected originally for good growth in northern Japan, was however found unsuitable for farming in the northeast of the United States of America and strains from four local *Porphyra* spp. were screened in preference (Yarish *et al*., 1998). Duarte *et al*. (2007) considered 19 seaweeds to be already domesticated.

Freshwater macrophytes

Edwards (1980) reviewed the importance of farmed and wild harvested freshwater macrophytes. Their genetic resources have been neglected to date in the development of mechanisms for the documentation, conservation and sustainable use of plant genetic resources. Among the 40 or more species of freshwater macrophytes that are farmed and wild-harvested as human food (e.g. watercress, water chestnut, lotus) or as green fodders (duckweeds) and fertilizers (Azolla) some are of great importance in the nutrition of poor rural and urban people; for example, water spinach (*Ipomoea aquatica*) in and around large Asian cities. Farmed and wild-harvested freshwater macrophytes are also used as ornamental species in the aquarium trade and for garden ponds. Hasan and Chakrabati (2009) reviewed the use of algae and aquatic macrophytes as fish feeds in inland aquaculture. Algae can supply only 10 to 15 percent of the dietary protein requirements of farmed fish and most species of floating, submerged and emergent macrophytes have little potential as fish feeds. The main exception is duckweed, which could be a major feed source in some polycultures. Azolla has some limited potential as a feed component. The genetic resources of most farmed and wild-harvested freshwater plants are important because of their uses as human food or as organic fertilizers, and are not analogous to those for the fodder plants of livestock.

Crustaceans

Crustaceans are important in capture fisheries and in aquaculture. Annual world production of farmed and fished crustaceans, which often enter the same markets, is about 5.8 million tonnes, valued at US$18 billion (FAO 2007, 2008). Copepods and other crustaceans in the zooplankton and benthic meiofauna, as well as krill (*Euphausia superba*), form huge biomasses in the foodwebs from which fish are harvested. The most important fished and farmed crustaceans are all marine and brackishwater decapods: crabs, lobsters, prawns and shrimps. Shrimp farming accounts for about 5 percent of world aquaculture production by weight and 15 percent by value.

Farmed freshwater prawns, mostly *Macrobrachium rosenberghi* and *Macrobrachium nipponense*, have an annual value of about US$2 billion, and the farming of other *Macrobrachium* spp. is beginning in Asia, Latin America and the Pacific (New, 2002; M.B. New, personal communication to RP). Freshwater crayfish (*Procambarus clarkii*, *Astacus* spp., *Pacifastacus* spp., *Orconectes* spp. and *Cherax* spp.) are also important in inland fisheries and/or aquaculture. Diverse strains of the brine shrimp, *Artemia salina*, and a variety of copepods are used as live foods in fish hatcheries. At least 60 crustacean species have been farmed, commercially or experimentally, and over 50 have been used in the aquarium trade (Pullin *et al*., 1998).

The purposeful or accidental spread of freshwater and estuarine crustaceans as alien species has caused large adverse impacts. Alien astacid crayfish have exterminated thousands of local populations of the five native European species and now threaten some of the 390 native North American species, which comprise 75 percent of the world's total (Lodge *et al*., 2000). Introduced Louisiana swamp crayfish (*Procambarus clarkii*) have changed lakes from being clear water, macrophyte-dominated to turbid, Microcystis-dominated (e.g. Rodríguez *et al*., 2003).

The Chinese mitten crab (*Eriocheir sinensis*) has spread throughout northern European estuaries and rivers from the Baltic to the Mediterranean, feeding on indigenous fauna and flora (Rainbow *et al*., 2003). In all such cases, any apparent gain in aquatic genetic resources as farmed and feral populations of new species must be viewed against the loss of wild aquatic genetic resources and irreversible changes to aquatic ecosystems, lessening or stopping completely the supply of their former goods and services. Farming of white-legged shrimp (*Litopenaeus vannamei*), as an alien species, accounts for over 80 percent of Asia-Pacific farmed shrimp production. No significant adverse ecological impacts have yet been recorded from introductions of this or other marine and brackishwater shrimp species.

All crustacean life history stages, including for many species their planktonic larvae, face the challenges of climate change, including ocean acidification, which could compromise exoskeleton formation and impair health and temperature tolerance (Metzger *et al*., 2007; Pane and Barry, 2007; Spicer *et al*., 2007), though definitive studies on this are lacking.

Hawksworth and Kalin-Arroyo (1995), citing Ward *et al*. (1992), gave the average total expected heterozygosity of 80 crustacean species as 0.052 ± SE 0.0005 and the proportion of total heterozygosity due to differences among populations (GST) as 0.169 ± SE 0.061. This suggests that there is scope for the genetic improvement of farmed crustaceans as well as for the adaptation of wild crustacean populations to changing environments, including short-term climate fluctuations and long-term climate change. However, local populations of most crustacean species show low genetic diversity (Thorpe *et al*., 2000). Penaeid shrimp genetics have long been studied for the purposes of identifying and managing fished stocks and for applications in aquaculture, particularly for developing disease-free or disease-resistant lines (e.g. Benzie, 1998).

Molluscs

Hundreds of marine and brackishwater mollusc species are fished and farmed. The most important, in terms of worldwide catches and values, are the cephalopods (cuttlefishes, octopus and squids), with probably over 50 species fished, but none yet farmed. Marine bivalve molluscs (clams, cockles, mussels, oysters, pearl oysters and scallops) are widely fished and farmed and marine gastropods (abalone, conches, topshells, whelks and winkles) are harvested widely in local capture fisheries. Farmed abalones (*Haliotis* spp.) are among the highest value species in aquaculture. Freshwater gastropods are important foods for benthic-feeding finfish and are used to limited extents for human consumption. Some freshwater mussels (Unionidae) are harvested for pearls. Worldwide, mollusc farming yields over 14 million tonnes annually, valued at about US$12 billion (FAO, 2008a). Mollusc fisheries yield about 7.6 million tonnes, comprising about 58 percent cephalopods, 23 percent bivalves and 2 percent gastropods (FAO, 2007a).

The geographical ranges of farmed mollucs have become larger through introductions for aquaculture. Introduced populations often adapt well to new environmental challenges, including climate fluctuations, and spread through natural spawning and distribution of planktonic larvae.

The geographical ranges of farmed and fished bivalves, including some hybrid populations, will therefore continue to change. For example, the West Pacific subtropical and temperate Manila clam, otherwise called the short-neck clam (*Ruditapes philippinarum*), recently became established on the south coast of England, after a controversial introduction for aquaculture (Humphreys, 2010).

Bivalve and pteropod molluscs are likely to be susceptible to ocean acidification (Gazeau *et al*., 2007; Kurihara *et al*., 2007; Fabry *et al*., 2008), but climate change will also enable some opportunistic species, such as the Pacific oyster (*Crassostrea gigas*) to spread and to be farmed and fished in newly warmed areas. Their pathogens and parasites will also spread. Two protozoan parasites of bivalves (*Perkinsus marinus* and *Haplosporidium nelsoni*) have spread northwards from the Gulf of Mexico to Delaware Bay and further, causing mass mortalities in Eastern oysters (*Crassostrea virginica*). It is thought that winter temperatures forbid the development and expansion of the MSX disease caused by *Perkinsus* (Harvell *et al*., 1999; Daszak *et al*., 2000), and the poleward spread of this and other pathogens can be expected to continue as winter conditions become rarer.

Hawksworth and Kalin-Arroyo (1995), citing Ward *et al*. (1992), gave the average total expected heterozygosity of 105 mollusc species as 0.145 ± SE 0.010 and the proportion of total heterozygosity due to differences among populations (GST) as 0.263 ± SE 0.036. This suggests that there is good scope for the genetic improvement of farmed molluscs as well as for the adaptation of wild molluscan populations to changing environments, including short-term climate fluctuations and long-term climate change. Thorpe *et al*. (2000) included molluscs among the exploited marine invertebrates for which some populations are likely to be cryptic species. They also pointed out that genetic variability is generally low in cephalopod populations, and that it is very important to manage fished squid stocks well. Overfishing the main genetic stock of a squid fishery for even a single year can eliminate that stock. Local wild and farmed populations of molluscs must therefore be seen as important genetic resources for the future of capture fisheries and aquaculture.

Other aquatic invertebrates

Many other aquatic invertebrates are important for food and agriculture, either as fished or farmed species, or as providers of ecosystem services (principally food and shelter) to fished and farmed species. For most populations of these species, information on their genetic diversity is either lacking or very limited. The most important fished and/or farmed species for human consumption are the edible echinoderms: sea cucumbers; and sea urchins, for their gonads. Diverse species from other phyla are also fished and/or farmed for human food, including coelenterates (jellyfish), echiurans (spoon worms), and tunicates (sea squirts). Reef-building corals are the bases for entire invertebrate and finfish communities. The aquatic larval stages of insects are the main foods of many exploited species of freshwater finfish. Diverse strains of the rotifer (*Brachionus plicatilis*) are important live foods in fish hatcheries.

The likely impacts of climate change on sea urchin and sea cucumber aquaculture and fisheries have not yet been studied. The weakening of the calcareous structures of sea urchins through ocean acidification is an obvious concern. Similarly, the growth and survival of sea cucumbers could be impeded by poor development of their spicules (Kinch *et al*., 2008). On the other hand, it is possible that climate change might reduce some of the predators of these valuable invertebrates, and that some of their algal food sources could be enhanced. Some disease outbreaks in sea urchins, causing lesions and reduced gonad development, have been correlated with higher sea temperatures (Lester *et al*., 2007).

Finfish

The world’s freshwater, marine and brackishwater finfish species number about 30 000 species. It is not possible to give accurate totals of the numbers of finfish species that are targeted by local and national capture fisheries, because statistics contain aggregated data for many species that are not named and are labelled as “*not elsewhere identified* (nei).” Aquaculture and capture fisheries are probably using over 5 000 food, ornamental, sport and bait finfish species. Finfish provide 15 percent of the total animal protein intake of around 2.9 billion people worldwide and the fisheries sector employs as many as half a billion people, many in subsistence fishing (FAO, 2008a). Many of the finfish species captured for human consumption are top predators of the food chain. Their harvesting, and particularly their overharvesting, has direct and negative impacts on the healthy functioning of many complex marine and aquatic food chains (Dungan *et al*., 1982; Myers and Worm, 2003).

Brander (2007) summarized the different climatic factors that influence directly the physiology, behaviour, growth, reproductive capacity, mortality and distribution of finfish stocks. Many of the most important genetic resources of finfish for inland fisheries and freshwater aquaculture are wild populations in waters that face some of the biggest adverse impacts from extreme climatic events, especially droughts and floods, and long-term climate change, especially water scarcity. Wild populations of tilapias in Africa are a prime example. Climate change is expected to affect freshwater finfish mainly through its influences on water availability and quality, especially in terms of higher temperatures and lower dissolved oxygen. Higher temperatures will also increase thermal stratification in temperate water bodies. Lentic environments depend upon wind-driven mixing to maintain oxygen levels. Changes in wind patterns will increase or decrease this mixing and will also affect the primary producers that supply oxygen and the microorganism that process wastes. The predictability, timing, frequency, duration, and inter-annual variability of peak and low water flows will also be altered with climate change. Freshwater finfish have evolved with their current hydrologic regimes and any changes will present them with new challenges to survival, growth and reproductive success. Melting of polar ice caps and thermal expansion of seawater will result in a sea level rise that will inundate important freshwater habitats in low-gradient rivers and river deltas. Increased temperatures could affect the toxicity and bioaccumulation of anthropogenic pollutants. However, increasing temperatures can have a positive effect on aquaculture of some species (increased growth rates, etc.) (see De Silva and Soto 2009 and De Silva 2011).

The most important genetic resources for freshwater fisheries and aquaculture are those of the fished and/or farmed carps, catfishes, characins, cichlids (especially tilapias), salmon and trout, but many other groups and species have local importance as food or for providing livelihoods through the aquarium trade. Mixed small indigenous species are extremely important for the food security and nutrition of poor people; for example, in Bangladesh (Thilsted *et al*., 1997). Diadromous finfish, that migrate to and from freshwater and marine waters, and are categorized as either: (i) anadromous species, such as salmons and sturgeons, which spawn in freshwater but grow and mature in the sea; or (ii) catadromous species, such as anguillid eels, which spawn in the sea, but grow and mature in freshwater. Eel and salmon species are fished and/or farmed in all regions.

The most important genetic resources for marine and brackishwater capture fisheries are those for clupeiods, gadoids, tunas, flatfishes, groupers, sharks and snappers, but hundreds of species from other groups have high importance, especially in multispecies coral reef and other coastal fisheries, on continental shelves and in the deep sea. Aside from the huge cage-farming operations for salmon, marine aquaculture uses a wide range of carnivorous finfish species, mainly flatfishes, groupers, sea basses, sea breams, snappers, tunas, yellowtails, and, to a limited extent so far, cobia. A few euryhaline finfish are farmed in marine, brackish and freshwater systems: principally the milkfish (*Chanos chanos*) and some saline-tolerant tilapia hybrids.

Climate change can affect the life histories of temperate marine finfish in many direct and indirect ways, including larval transport, larval connectivity, settlement and recruitment (early post-settlement survival and overwintering), growth rates, assemblage structure and range shifts, spawning and egg production (including nursery grounds). Climate change will affect fish catches, as well as the populations of invasive species. The spawning and early life history successes of many marine and brackishwater finfish species are temperature and oxygen related, including the timing of spawning events and egg hatching (e.g. Pauly and Pullin, 1988). Growth of fishes is generally temperature and oxygen dependent, but typically shows a thermal maximum (e.g. Munday *et al*., 2008). The indirect effects of climate change on finfish relate mostly to changes in habitats; for example, to key nursery habitats, such sea grass beds, mangroves and estuaries.

Some commercially important finfish have life cycles that involve obligatory migrations between spawning/nursery areas and feeding grounds. The impacts of climate on any ecosystems along these migration routes have large impacts on fish populations and on entire species. These apply particularly to diadromous migratory fish that have migrations to and from freshwaters and brackish/marine waters (e.g. eels, salmon and sturgeons). However, there are hundreds of fish species in marine ecosystems (e.g. herrings and tunas) and in rivers that must undertake long migrations to survive and reproduce. Many of the fish species of Amazonia, the Gangetic rivers, the Mekong basin and other large basins are migratory and are severely threatened by dam construction, pollution and water abstraction, in addition to climate change (e.g. Carolsfeld *et al*., 2003a).

Hawksworth and Kalin-Arroyo (1995), citing Ward *et al*. (1992) gave the average total expected heterozygosity of 195 finfish species as 0.051 ± SE 0.0003 and the proportion of total heterozygosity due to differences among populations (GST) as 0.135 ± SE 0.021. Grant (2007) summarized from earlier reviewers the total genetic diversity (HT), based on allozymes, for finfish as: freshwater (49 species), 0.062; anadromous (7 species), 0.057; and marine (57 species), 0.064. The corresponding average and median variances of allozyme frequencies among subpopulations (FST) were: freshwater, 0.222 and 0.144; anadromous, 0.108 and 0.081; and marine, 0.062 and 0.020. Within finfish species that are important in capture fisheries and/or aquaculture, there is often high genetic differentiation within wild and farmed populations. For example, genetic markers indicate that the wild breeding populations of European sea bass (*Dicentrarchus labrax*) are fragmented, not only between and within those of the Atlantic and the Mediterranean, but also between populations in the Eastern Mediterranean that are close together (Castilho and Ciftci, 2005).

Genetic variation among strains of farmed fish can have widespread and immediate applications. For example, some hatchery populations of the rainbow trout (*Oncorhynchus mykiss*) go through their spawning cycle twice a year, rather than the annual spawning cycle that is found in salmonids (Estay *et al*., 2010). Characterization of the genetic diversity of farmed finfish began to increase in the 1980s for the pursuit of genetic improvement in aquaculture. Information sources have continued to grow steadily, though mostly in forms that are not easily accessible by comparison with the information systems for plant, animal and forest genetic resources. Important sources of reference include the following compilations: Jhingran and Pullin (1988), Penman *et al*. (2005) and Jeney and Zhu (2009) for carps; Pullin (1988) for tilapias; and Agnèse (1998) for African freshwater fishes.

Marine Genetic Resources in Areas Beyond National Jurisdiction

The high potential value of MGRs in ABNJ became apparent after studies on the rich biodiversity of hydrothermal vents, seamounts and other deep seabed ecosystems. The UN General Assembly has invited FAO to contribute to the consideration of conservation and sustainable use of marine biodiversity in ABNJ. Some MGRs in ABNJ remain at or close to fixed locations on the seabed. Others move, as plankton or nekton, and will be derived from, or destined for, part-time residence within national Exclusive Economic Zones and inland waters. This applies particularly to migratory fish that have distinct and widely separated spawning, nursery and feeding grounds. Some MGRs in ABNJ will therefore comprise the same genetic material as that of some aquatic genetic resources in coastal zones. The potential roles of MGRs in ABNJ for adaptation to and mitigation of climate change have not yet been explored.

VIII. CLIMATE CHANGE AND AQUACULTURE SYSTEMS

Seed supply

Where seed supply in aquaculture is reduced or fails, aquaculture production is reduced or ceases. Seed supply for aquaculture comes from hatchery and nursery operations or from collection of wild organisms. With the exception of the few highly engineered hatcheries and nurseries that are in controlled environments and isolated from ambient temperatures, etc., hatcheries and nurseries are subject to the same climate change impacts and outcomes as aquaculture growout systems in terms of water quality and water supply. However, in many cases hatcheries are able to control water quality and so are less likely to be affected by climate change. From a genetic resources perspective, this has consequences for the entire aquaculture production cycle, because natural selection to hatchery and nursery environments acts strongly on fish broodstock and seed, in addition to any artificial selection that is practised. In particular, there can be very high natural mortalities in hatcheries and nurseries at early life-history stages: eggs, larvae, postlarvae, fry and fingerlings. Wild seed remain the basis for a minority of commercial aquaculture operations (e.g. for eels, mullet and most groupers) as well as for some rural subsistence aquaculture (e.g. De Silva and Phillips, 2007). Climatic change will reduce the availability of some wild seed for aquaculture.

Ponds

Most tropical and subtropical aquaculture is finfish culture in freshwater ponds. There are also widespread brackishwater and marine ponds, farming penaeid shrimp, carnivorous marine finfish and some herbivorous/omnivorous species, such as milkfish and mullets. Aquaculture ponds are mostly one metre or less in depth and range in area from less than one hundred square metres to tens of hectares. Ponds are subject to large diurnal and seasonal changes in water temperature. The main factors that contribute to determining pond water temperature are water depth, solar radiation, air temperature, wind velocity, humidity, water turbidity and pond topography. Rapid changes in air temperature are reflected rapidly in pond water temperatures, causing stress, impacting productivity and in extreme cases, fish kills. Freshwater ponds are prone to droughts, flooding and water quality changes, as well as to saline intrusions when they are close to coasts. In temperate regions, the main species farmed in ponds are catfish, carps, charrs and trout. The much larger pond farms of the tropics and subtropics raise mainly carps, tilapias, catfishes, freshwater prawns, characins and snakeheads. Brackishwater and marine ponds are prone to coastal erosion, storm damage and storm surges, as well as to large reductions in salinity after heavy rains or increase in salinity during droughts.

Tanks, raceways and self-contained recirculation systems

In urban and peri-urban aquaculture, stagnant freshwater tanks are used for farming some air-breathing fish species that are resistant to hypoxia; for example, clariid catfish. Tank aquaculture is subject to large variations in temperature, water quality and dissolved oxygen. In contrast, fast-flowing freshwater raceways, with highly oxygenated water, are commonly used for farming trout and other freshwater salmonids. The temperature, and therefore the dissolved oxygen, in raceway waters depend upon the water source, the rate of flow that can be sustained and the ambient temperature. Sustaining adequate water flow becomes a serious issue for raceway farming during reduced precipitation, especially in droughts, and with retreating glaciers. Bregnaballe (2010) provided a guide to recirculation aquaculture, describing it as both highly productive and environmentally friendly.

Some aquatic plants, such as microalgae, and fish such as eels, catfish, tilapias and many ornamental species, can be farmed in completely isolated and controlled environments, with recirculation of water and low or zero emissions, in similar manner to the production of salad plants, herbs and vegetables in hydroponic systems. These systems are costly. They are not yet contributing significantly to world supply of aquatic produce, but might become more attractive with climate change; for example, by contributing to multiple use/re-use of scarce freshwater and adding to its value in urban and peri-urban food production. This would require the development of breeds appropriate for those systems, drawing upon appropriate aquatic genetic resources from all sources, including genetic material from farmed, wild and feral populations.

Cages and pens

Cage and pen aquaculture is becoming an increasingly important (e.g. Halwart *et al*., 2007). Cages and pens are usually located in enclosed or semi-enclosed waters, which provide shelter; but new technology is allowing cage culture in more exposed, offshore locations. Cage and pen culture practices vary according to the species used and the environment. Most inland cage and pen culture occurs in tropical regions, primarily in reservoirs and lakes. Over-proliferation of cage and pen culture has often resulted in fish kills, disease outbreaks and lower profits, mostly as a result of overcrowding, overfeeding, declining water quality and disease (e.g. Abery *et al*., 2005; Ficke *et al*., 2007). In some inland water bodies, deoxygenation is caused by overturns, and restricts cage culture to one crop per year as opposed to two crops per year previously. Severe storms, reduced water quality from plankton blooms and land-based pollution threaten cage farming, especially in coastal waters. With the continued expansion of aquaculture, there is a trend for the development of offshore cage culture in larger cages with deeper nets located in deeper water. This culture technology will be less susceptible to water quality changes but more vulnerable to increasing frequency and intensity of storms.

Rafts and ropes

Raft and rope farming of molluscs and seaweeds has expanded rapidly, especially in coastal bays in Asia. Mollusc spat is either collected from the wild on ropes or produced in hatcheries. Rafts are used for different stages of the culture of oysters, clams and mussels. Trays, semi-rigid plastic mesh bags and cages can also be suspended from the rafts for nursery rearing of juvenile clams and oysters, and for growout of oysters. One of the most productive methods of off-bottom culture of single oysters is by means of trays suspended from rafts or long lines. These systems are also widely used for rearing juvenile clams up to the point where they can be seeded on tidal flats. The larval stages of farmed molluscs are pelagic and any changes in ocean circulation affects where they settle. Scallop spat are stocked into suspended pearl nets tied to a long-line deep enough to avoid temperature and salinity fluctuations. Once they have reached around 3 cm in size, the scallops are removed from the pearl nets, graded and either ear hung or put into lantern nets. These methods of mollusc production are still largely dependent on collection of spat from the wild and are therefore at risk from changes in recruitment and from any adverse effects of lower pH on mollusc growth and reproduction.

Tidal flat culture

Tidal flat culture of bivalve molluscs, such as clams, particularly the short neck clam (*Ruditapes philippinarum*), and oysters, is one of the world’s largest aquaculture operations; for example on the very extensive mudflats along the coasts of China and the Republic of Korea. Farmers rely heavily on natural spatfall for most species, but hatchery seed production and transplanting operations are also used to achieve desired stocking densities. In Canada, rigid trays, semi-rigid plastic mesh bags and cages are used for near-bottom intertidal oyster growing on racks as well as on-bottom intertidal oyster and clam nursery and growout systems. Climate change will alter greatly the ecology and boundaries of tidal-flat culture as the sea level rises and as extremes of temperature, precipitation increase. Another major factor will be the severe storms that change soft substrates and change the areas in which these species can survive and be profitably farmed. As with raft and rope culture of molluscs, larval recruitment for tidal-flat culture is prone to any changes in ocean circulation and the farmed organisms are at risk from increasing ocean acidification.

Integrated farming systems

Integrated crop–livestock–fish farming systems, and fertilization of fishponds with excreta and wastewater, have centuries-long traditions in China and neighbouring countries (Little and Muir, 1987; Edwards, 2004). Despite a large research effort and information base (e.g. Halwart and Gupta, 2004) rice–fish integrated farming has not been widely practised, and integrated farming systems in general have declined as intensification of fertilization practices and feedlot systems has separated their previously interdependent component enterprises in pursuit of higher yields. Climate change might, however, encourage a return to some of the principles and practices of integrated farming, particularly with respect to multipurpose use of scarce freshwater resources and to pursuing intersectoral approaches as the norm, thereby spreading risks of harvest reductions and sustaining the health and productivity of watersheds. Integrated farming systems spread risks among multiple enterprises and produce. They can optimize use and reuse of resources, including feeds, fertilizers, energy and water, and reduce nutrient emissions.

Integrated Multi-Trophic Aquaculture (IMTA)

"Multi-Trophic" refers to the incorporation of species at different trophic or nutritional levels in the same system (Neori *et al*., 2004). "Integrated" refers to the more intensive cultivation of the different species in proximity to each other, connected by nutrient and energy transfers through water. IMTA is a practice in which the nutrients released from organisms that are fed are then recycled to become inputs (fertilizers, food) for others that extract their own food from the system. Fed aquaculture (e.g. fish, shrimp) is combined with inorganic extractive (e.g. seaweed) and organic extractive (e.g. oyster or mussel) aquaculture to create balanced systems for environmental sustainability through biomitigation (Chopin, 2006). Ideally, the biological and chemical processes in an IMTA system should be in balance. This is achieved through the appropriate selection and proportions of different species providing different ecosystem functions (Chopin, 2006). A working IMTA system can result in greater total production, from mutual benefits to the co-cultured species, and in improved ecosystem health. As with integrated farming and other multi-enterprise/multi-product systems, IMTA can spread economic risk and increase energy and nutrient efficiency.

Factors that make aquaculture more or less vulnerable, faced with climate change

Table 5 summarizes the factors that will tend to increase or decrease the vulnerability of aquaculture operations faced with climate change.

Table 5. Site, seed supply, production cycle, environmental tolerance and trophic level factors that will tend to make aquaculture more or less vulnerable when faced with climate change.

More vulnerable	Less vulnerable
Freshwater	Marine water
Shallow water (e.g. ponds).	Deep water (e.g. cages)
Wild fry/seed collection	Hatchery seed production
Long culture cycle	Short culture cycle
Narrow tolerance ranges	Wide tolerance ranges
High trophic level species	Low trophic level species

IX. CLIMATE CHANGE AND FISHERIES

Disaggregating climate change from other anthropogenic drivers of variability in fished populations is difficult. Most began to have significant effects before the availability of reliable time series for analytically derived or survey-based estimates of fish abundance and have had parallel histories of intensification over recent decades. Various drivers are interactive; for example, cod populations in the northeast Atlantic are more likely to be influenced by the NAO when their biomass is low, due to heavy exploitation, than when it is high (Brander and Mohn, 2004). Fishing, and in particular overfishing, can make fish populations more vulnerable to effects of climate change, as well as to the impacts of invasive species on population abundance and food-web dynamics (Brander, 2007; Daskalov *et al*., 2007; MacKenzie *et al*., 2007).

Culture-based fisheries

Culture-based fisheries are maintained by the regular stocking of fish and/or improvement of aquatic ecosystems to produce fish. The world's most successful culture-based fisheries are in inland waters, especially in closed systems such as lakes and reservoirs, using a wide range of warmwater species and hybrids, particularly carps and tilapias (FAO, 1999; Lorenzen *et al*., 2001; De Silva *et al*., 2006). Culture-based carp fisheries are operated on a large scale in Asian reservoirs and lakes, particularly in China (De Silva *et al*. 1991). Some European lakes are stocked regularly with coregonids. There are also major culture-based fisheries, commercial and recreational, for freshwater and diadromous salmonids.

The success of culture-based fisheries in coastal waters has been highly variable, with about 125 species having been tried (Mustafa, 2003). Politicians and the public often assume that mass seeding of coastal waters will always result in higher fisheries production, but proof of this is lacking for many operations, and the impacts of predation and movement out of fishing areas mean that some are not worth the large investments being made in hatcheries and environmental modifications such as artificial reefs. The prospects for success of culture-based fisheries in open marine waters are higher for invertebrate species that are relatively non-motile (e.g. molluscs and sea cucumbers) and for fish that either do not leave a the restricted environments upon which they depend for food and refuges (e.g. groupers) or that show highly predictable migrations to and from easily accessible and restricted home waters (e.g. salmon).

Inland fisheries

Inland fisheries production increased throughout the last half century and reached an estimated 10 million tonnes of fish and crustaceans in 2008 (FAO Fishstat, 2010). Nevertheless, inland fisheries production and values are often under-reported (Coates, 2002). The recent United Nations Environment Programme and WorldFish Centre study of inland fisheries estimated the world inland fisheries catch as probably around 20 to 30 million tonnes/year (UNEP/WorldFish, 2010).

Inland waters have high genetic diversity across freshwater invertebrate and finfish taxa, at inter- and intraspecific levels. Lévêque *et al*. (2005) stated that the world's freshwaters contain about 100 000 animal species, including 13 400 teleost fish, 10 000 crustaceans and 5 000 molluscs. In the present context, the most important aquatic genetic resources for inland fisheries are those of the fished species of freshwater food and ornamental fish, as well as those for their food organisms.

Grant (2007) found that inland fisheries target mostly naturally fragmented populations, many of which are at risk from inbreeding depression or hybridization with introduced fish, and that the loss of between-population genetic diversity in fisheries for diadromous species, such as salmon, has become serious as land-based development has proceeded. Inland fisheries are often overfished (Allan *et al*., 2005) and many inland aquatic habitats are being degraded or lost. Fish that spend any part of their life histories in freshwater are ten times more threatened than brackishwater or marine fish (Froese and Torres, 1999). Gopal (2005) forecast that climate change will pose increasing threats to Asian freshwater fish, largely through reduced availability of water. Ficke *et al*. (2007) predicted that climate change would lead to increasing stresses for freshwater fish globally, in natural and artificial systems, and emphasized increased water diversions by humans as a major factor. Climate change will alter temperatures, hydrological regimes and water quality in the freshwater ecosystems that support inland fisheries (Schindler, 2001), and can exacerbate existing problems such as overfishing, diseases and impacts of alien species. The continuity of watercourses and the connections between water bodies have been widely interrupted by dams, water diversions and flood-control structures, often hindering or preventing fish movements, with serious negative impacts on fisheries. All of this gives cause for concern for conservation and sustainable use of the aquatic genetic resources and ecosystems upon which inland fisheries depend.

Climate change presents some freshwater fishes with new environments in terms of temperature, food sources, spawning areas and challenges from pathogens, parasites and predators. However, higher temperatures mean lower dissolved oxygen and can exacerbate the toxic effects of common pollutants of freshwaters, such as organophosphates and heavy metals (e.g. Murty, 1986). The temperature tolerance ranges of aquatic organisms are species specific and include both stenothermal (narrow thermal range) species such as Arctic charr (*Salvelinus alpinus*) and eurythermal (wide tolerance range) species such as common carp (*Cyprinus carpio*). Sublethal impacts on fish physiology, particularly on growth and reproduction, can cause significant changes in the structure and composition of freshwater flora and fauna, from the tropics to the boreal regions. Some temperate fishes, such as salmonids, cannot reproduce successfully when the low winter temperatures that are essential for their spawning and egg stages no longer occur. Elliot and Elliot (2010) noted that winter stream temperatures in southern Britain and Ireland will soon exceed the upper lethal limits for survival of Atlantic salmon and brown trout eggs if the present rates of temperature increase continue. For tropical freshwater fish living in marginal habitats, the effects of warming will be similar to those predicted for temperate systems. The geographical ranges of fish in warmed boreal freshwaters are expected to contract, especially at lower latitudes, as they face competition from fishes whose temperate tolerances allow them to widen their ranges towards the poles (ACIA, 2004; Reist *et al*., 2006).

Inland fisheries are affected profoundly by changes in precipitation and run-off, with climate change increasingly implicated in reduced or unpredictable yields. Decreased flows have negative impacts on freshwater fish and inland fisheries, especially in the tropics (Welcomme, 1979). Lake and river fisheries in Africa are impacted heavily by reduced water levels. With rainfall levels declining over southern Africa in recent years, dry periods have become more frequent and fish yields are declining accordingly (FAO, 2007b). Many inland fisheries are impacted severely by reduced water flows and by water abstraction for agriculture, domestic supply and industry. Climate change has already begun to affect seriously the flow regimes of streams (Mauget, 2003). Fish in lotic systems are adapted to specific hydrological conditions and changes in these conditions can have negative effects on them and favour invasive species (Baltz and Moyle, 1993; Poff and Allan, 1995). Increased evapotranspiration can reduce the volume and quality of freshwater fish habitats during dry periods. The biology and ecology of fish in large rivers are strongly linked to the hydrological regime in the main channel and the regular flooding of the adjacent floodplain. The absolute and relative abundance and biomass of fish species inhabiting large rivers are predicted to change in response to both natural intra-annual variations in flooding regimes as well as long-term climatic shifts (Allison *et al*., 2004). The impact of climate change on river fisheries and fisher livelihoods is likely to vary greatly among river basins, according to regional differences in the effects of climate change on the hydrological regimes of rivers and floodplains.

Lower dry-season flows can facilitate saline intrusions, especially for extremely low-gradient rivers such as the lower Mekong and the Amazon. In dry years, when the Mekong’s discharge drops below 1 500 m^3/s, seawater penetrates the river system as far as 50 km from the coast (Hori, 2000). Increased saline water intrusions can reduce available habitats for freshwater fish species, leading to reductions in inland fish stock biomass. Rising sea levels can also increase erosion and inundate important freshwater habitats in the deltaic regions of temperate coastal streams (Wood *et al*., 2002). Dry-season flow rates are predicted to decline in southern Asia and in most African river basins, resulting in reduced fish yields. In the longer-term, larger changes in river flows are anticipated as glaciers melt, reducing their capacity to sustain regular and controlled water flows (FAO, 2007b). In basins where run-off and discharge rates are expected to increase the seasonal inundation of floodplains, fish yields might increase because of larger fish spawning and feeding areas. These benefits, however, might be offset by declines in dry season waters and fisheries. In Bangladesh, for example, a 20–40 percent increase in annually flooded areas could raise annual freshwater fish yields by 60 000 to 130 000 tonnes (Allison *et al*., 2005). In addition, changes to hydrological regimes and increased risks of droughts and flooding can increase incentives to invest in large-scale infrastructure projects, such as flood defences, hydropower dams and irrigation schemes, which are already known to have complex (and often negative) impacts on inland fisheries (e.g. Shankar *et al.*, 2004).

Small changes in the water levels of lentic systems will likely have minimal impacts on freshwater pelagic fishes, but could have more serious consequences for species with narrow bathymetric ranges, such as some of the cichlids in the African Great Lakes. These fish, which are important for local food security, inhabit shallow, sandy areas that form a small percentage of the total lake habitat (Ribbink, 1987). African Great Lake fisheries provide employment and contribute to food security, government tax revenues, domestic markets and exports, but are already experiencing high climatic variability, with fluctuations in primary production and fish yields. Underlying these fluctuations in some parts of Africa is a trend of declining rainfall and surface-water availability, and other factors that affect productivity, such as changing wind regimes. For example, Lake Tanganyika has important fisheries for small pelagic species. Declining wind speeds and rising water temperatures have reduced mixing of nutrient-rich deep waters with the surface waters that support pelagic fish production. Along with overfishing, this may be responsible for declining fish yields (FAO, 2007b).

Temperate freshwater lake fishes that rely upon littoral vegetation for reproductive success often fail to produce strong year classes in drought years when lake levels are low (Moyle and Cech, 2004). Small changes in water levels will reduce or eliminate these crucial habitats, with reduced recruitment to fisheries. In temperate and subarctic lentic systems, climatic change can have profound effects on primary production and the trophic state of inland waters through changes in water temperature and stratification patterns (Lofgren, 2002). The trophic status of aquatic systems is defined by nutrient concentration. Rising air temperatures will increase surface water temperature and influence thermal stratification in rivers, lakes and freshwater wetlands. Higher frequencies of extreme temperatures in summer and reduced winter freezing are likely to affect thermal stratification and species composition of lakes. Warmer winters will increase open-water evaporation rates and reduce water levels, unless offset by increases in precipitation or changes in other factors that affect evaporation rates.

Precipitation, wind and stratification affect the trophic status of inland water bodies, especially in the tropics (Bootsma and Hecky, 2003). The natural trophic state of an aquatic system is a function of volume, water-residence time, and nutrient input from the surrounding watershed (Kalff, 2000). However, climate change can alter the trophic status of aquatic systems. Lower stream flows could increase water residence times and reduce flushing of nutrients from lake systems, thereby increasing trophic status (Bertahas *et al.*, 2006). Likewise, an increase in stream flows and rates of flushing of pollutants could reduce eutrophication rates. Increases in temperature may enhance eutrophic conditions by stimulating explosive macrophyte growth. Changes in trophic state often affect fish communities negatively, through direct effects on macro-invertebrate prey and through effects on the algal community that support the zooplankton (Adrian, 1998). The general result of eutrophication in temperate lakes appears to be the replacement of more economically important species, such as salmonids and centrarchids with smaller, less desirable, species such as some cyprinids (Persson *et al.*, 1991) and gizzard shad (*Dorosoma cepedianum*) (Bays and Chrisman, 1983). Tropical inland water temperatures do not fluctuate seasonally as much as those in temperate and subtropical zones. Therefore, nutrient cycling in a tropical lake, is largely a function of wind-induced mixing (Kurki *et al.*, 1999).

Freshwater species distributions could shift polewards. Widespread species extinctions are likely at lower latitudes. Expansion of the distribution of species is likelt at the higher latitudes of their ranges. For example, a 3.8 °C increase in mean annual air temperature is projected to eliminate more than 50 percent of the habitat of brook trout in the southern Appalachian Mountains, United States of America, whereas a similar temperature increase could expand the ranges of smallmouth bass and yellow perch northward across Canada by about 500 km. Whether fish are able to move or will become extinct in response to changes in or loss of habitat will depend on the availability of migration routes (IPCC, 2007b).

Coastal and open sea fisheries

FAO (2005) summarized recently the diversity and status of the world's marine fisheries, including a review on climate variability and its implications (Csirke and Vascocellos, 2005). Coastal and offshore marine fisheries target thousands of fish species. Fisheries for pelagic fish, including small-sized species (anchovies, herrings, sardines, etc.) and large-sized species (tunas, bonitos, billfish, etc.), contribute about 50 percent of the world catch from coastal and offshore waters. Fisheries for demersal fish (including flatfish, cods, hakes and haddocks) contribute about another 15 percent, with a huge variety of crustaceans, molluscs, other invertebrates, and finfish comprising the remainder. Hundreds of species of edible seaweeds, invertebrates and shore fishes, are hand-gathered by coastal dwellers, during low-tide periods on mudflats, rocky shores and inshore reefs. Long-term shifts in temperature, wind patterns and hydrological cycles and short-term climate fluctuations have occurred throughout the history of coastal and open sea fisheries. Most arid and semi-arid coastal states will be highly exposed to future increases in temperature, linked to changes in precipitation, hydrology and current systems. These will have serious impacts on fisheries livelihoods and food and nutrition security in many countries and especially in those with high nutritional dependence on fish and low capacity to adapt (FAO, 2007b).

Coastal fisheries

Coastal fisheries exploit wetland, estuarine, coral reef and near-shore areas. Many coastal fisheries have declined markedly because of overfishing and the degradation of coastal ecosystems by agriculture, human settlements, industry and tourism. Countermeasures have had very limited success to date, though well-sited and well-managed marine protected areas are beginning to pay dividends. Coastal fishing operations are often disrupted by poor weather, and extreme climatic events damage fishing vessels, gear and shore-based infrastructure. Coastal cities are increasingly at risk from sea level rise and extreme weather, especially in rapidly developing Asian economies (Nicholls *et al*., 2007).

Grant (2007) found extinction of genetically unique subpopulations and overall losses of genetic diversity to pose the greatest threats to genetic resources for coastal and offshore fisheries, and cited overfishing and climate change as causes. Coastal fish habitats and fishery resources will be impacted through sea level rise, warming sea temperatures, extremes of nutrient enrichment (eutrophication) and invasive alien species. Many small-scale traditional inshore fisheries depend upon highly vulnerable ecosystems, such as coral reefs, sea grass beds, mangroves and littoral forests. Two-thirds of the world's coral reefs occur in the territorial waters of developing nations, together with many other inshore fisheries resources, all of which are potentially vulnerable to impacts of climate variability. Most marine fish have planktonic early life-history stages (eggs and larvae) and many have nursery phases in highly vulnerable habitats such as mangroves and sea grass beds. Any adverse impacts on those habitats can reduce recruitment to fisheries. Coastal wetlands, including mangroves and sea grass beds, will be impacted by sea level rise, especially where coastal development restricts landward expansion of the ecosystem (Nichols *et al.*, 2007).

Coral reefs fisheries are at risk from the elevated water temperatures that cause coral bleaching and from ocean acidification, in addition to a range of more direct local impacts (Hoegh-Guldberg *et al*., 2007). Coral reefs in the western Indian Ocean region experienced very severe bleaching and mortality because of the El Niño of 1998 to 1999 and were bleached again in 2005. On inner reefs of the Seychelles, live coral cover dropped from 27 percent to 3 percent and coral-feeding fish species disappeared (Graham *et al*., 2006). Ecological studies undertaken in 2005 found a reduced abundance of small fish. This might indicate a time lag in the impacts of bleaching on commercially important fish, with the erosion of dead corals eventually affecting recruitment of commercially important fish species (Graham *et al*., 2007). Fishing, hurricanes, bleaching and disease have resulted in a loss of 80 percent of Caribbean hard coral cover (Glynn, 1988). The projected changes to coral reefs are likely to put the marine ornamental fish trade increasingly at risk (Warbitz *et al*., 2003).

Temperature is a determinant for the formation of aggregations and initiation of spawning behaviour of many fish. Climate change is expected to increase the frequency and severity of ENSO events and hurricanes and coral bleaching, and to have negative impacts on reef and reef-associated fisheries, many of which are important to the coastal poor (FAO, 2007b). Increased sea temperatures and heavy precipitation affect sea grass and mangrove communities, including the early life-history stages of commercially important fish. Further losses of mangroves are expected from severe storms. As species distributions change in response to climate change, small-scale fishers may be less able to adapt by following them, because of limited mobility. However, while some fisher folk will see the disappearance of their target species, others could see an increase in landings of species of high commercial value. For example, in the Humboldt Current system during El Niño years, landings of shrimp and octopus increase in northern Peru, while to the south, tropical warm-water conditions increase the landings of scallops. These species have higher market values than more traditional species and international markets have developed for them (Badjeck, 2008). Additionally, input of freshwater in estuaries may favour the appearance of brackishwater species. For example, during the El Niño of 1997 to 1998, increased rainfall in northern Peru changed salinity patterns in estuaries, favouring the mullet fishery (Badjeck, 2008).

Marine pelagic fisheries

Pelagic fish are caught in surface, mid- and deeper waters. The open seas that support marine pelagic fisheries are the largest ecosystems on Earth. Small pelagic finfish have an adult body size less of than 50 cm. Large pelagic finfish have an adult body size greater than one metre. Species of intermediate size, such as skipjack tuna, are typically grouped with the large pelagic species, which include the billfish (swordfish and marlin) and sharks. Most tunas are regarded as highly migratory fish, moving large distances at sea, but they are also marine pelagics and so are included here. Small pelagics are found typically in shallow embayments and shelf waters, whereas large pelagics range widely, in continental shelf waters and in the open ocean (Hunt and McKinnell, 2006). Many large-scale marine fisheries depend mainly on pelagic fisheries. Small pelagic fishes are particularly sensitive to climate variations (e.g. Jacobsen *et al*., 2001).

Pelagic cephalopod fisheries landings, mainly squids, were 4.3 million tonnes in 2006 (FAO, 2008a). Recent catch trends for the three main squid species show very different patterns. Catches of jumbo flying squid in the Eastern Pacific have continued to boom, growing almost fivefold since 2000. However, in the same period, catches of Japanese flying squid in the Northwest Pacific have declined. In the Southwest Atlantic, catches of the Argentine shortfin squid have recovered after a dramatic drop in 2004–2005.

Climate change is likely to have positive and negative impacts on marine pelagic fisheries. An extreme example of a positive impact is the potential creation of an entirely novel open water fishery as a result of the melting of the Arctic Ocean. The adaptive capacity of economies, fishing sectors, communities, individuals and governance systems will determine the extent to which they are able to maximize the opportunities created by new fisheries. In the open ocean, sea level rise will be of little consequence for pelagic species, and temperature change will be the main impact (Hobday *et al*., 2008). Temperature is one of the strongest drivers of pelagic fish distribution (Laurs *et al*., 1984; Kitagawa *et al*., 2006). For example, in Australia, increased sea surface temperatures associated with the increased southward intrusion of the boundary currents along the east and west coasts, appear to have resulted in the increased southward extension of the distribution of tropical and subtropical small pelagic fishes. Changes in rainfall and salinity are not likely to influence the large pelagic species in southern Australian waters, as the change in salinity in the open ocean is expected to be negligible. In contrast, changes in rainfall and salinity are likely to have a detectable effect on the distribution of pelagic fishes off Northern Australia. This is due to numerous large rivers discharging large volumes of low salinity, turbid water into coastal regions where sediment plumes may extend tens of kilometres offshore (Vance *et al*., 1998). Large pelagic fish are mainly visual feeders and are likely to be forced further from the coast to feed in clearer waters (Griffiths *et al*., 2007).

The distribution of marine pelagic stocks and catches can change across national boundaries. A lack of well-defined and stable fishery resource boundaries presents particular challenges for fisheries governance in the context of climate change. Changes in fish stock distribution and fluctuations in the abundance of conventionally fished and "new" species may disrupt existing allocation arrangements. For instance, changes in Pacific salmon distribution as a result of sea surface temperatures and circulation patterns have led to conflicts over management agreements between the United States and Canada (Miller, 2000). Similarly, it is forecast that temperature changes in the Pacific Islands could lead to a spatial redistribution of tuna resources to higher latitudes within the Pacific Ocean, leading to conflicts over the stock of tuna between industrial foreign fleets and national ones restricted to their EEZs (World Bank, 2000). Rigid spatial management tools, such as permanently closed areas to protect spawning or migration areas, management schemes based on EEZ boundaries, or transboundary fisheries management agreements, might become inappropriate for new spatial fish stock configurations. Temporal management instruments (e.g. closed seasons) may also become ineffective if the seasonality of target species changes in response to altered climate regimes. Industrial fisheries are also prone to the direct climate change impacts of sea level rise and increasing frequency and intensity of extreme weather (Nicholls *et al*., 2007).

In the Pacific, the ENSO has a major impact on the Peruvian anchoveta fishery, which contributes more than 10 percent of world fish landings and is the world's biggest source of fishmeal and fish oil. Its productivity depends on a seasonal upwelling of cold, nutrient-rich deep water. This is highly vulnerable to changes in climate and currents. Annual catches of Peruvian anchoveta fluctuated with the ENSO between 1.7 and 11.3 million tonnes during the past decade. Increased sea surface temperatures also bring in species that offer new fishery resources. For example, in Peru, during the El Niños of 1982 to 1983 and 1997 to 1998, penaeid shrimps and rock lobsters from the Panamic Province (Baja California to Ecuador) appeared in Peru (Arntz, 1986). These species, along with dolphin fish, tuna and diamond shark, created a new economic opportunity for the artisanal fishing sector (CAF, 2000). Positive indirect impacts for some fisheries may result from declines in other fisheries that compete for the same global markets. When the Peruvian anchoveta catch is reduced, other industrial fisheries can make high profits; for example, the Baltic sprat fishery from Denmark (MacKenzie and Visser, 2001).

The ENSO affects the distribution of tropical tunas (Lehodey *et al*., 1997). Climate change is likely to affect regional tuna fisheries in two major ways: by raising average ocean surface temperatures to levels currently experienced during medium-intensity El Niños (Timmermann *et al*., 1999) and by increasing year-to-year climate variability. The impacts are likely to be pervasive, affecting the distribution, abundance, and catchability of tunas. The distribution of tunas is affected by the location of the Western Pacific Warm Pool (WPWP), an area of surface waters with temperatures higher than 28 °C, that produces virtually all of the tuna caught by purse seining and destined for canning, whereas longlining of deep water tuna for sashimi is distributed across tropical and subtropical oceans. The WPWP is typically nutrient poor. By contrast, the colder waters of the central equatorial Pacific generate an upwelling of colder, nutrient-rich waters. These two ocean areas meet in a zonal band called the "cold tongue", the primary productivity of which is strongly affected by ENSO variability. During El Niño years the WPWP can extend eastward into the central Pacific by nearly 4 000 km. Tuna fisheries, particularly skipjack fisheries, move with the WPWP. During El Niño years, countries in the Central Pacific, such as Kiribati and Samoa, experience higher purse seine tuna catches. Countries in the Western Pacific, such as the Solomon Islands and Marshall Islands, enjoy higher catches during La Niña years. The northern movement of Pacific tuna stocks would mean that existing infrastructure (e.g. landing facilities and processing plants) would no longer be conveniently located close to the fishing grounds (Miller, 2007).

Harvests of skipjack tuna, the dominant offshore species in the tropical Pacific, are expected to increase in the medium term (2035) by nearly 20 percent relative to catches in 1980–2000, but may suffer a net loss by the end of the century depending on the extent of climate change. The increased skipjack harvest would not be evenly spread across the Pacific, however. The western parts of the region (primarily around Palau, the Federated States of Micronesia, Papua New Guinea and Solomon Islands) will see medium-term gains (about 11 percent), declining back to normal levels or even less by century end. In the eastern part of the region, skipjack catches could increase by nearly 40 percent in the medium term and remain at those levels or slightly less.

Marine demersal fisheries

Demersal fish are caught at or near the seabed, mostly on continental shelves. Marine demersal fisheries are very important commercially and are vulnerable to some of the impacts of climate change. The walleye pollock (*Theragra chalcogramma*) fishery in the North Pacific, including the Bering Sea, is one of the world's largest marine fisheries, contributing much the world's supply of white fish for convenience-food fish products. Genetic differences among walleye pollock stocks seem to be small (Kim *et al*., 2000).

Distribution shifts, generally northwards, have been documented for a range of demersal species in the North Sea and have been attributed to warming, although the effects of fishing cannot be excluded (Perry *et al*., 2005). For example, the southern European/Mediterranean red mullet (*Mullus barbatus*) extended its northward distribution, with North Sea landings from about 1990 (Pinnegar *et al*., 2005). Temperature influences on the production and distribution of plankton also affect the distribution of demersal fishes. The Gulf Stream has made it rare for winter temperatures of deeper waters in the northern North Sea to dip below 6 °C. Its demersal fishing grounds have warmed over the last 30 years and now show less seasonal temperature variation than those located further south, where winter temperatures can fall to 3 °C (Fisheries Research Service, 2010). Young cod (*Gadus morhua*) are found increasingly in the colder southern North Sea, whereas young haddock (*Melanogrammus aeglefinus*) are found more in the deeper northern waters, preferring temperatures above 5 °C. These distributions will shift further with climate change. In the northern North Sea, there has been a decline in the abundance of the copepod *Calanus finmarchicus*, an important zooplankton prey item for cod and other demersal fish larvae. This has been correlated with recent failures in cod recruitment (Beaugrand, 2002, 2003). Climate variability on a decadal scale might reduce recruitment to fisheries of winter spawning flatfish in the Bering Sea, possibly through dispersion of larvae to favourable near-shore nursery habitats (Wilderbuer *et al*., 2002).

Fisheries for highly migratory fish

Highly migratory fish include species that are diadromous – such as eels, salmon and sturgeons – and species that move large distances at sea and in freshwaters. All are vulnerable to climate change. The timing, routes and extents of fish migrations will be affected greatly by climate change. For example, salmon depend on the timing of seasonal events and use environmental variables as migratory cues (Friedland *et al*., 2003). Whalen *et al*., (1999) reported that peak migration of salmon occurs later in spring for tributaries with lower temperature and annual variation in the timing of peak migration of Atlantic salmon is related to variation in annual temperatures (McCormick *et al*., 1998). Reduced precipitation and water flow restricts upstream migration of salmon returning from the sea to spawn and may influence the ability of salmon smolts to migrate to the sea (Solomon and Sambrook, 2004). Few species will be as intensely affected by climate change as Atlantic salmon (Ottersen *et al*., 2004).

Glass eel recruitment depends on favourable speed and direction of currents (for transport) and suitable conditions for egg hatching and larval survival (temperature, food abundance). Variation in oceanic conditions may help explain variation in recruitment to coastal rivers. Long-term trends in oceanic conditions, either natural or human-influenced, including climate change, could profoundly affect eel fisheries. The decline of the European eel (*Anguilla anguilla*) has been reported since the 1940s in Northern Europe and since the 1980s in the rest of its continental range. Recruitment indices are strongly correlated with the NAO, sea surface temperature anomalies, and position of the Gulf Stream (Knights, 2003). Climate change is expected to affect American eels through changes in oceanic conditions (currents and vertical mixing) and sea surface temperatures.

Climate change will also have profound effects on fishes that migrate between open water masses, especially for feeding and spawning, and hence will affect their fisheries. Temperature is the main climate change factor that will affect fish migrations. For example, the flounder (*Platichthys flesus*) makes its spawning migration one to two months earlier when conditions are cooler (Sims *et al*., 2004). Basking sharks are sensitive to temperature variations as low as 0.001 °C (Brown, 2003). The interannual variation in relative abundance of basking sharks off southwest Britain was positively correlated with fluctuations in sea surface temperature (Cotton *et al*., 2005). At a local scale of 0.01 to 10 km, however, basking shark distribution and movements are largely determined by the abundance of adult copepods, *Calanus helgolandicus*, the distribution of which is also influenced by climate change (Sims and Quayle, 1998).

Deep-sea fisheries

Deep-sea fisheries are undertaken mostly at depths from 400 to over 2 000 m, on continental slopes and around seamounts, with some target species not yet adequately described and named. Smith (2007) reviewed genetic resources for the main target species – e.g. orange roughy (*Hoplostethus atlanticus*), the oreos (*Pseudocyttus maculates*, *Allocytus niger* and *Neocyttus rhomboidalis*), toothfish (*Dissostichus* spp.) and roundnose grenadier (*Coryphaenoides rupestris*) – and the evidence that most deep-sea fishes are harvested unsustainably and with serious damage to their supportive ecosystems and to other biota, especially ancient coral communities on seamounts. He emphasized the losses of genetic diversity that these irresponsible operations can cause to small, isolated populations. In the face of these non-climate related issues, little attention has yet been paid to the potential impacts of climate change on deep-sea fisheries. Increasing ocean temperature will probably be the most important influence on the fish and the fisheries (Wernberg *et al*., 2009). A major change in the community structure of the dominant epibenthic megafauna was observed at 4 100 m depth in the northeast Pacific and was synchronous with a major El Niño between 1997 and 1999 (Ruhl and Smith, 2004).

Factors that make fisheries more or less vulnerable, faced with climate change

Table 6 summarizes the factors that will tend to increase or decrease the vulnerability of fisheries operations faced with climate change.

Table 6. Ecosystem, seed supply, life history, environmental tolerance and mobility factors that will tend to make fisheries more or less vulnerable, when faced with climate change.

More vulnerable	Less vulnerable
Inland	Marine
Shallow water	Deep water
Long pelagic stage	Short pelagic stage
Complicated life cycle	Simple life cycle
Narrow tolerance ranges	Wide tolerance ranges
Sessile species	Mobile species

X. REGIONAL IMPLICATIONS OF CLIMATE CHANGE FOR AQUATIC GENETIC RESOURCES

Information on the predicted regional climatic changes shown in Tables 7 to 12 is taken mainly from IPCC Special Reports on Climate Change: Regional Impacts of Climate Change and UNFCCC (2006, 2010) The implications of the different predicted climate changes are covered in previous sections.

Africa

Africa is under pressure from climate stresses and is highly vulnerable to the impacts of climate change. Many areas in Africa have climates that are among the most variable in the world on seasonal and decadal time scales. Floods and droughts can occur in the same area within months of each other. These events can lead to famine and to temporary or chronic loss of livelihoods and suffering. Many factors contribute to and compound the impacts of current climate variability in Africa and will have negative effects on the continent's ability to cope with climate change. These include poverty, illiteracy and lack of skills, weak institutions, limited infrastructure, lack of technology and information, low levels of primary education and health care, poor access to resources, low management capabilities and armed conflicts. The overexploitation of land resources including forests, increases in population, desertification and land degradation pose additional threats. African nations possess a very wide variety of lacustrine, riverine and marine habitats, with more than 800 freshwater and marine species. Ten ichthyofaunal regions, based largely on present-day drainage systems, were delineated for Africa by Lowe-McConnell (1987).

With climate change, the climate in Africa is predicted to become more variable, and extreme weather events are expected to be more frequent and severe, with increasing risk to health and life (UNFCCC, 2010). This includes increasing risks of drought and flooding in new areas and inundation due to sea level rise in coastal areas. Africa will face increasing water scarcity and stress with a subsequent potential increase of water conflicts. Almost all of the 50 river basins in Africa are shared among several states, with many transboundary issues (UNFCCC, 2010). Climate change is an added stress to already threatened habitats, ecosystems and species in Africa, and is likely to trigger species migrations and lead to habitat reduction. Up to 50 percent of Africa's total biodiversity is at risk due to reduced habitat and other human-induced pressures (UNFCCC, 2010). The latter include land-use conversion due to agricultural expansion and subsequent destruction of habitat, pollution, poaching, civil war, high rates of land use change, population growth and the introduction of exotic species. In Africa, mangrove health is adversely affected by threats from increasing land-based pollution, decreasing freshwater discharge from rivers and overharvesting (Watson *et al*., 2000).

Coastal infrastructure in 30 percent of Africa's coastal countries, including Egypt, the Gambia, the countries of the Gulf of Guinea, Senegal, and the entire east-southern African coast, is considered at risk of partial or complete inundation due to accelerated sea level rise. For example, in the United Republic of Tanzania, a sea level rise of 50 cm would inundate over 2 000 km^2 of land, costing around US$51 million (UNEP, 2010). Future sea level rise also threatens lagoons and mangrove forests of both eastern and western Africa, and is likely to impact urban centres and ports, such as Cape Town, Dar Es-Salaam and Maputo. West and Central African coastal states (e.g. Angola, Cameroon, Gabon, the Gambia, Nigeria, Senegal, Sierra Leone) have low-lying coasts with extensive lagoons that are susceptible to erosion and hence are threatened by sea level rise, particularly because most of the countries in this area have major and rapidly expanding cities on the coast (Watson *et al*., 2000). Sea level rise and climatic variation may reduce the buffer effect of coral and patch reefs along the east coast of Africa, increasing the potential for erosion. In the United Republic of Tanzania and Mozambique, the degradation of the coral reef resources due to increasing population pressures and coral bleaching is one of the most important management issues (UNEP, 2006). Bleaching has caused the decline of 30 percent of the reefs, and the threats posed by a growing population are probably slowing their recovery. In Mozambique and southern United Republic of Tanzania, there have been increased rates of reef erosion, due in part to the bio-erosion of dead coral tables and plates (Watson *et al*., 2000).

Fisheries are important sources of revenue, employment and protein in Africa. In coastal regions that have major lagoons or lake systems, changes in freshwater flows, and more intrusion of saltwaters into the lagoons, would affect species that are the basis of inland fisheries or aquaculture (Bates *et al*., 2008). Table 7 summarizes the likely impacts and outcomes of climate change for Africa.

Table 7. Summary of predicted climate change for Africa

Temperature
• Higher warming (× 1.5) throughout the continent and in all seasons compared with

global average. • Drier subtropical regions may become warmer than the moister tropics.
Precipitation
• Decrease in annual rainfall in much of Mediterranean Africa and the northern Sahara, with a greater likelihood of decreasing rainfall as the Mediterranean coast is approached. • Decrease in rainfall in southern Africa in much of the winter rainfall region and western margins. • Increase in annual mean rainfall in East Africa. • Increase in rainfall in the dry Sahel may be counteracted through evaporation.
Extreme events
• Increase in frequency and intensity of extreme events, including droughts and floods, as well as events occurring in new areas.
Coastal zones
• Threat of inundation along coasts in eastern Africa and coastal deltas, such as the Nile Delta, and in many major cities due to sea level rise, coastal erosion and extreme events. • Degradation of marine ecosystems including coral reefs off the East African coast. • Cost of adaptation to sea level rise could amount to at least 5–10 percent of GDP.

Latin America/Caribbean

Latin America has exceptionally high biodiversity and a wide variety of ecosystems, climatic regions, topographies and land-use patterns. The region has already been experiencing climate-related changes with the frequency and intensity of extreme events, particularly those associated with the ENSO. The following sectors and areas are particularly vulnerable to climate change: the agriculture, aquaculture, fisheries, forestry and water resources sectors; the Andean glaciers; and the Amazon Basin (UNFCCC, 2006).

According to UNFCCC (2010), the Amazon Basin is one of the Earth's richest reserves of biodiversity. Thousands of species of plants, over a million insect species, more than 700 fish species, 1 000 bird species and over 300 mammalian species. The reduction of tropical forest area, especially in the tropical rainforests, will probably entail the loss of many species. Climate change threatens to affect substantially the Amazon region, which in turn is expected to alter global climate and increase the risk of biodiversity loss. By 2050, for a projected increase of 2° C surface temperature, severe species loss is predicted over central Brazil, Mexico and in dry areas of Argentina, Bolivia (Plurinational State of) and Chile. The central-eastern Amazon is predicted to undergo an irreversible process of "savannization".

Also according to UNFCCC (2010), as Andean glaciers become reduced, with some disappearing this century, there are likely to be serious effects on ecosystems. The Chacaltaya Glacier in Bolivia (Plurinational State of) is predicted to disappear within the next 15 years. Countries such as Bolivia (Plurinational State of), Chile, Ecuador and Peru, depend on glacial seasonal discharge for much of their water supply. High rates of glacier recession correspond with greater flows of water, which cause erosion, flooding and mudslides in lowland areas. However, as the glaciers disappear, such flows will tail off dramatically, leading to serious water shortages, reduced hydropower, greater risks of drought and serious environmental degradation.

Torrential rains and resulting floods, including those associated with tropical cyclones, have resulted in severe economic losses and social disruption in the region in recent years. For example, in 1998, hurricane Mitch caused 10 000 deaths and severe damage to infrastructure, with Honduras and Nicaragua the worst hit. This event changed the topography of fisheries and aquaculture areas (e.g. at Estero Real in Nicaragua). Northeast Brazil, on the other hand, is particularly affected by drought and its associated socio-economic impacts. There are uncertainties over the effects of climate change on rainfall in Latin America. It is predicted, however, that arid and semi-arid areas will receive even less rain under climate change

(UNFCCC, 2006). Low-lying coasts in many countries (Argentina, Belize, Colombia, Costa Rica, Ecuador, Guyana, Mexico, Panama, El Salvador, Uruguay and Venezuela, Bolivarian Republic of) and their large coastal cities (Buenos Aires, Rio de Janeiro, Recife, etc.) are among the most vulnerable to extreme weather events such as rain, windstorms and hurricanes with their associated storm surges and sea level rise. Warmer seas throughout the region are affecting marine fish, with negative consequences for fisheries.

According to UNFCCC (2010), sea level rise is likely to have adverse impacts on coastal morphology (e.g., in Peru), and on mangroves (e.g. in Brazil, Ecuador, Colombia and Venezuela, Bolivarian Republic of). Mangrove forests located in low-lying coastal areas are particularly vulnerable to sea level rise, increased mean temperatures, and hurricane frequency and intensity, especially in Mexico, Central America and Caribbean continental regions and could disappear unless they are better managed. Sea level rise is likely to have adverse effects on availability of freshwater on the Pacific coasts of Costa Rica and Ecuador and around the River Plate estuary. Mesoamerican coral reefs (e.g. those in Mexico, Belize and Panama) and the locations of some fish stocks in the southeast Pacific (e.g. Peru and Chile) are also likely to be affected. Saline intrusion could become an increasingly serious problem in coastal areas due to sea level rise. Sea level rise in some areas may lead to a reduction in the salinity of hypersaline lagoons negatively affecting biodiversity, but this could afford some opportunities for aquaculture and fisheries. Table 8 summarizes the likely impacts and outcomes of climate change for Latin America/Caribbean.

Table 8. Summary of predicted climate change for Latin America/Caribbean

Temperature
• Warming above the global mean is predicted in most of Latin America. • In southern South America warming similar to global mean.
Precipitation, snow and ice
• Decrease in annual precipitation in most of Central America and in the southern Andes, although large local variability in mountainous areas. • Increase in winter precipitation in Tierra del Fuego. • Increase in summer precipitation in southeastern South America. • Uncertain rainfall changes over northern South America, including the Amazon forest. • Increasing reduction and disappearance of Andean glaciers.
Extreme events
Increasing frequency and intensity of extreme events, many related to ENSO, particularly: • intense rainfall events, causing landslides and severe floods; • dry spells and drought (e.g. in northeast Brazil); • heat waves, with particularly major effects in megacities due to heat-island effects; and • increase in intensity of tropical cyclones in the Caribbean.

North America

North America has experienced locally severe economic damage, plus substantial ecosystem, social and cultural disruption from recent weather-related extremes, including hurricanes, other severe storms, floods, droughts, heat waves and wildfires. Over the past several decades, economic damage from severe weather has increased dramatically, due largely to increased value of the infrastructure at risk. Although North America has considerable adaptive capacity, actual practices have not always protected people and property from adverse impacts of climate variability and extreme weather events. Especially vulnerable groups include indigenous peoples and those who are socially or economically disadvantaged. Coastal communities and habitats will be increasingly stressed by climate change impacts interacting with development and pollution.

Climate change will constrain North America's over-allocated water resources, increasing competition among agricultural, municipal, industrial and ecological uses.

In North America, a 50 cm rise in sea level could inundate 8 500 to 19 000 km^2 of dry land, expanding the 100-year floodplain by more than 23 000 km^2 and eliminating as much as 50 percent of coastal wetlands. In many areas, wetlands and estuarine beaches might be squeezed between the advancing seas and the dikes or seawalls built to protect human settlements (Watson *et al*., 2000). Sea level rise is exacerbating the impacts of progressive inundation, storm-surge flooding and shoreline erosion. Storm impacts are likely to become more severe, especially along the Gulf and Atlantic coasts. Salt marshes and other coastal habitats, as well as their dependent species, are threatened by sea level rise, by fixed structures blocking landward migration, and by changes in vegetation. Population growth and the rising value of infrastructure in coastal areas are increasing vulnerability to climate change.

Rising temperatures will diminish snowpack and increase evaporation, affecting seasonal availability of water. Higher demand from economic development, agriculture and population growth will further limit surface and groundwater availability. In the Great Lakes and major river systems, lower levels are likely to exacerbate challenges relating to water quality, navigation, recreation, hydropower generation, water transfers and binational relationships. Table 9 summarizes the likely impacts and outcomes of climate change for North America.

Table 9. Summary of predicted climate change for North America

Temperature
• Abnormally hot days and nights are very likely to become more frequent. • Cold days and cold nights are very likely to become much less frequent. • The number of days with frost is very likely to decrease. • Heat waves very likely to further increase in frequency and intensity
Precipitation
• Heavy downpours are very likely to further increase in frequency and intensity • Substantial areas of North America are likely to have more frequent droughts of greater severity. • On average, precipitation is likely to be less frequent but more intense, and precipitation extremes are very likely to increase.
Extreme events
• Climate models indicate that currently rare extreme events will become more common. • Increasing frequency of weather extremes including hurricanes, other severe storms, floods, droughts, heatwaves and wildfires. • Hurricane wind speeds and storm surge levels are likely to increase. • The strongest cold-season storms are likely to become more frequent, with stronger winds and more extreme wave heights.
Coastal zones
• Sustained (months-long) unusually high temperatures could lead, for example, to more bleaching and deaths of corals.

Asia

Asia encompasses boreal, temperate, subtropical, tropical and arid/semi-arid climatic zones. The region faces formidable environmental and socio-economic challenges in its effort to protect its natural resources. Asia's ecosystems are under enormous pressure to support the growing demand for natural resources. The most affected areas are coastal and marine ecosystems, forests and mountainous regions, and the flora and fauna within them. Terrestrial and aquatic ecosystems are being degraded, threatening to undermine food security. In addition, water and air quality are deteriorating while continued increases in consumption and associated waste have contributed to the exponential growth in the region's existing environmental problems. The region is highly subject to natural hazards, such as the 2004 Indian Ocean Tsunami, the 2005 Pakistan Earthquake, and the 2006 landslides in the Philippines. There is evidence of prominent increases in the intensity and/or frequency of many extreme weather events such as heat waves, tropical cyclones, prolonged dry spells, intense rainfall, tornadoes, snow avalanches, thunderstorms and severe dust storms in the region (Cruz *et al*., 2007). Climate change will affect many sectors in Asia, including: human health, agriculture and food security, ecosystems and biodiversity, water resources, and coastal zones. Many environmental and developmental problems in Asia will be exacerbated by climate change. Under climate change, predicted rainfall increases over most of Asia, particularly during the summer monsoon, could increase flood-prone areas in East Asia, South Asia and Southeast Asia. In Central and South Asia, crop yields are predicted to fall by up to 30 percent, creating a very high risk of hunger in several countries.

In the short term, the melting of glaciers in the Himalayas brings increased risk of flooding, erosion, mudslides and glacial lake outburst floods (GLOF) in Nepal, Bangladesh, Pakistan and north India during the wet season. Because the melting of snow coincides with the summer monsoon season, any intensification of the monsoon and/or increase in melting is likely to contribute to flood disasters in Himalayan catchments. Longer-term climate change could lead to a rise in the Himalayan snowline and disappearance of many glaciers, causing serious impacts on the populations relying on the seven main rivers that are fed by melt water. Throughout Asia, one billion people could face water shortages, droughts and land degradation by the 2050s (Christensen *et al*., 2007; Cruz *et al*., 2007). Asian inland fisheries at higher elevations are likely to be adversely affected by lower availability of oxygen due to higher temperatures. On the plains, the timing and amount of precipitation could also affect the migration of fish species from the river to the floodplains for spawning, dispersal and growth (FAO, 2003a).

Sea level rise and changes in seawater temperature and salinity, wind speed and direction, strength of upwelling, mixing-layer thickness and predator response to climate change have the potential to substantially alter fish breeding habitats and food supply for fish, and ultimately the abundance of fish populations in Asian waters with associated effects on coastal economies (Cruz *et al*., 2007). Especially along low-lying coasts, sea level rise is likely to be the major climate-related impact. Densely settled and intensively used low-lying coastal plains, islands, and deltas are especially vulnerable to coastal erosion and land loss, inundation and sea flooding, upstream movement of the saline/freshwater front, and seawater intrusion into freshwater lenses. Especially at risk are large deltaic regions of Bangladesh, Myanmar, Viet Nam, and Thailand, and the low-lying areas of Indonesia, the Philippines and Malaysia (Watson *et al*., 2000).

According to IPCC (2007b) Sea level rise could flood the residences of millions of people living in the low-lying areas of South, Southeast and East Asia such as in Viet Nam, Bangladesh, India and China. Sea level rise and coastal erosion are also causing widespread damage to Asian island states such as the Maldives. Asian coral reefs might be able to adjust to sea level rise, but will suffer bleaching increasingly, from higher temperatures (Watson *et al*., 2000). Coral bleaching in Asia coincides with El Niños and is aggravated by other factors such as high solar radiation, currents, wave energy, tidal fluctuations and reef morphology (Capili *et al*., 2005). Thirty percent of Asian coral reefs could be lost in the next 10 years (Cruz *et al*., 2007). IPFC (2007b) has estimated that their loss might be as high as 88 percent (59 percent of the global total) in the next 30 years.

Flooding, particularly in large deltas, could increase brackishwater fisheries, but could also seriously affect some aquaculture operations and infrastructure. Reductions in dry-season flows may reduce recruitment of some species. Saltwater intrusion in estuaries due to decreasing river runoff can be pushed 10–20 km further inland by rising sea levels (Bates *et al*., 2008). Table 10 summarizes the likely impacts and outcomes of climate change for Asia.

Table 10. Summary of predicted climate change for Asia

Temperature
• Warming above the global mean in central Asia, the Tibetan Plateau, northern, eastern and southern Asia. Warming similar to the global mean in Southeast Asia. • Fewer very cold days in East Asia and South Asia.
Precipitation, snow and ice
• Increase in precipitation in most of Asia. Decrease in precipitation in central Asia in summer. • Increase in the frequency of intense precipitation events in parts of South Asia, and in East Asia. • Increasing reduction in snow and ice in Himalayan and Tibetan Plateau glaciers.
Extreme events
Increasing frequency and intensity of extreme events particularly: • droughts during the summer months and El Niño events; • increase in extreme rainfall and winds associated with tropical cyclones in East Asia, Southeast Asia and South Asia; • intense rainfall events causing landslides and severe floods; and • heat waves/hot spells in summer of longer duration, more intense and more frequent, particularly in East Asia.
Coastal zones
• Climate change will exacerbate the already serious problem of relative sea level rise because of subsidence and heavy groundwater withdrawal. • Defence against sea encroachment would be the only viable response because of the high concentration of population and economic activities. • Contamination of groundwater by seawater intrusion would further worsen the water resource shortage problem.

Europe

Wide-ranging impacts of changes in current climate have been documented in Europe. The warming trend and spatially variable changes in rainfall have affected the sizes of glaciers and the extent of the permafrost, as well as other natural and managed ecosystems: lengthening some growing seasons and causing shifts in the ranges of some species. The European heat wave in 2003 had major impacts on biophysical systems and society. The observed changes are consistent with projections of impacts due to climate change. Climate-related hazards will mostly increase, although changes will vary geographically. Future climate scenarios in Europe indicate significant warming, greater in winter in the north and in summer in southern and central Europe. Mean annual precipitation is projected to increase in the north and decrease in the south. Differences in water availability between regions are anticipated to become sharper (annual average runoff increases in the north and northwest, and decreases in the south and southeast). Winter floods are likely to increase in the maritime regions and flash floods are likely to increase throughout Europe. Coastal flooding related to increasing storminess and sea level rise is likely to threaten up to 1.6 million additional people annually. Water stress will increase, as well as the number of people living in river basins under high water stress in central and southern Europe. The percentage areas under high water stress are likely to increase from 19 percent today to 35 percent by the 2070s, and the additional number of people affected by the 2070s is expected to be between 16 million and 44 million. The most affected regions are likely to be southern Europe and some parts of central and eastern Europe, where summer flows might be reduced by up to 80 percent.

Climate change will impact a European fisheries sector that is characterized by full utilization, overcapacities and sharp conflicts between fleets and among competing uses of aquatic ecosystems. The fishing industry is a significant income earner in Europe, but in recent decades the industry has experienced numerous problems related to fishing rights and quotas, dwindling stocks due to overfishing, and disputes as part of the European fishing fleet encroaches upon areas traditionally exploited by other nations (e.g. eastern Canada, the western African coast). Climate change impacts are likely to exacerbate existing stresses on European fish stocks, notably: overfishing, diminishing wetlands and nursery areas (perhaps aggravated by sea level rise), pollution and increasing solar radiation.

Higher temperatures are likely to lead to increased species richness in freshwater ecosystems in northern Europe and decreases in parts of southwestern Europe (Bates *et al*., 2008). Table 11 summarizes the likely impacts and outcomes of climate change for Europe.

Table 11. Summary of predicted climate change for Europe

Temperature
• A general increase in temperature, greatest in winter in northerly latitudes. • Significant warming in summer in southern and central Europe
Precipitation
• Precipitation changes are considerably more uncertain, but one could expect generally wetter conditions in the north, drier conditions in the south and increasingly drier conditions from west to east. • Winter precipitation may be greater than today, while summer precipitation is likely to decrease. • Many regions in the southern and interior parts of Europe could experience a general decrease in runoff, though the change in runoff may range between -5 percent and +12 percent. • More droughts could be expected in southern Europe, and the potential for winter and springtime flooding could be greater in northern and northwestern Europe. However, this pattern is not the same for all general circulation models (GCMs).
Extreme events
• Hotter summers with every second summer hotter than 2003. • Increase frequency of intense precipitation. • Increase frequency of summer droughts.
Coastal zones
• Intrusion of saline waters into coastal aquifers and the expected reduction in precipitation could aggravate the problem of freshwater supply in some areas. • Sea level rise will place additional stress on coastal zones already stressed by other factors (urbanization, coastal developments, pollution, etc.). • Sensitive zones include areas already close to or below mean sea level (such as the Dutch and German North Sea coastlines, the Po River delta, and the Ukrainian Black Sea coast), areas with low intertidal variation (such as the coastal zones of the Baltic Sea and the Mediterranean), and coastal wetlands. • Changes in the nature and frequency of storm surges, particularly in the North Sea, are likely to be of considerable importance for low-lying coastal areas.

Oceania

Oceania comprises the small island states and territories of Melanesia, Micronesia and Polynesia, as well as Australia and New Zealand, and is the world’s largest sea area. The small island states of Oceania are highly vulnerable to the effects of climate change and are already feeling its impacts. The climate of small islands is influenced by large ocean atmosphere interactions such as trade winds, ENSO and monsoons. Small islands are characterized by the concentration of large settlements with associated economic and social activities at or near the coast. Their arable lands, water resources and biodiversity are already under pressure from sea level rise. Increases in population and the unsustainable use of available natural resources add further problems. Tropical storms and cyclones cause storm surges, coral bleaching, inundation of land, and coastal and soil erosion with resulting high-cost damages to socio-economic and cultural infrastructure. For example, among Pacific islands, cyclones accounted for 76 percent of the reported disasters between 1950 and 2004, with the average costs relating to damage caused per cyclone standing at US$ 75.7 million, at 2004 values (UNFCCC. 2010).

For Oceania, the projected impacts of climate change cross all sectors and the vulnerability and low adaptive capacity of small islands are inextricably linked to their socio-cultural and economic contexts. Vulnerabilities include low availability of resources, small but rapidly growing populations, remoteness, susceptibility to natural disasters, excessive dependence on international trade, and vulnerability to global developments. Water supply in small islands is likely to be affected by climate change. Freshwater lenses are predicted to reduce in size due to increased demand and reduced rainfall. Freshwater supplies are also threatened by saltwater intrusion due to storm surge and sea level rise (UNFCC, 2010). Climate change is expected to exacerbate water resource problems in both in southern and eastern Australia, as well as in the North Island and some eastern regions of New Zealand.

Significant loss of biodiversity is projected to occur by 2020 in some ecologically rich sites, including the Great Barrier Reef and Queensland Wet Tropics. Other sites at risk include the Kakadu wetlands, Southwest Australia, and the sub-Antarctic islands and uplands of both Australia and New Zealand. Both countries have substantial adaptive capacity due to well-developed economies and scientific and technical capabilities, but there are considerable constraints to implementation and major challenges from changes in extreme events (IPCC, 2007b).

Across Oceania, ongoing coastal development and population growth in low-lying coastal areas and islands are projected to exacerbate risks from sea level rise and increases in the severity and frequency of storms and coastal flooding. Coastlines will almost certainly suffer from accelerated coastal erosion as well as inundation of settlements and arable land, with associated social and economic consequences. Sea level rise, increasing sea surface temperatures and acidification of the oceans will entail a loss of mangrove forests and coral reefs and reduced fish stocks throughout this region. According to Watson *et al*. (2000), the tropical coral reefs of Oceania, including the Great Barrier Reef, might be able to adjust to sea level rise, but will be vulnerable to the bleaching and death of corals induced by episodes of higher sea temperatures and other stresses. Ocean acidification and increased thermal stress are the likely causes of a more than 10 percent reduction in the growth rates of massive Porites corals on the Great Barrier Reef (Hoegh-Guldberg, 1999).

Tuna fisheries are very important across Oceania and are often the main basis for small island economies whose other exploitable resources are limited. The future food security and economic development of the Pacific region will undoubtedly be linked to the responsible and sustainable management of its tuna resources (ADB, 2001) (see Section 8 Pelagic Fisheries). Table 12 summarizes the likely impacts and outcomes of climate change for Oceania.

Table 12. Summary of predicted climate change for Oceania

Temperature
• All South Pacific small island states will experience warming. Warming will be lower than the global average.
Precipitation
• Increase in annual rainfall in the equatorial Pacific.

• Decrease in rainfall in parts of the east Pacific.
Extreme events
• Increasing intensity of tropical cyclones, storm surge, coral bleaching and land inundation.
Coastal zones
• Most infrastructure, settlements and facilities located on or near the shore and will be affected by sea level rise, coastal erosion and other coastal hazards, compromising the socio-economic well-being of island communities and states. • Accelerated beach erosion, degradation of coral reefs and bleaching will all have impacts on incomes from fishing and tourism. • Habitability of some small islands will be threatened due to reduction in island size, or even complete inundation.

XI. AQUATIC GENETIC RESOURCES AND ADAPTATION TO, AND MITIGATION OF, CLIMATE CHANGE

11.1 Aquatic genetic resources and adaptation to climate change

Adaptation is ongoing

When considering the ongoing and potential adaptations of aquatic organisms to climate change, it must be emphasized that climate change impacts are interactive with other key stressors. For example, overfishing has affected some taxa, by direct effects on overall abundance, size-selective harvesting, general habitat degradation (especially with trawling) and loss of genetic diversity (e.g. Smith, 2007). Siltation, exposure of acid sulphate soils, dams, dredging effects and a host of other deleterious interventions can exacerbate negative climate change effects on aquatic ecosystems and their biota. Aquatic Protected Areas are often the only interventions made to reduce those negative effects, especially for conservation of aquatic genetic resources.

Throughout the ecosystems that host and support aquaculture and fisheries, adaptation to short-term climate fluctuations and to long-term climate change is an established and ongoing process that is being achieved mainly through natural selection and assisted, to lesser but important extents in aquaculture, fisheries management and conservation, by biotechnology. Climate change and natural selection are continually restructuring and redistributing wild fish populations (e.g. Brander, 2007; Pardiñas *et al.*, 2010; Pörtner and Peck, 2010). Coral reefs that are affected by high temperatures and diseases are adapting through their immune responses and by recourse to different symbiotic zooxanthellae (e.g. Berkelmans and van Oppen, 2006; Mydlarz *et al.*, 2010). Some will not survive as climate change proceeds, but others might be able to “buy time” until greenhouse gas reduction measures are put in place. Within the environmental limits to survival, growth and reproduction that apply to all organisms, the key to maximizing such adaptations to climate change is having adequate genetic variation in tolerance traits.

There is, however, a lack of understanding as to how gene expression and phenotypic plasticity in general can be linked to genetic variation in stressed aquatic organisms. This problem is echoed in a review of the limited extents to which microarray technology and genomics have been useful to date in aquaculture and ecology, especially ecotoxicology (Hook, 2010). This missing, or tenuous link, has wider implications right across evolutionary theory. Cohen (2010), reviewing a new compilation on multiple and interactive mechanisms in evolution (Pigliucci and Müller, 2010), stated: “*it’s the morphology that leads the genetic change, not the converse. Yes, mutations are there, doing the fine-tuning, but the big evolutionary changes –perhaps even down as far as speciation – are presaged and guided by often-adaptive changes of form*.”

Schreck (1981) provided insightful conceptual diagrams of the fluctuating importance and interactive nature of what he called “*representative performance vector*s” such as temperature, dissolved oxygen and disease (for all of which there are corresponding and interactive tolerance traits) throughout the life of a fish, from embryo to senescence; and also illustrated the interplay between the genetic and environmental limiting factors to fish realizing their "*potential performance capacity*." Populations of the same species of aquatic organisms, particularly those that have sessile adult stages (e.g. corals and sponges) show wide variations in size and morphology in different habitats. Similarly, captive fish populations take on different shapes and colours from their wild conspecifics. The implications of this for the adaptation of aquatic organisms to climate change are not well understood, but the importance of phenotypic plasticity should be kept in mind. Adaptations depend upon the outcomes of genotype/phenotype/environment interplays. Beyond whatever genetic data predict, some pleasant and unpleasant surprises are likely as aquatic organisms either adapt or fail to adapt to climate change.

Traits for adaptation to climate change

In aquatic organisms, the most important traits for adaptation to and mitigation of climate change relate to their fitness in aquatic ecosystems and their performance in aquaculture and fisheries. These traits are highly interactive. They include survival, fecundity, tolerance to low water quality, disease resistance, growth, feed conversion and product quality. Short-term climate fluctuations and long-term climate change are best viewed as additional stressors on fish. The adaptability of fish to stress was considered in a series of reviews edited by Pickering (1981). These remain important sources of background information, together with the very recent compilation on fishes and climate change (Winfield and Craig, 2010).

During all the life history stages of fish, stress comes from many interactive stressors and is compensated for by many interactive mechanisms. Schreck (1981) noted that, at any stage in life, an individual fish genotype will determine its potential capacity to respond to stress whereas its environment and "N-dimensional" stress will determine its realized capacity. Beyond that holistic approach to stress in fish, the most important advance in studying and attempting to forecast adaptation to climate change in most fish has been the realization that aerobic scope is the most important indicator. Any fish–environment combination must supply the fish with adequate oxygen, without which it cannot adapt to any other stress. With that in mind and before considering interactive traits in fish for adaptation to climate, it is first important to consider the special features of life in water.

There are two key differences between most fish and all terrestrial animals concerning adaptation to climate change. First, all fish, apart from the minority of specialists that have special organs to obtain oxygen from the air, must breathe oxygen that is dissolved in water. Terrestrial animals, apart from those at high altitudes, enjoy almost constant availability of atmospheric oxygen. The concentrations of dissolved oxygen available to fish in clean freshwaters vary from 14.60 mg/litre at 0 °C to 7.54 mg/litre at 30 °C and 5.95 mg/litre at 45 °C, which is about the lethal upper limit for any fish. Moreover, these oxygen concentrations are reduced by up to about 8 percent as salinity increases to 20 parts per thousand and are reduced further in turbid and/or polluted waters (APHA *et al*., 1981). Second, apart from some tunas and lamnid sharks, all fish are ectotherms (poikilotherms) and their body temperatures are always the same as those of their surrounding environments. Higher temperatures increase the metabolic rate of fish, as ambient oxygen concentrations fall. A 10 °C rise in ambient water temperature will approximately double the metabolic rates of fish, though many have evolved biochemical mechanisms and behavioural patterns to lessen such impacts. Lower temperatures decrease metabolic rates, appetites and immune responses of fish.

Pauly (2010) explained thoroughly the central role of oxygen in determining the survival, growth, condition, maturation and spawning of finfish. His key premise is that oxygen transfer in fish is always limited by a surface that becomes proportionately smaller as the fish gets bigger. The surface area of fish gills and, especially in early life-history stages, of the entire skin, together with other important features – the thickness of the water–blood oxygen diffusion path across the gill lamellae; the flow of water over the gills by means of opercular pumping and swimming; and the flow of blood through the gills – place limits on how much oxygen a fish can breathe at any ambient concentration. This means that all adaptations of fish to climate change, apart from that of the minority that are air-breathing species (e.g. clariid catfish, anguillid eels, mudskippers and snakeheads) must be seen against the baselines of their available dissolved oxygen and their capacities to breathe that oxygen, in terms of their respiratory structures, physiology and behaviour. For the vast majority of fish that breathe dissolved oxygen, short-term climate fluctuations and long-term climate change will elevate the importance of tolerance to hypoxia. Corkum and Gamperl (2009) showed that the cunner (*Tautogolabrus adspersus*) is much more tolerant of hypoxia than the Greenland cod (*Gadus ogac*) and attributed this to the cunner's superior ability to depress its metabolism. Pörtner and Knust (2007) stated as a general conclusion that "*Decrements in aerobic performance in warming seas will thus be the first process to cause extinction or relocation to cooler waters*." In short, when it gets hot, some fish have to move or die because they cannot breathe.

There are huge implications here for capture fisheries and aquaculture. Even if, they can find adequate food supplies, freedom from lethal disease and parasite challenges and predators, and good spawning areas, fish will survive, grow, maintain good condition, mature and reproduce only where they can find acceptable water quality: especially in terms of its dissolved oxygen, temperature, salinity, turbidity and pollutants. Ability to adapt to hypoxia associated with higher temperatures and dirtier waters will be vital for many fished and farmed species. This situation favours survival and spread of fish that are euryoecious, meaning able to withstand and prosper in variable and challenging environments, like weeds in a wide range of soils. For wild populations, some r-selected species are likely to be more capable of adapting to climate change than K-selected species in general. The farming of fish species that have short generation times and short production cycles is likely to have advantages over those for which breeding and production take longer. This has been seen, for example, in the success of tilapia farming, where a fish can easily be brought to maturity or to market size in six months. The longer that a crop of farmed fish is held, the longer it is at risk from unfavourable climatic events.

Some fish species that evolved in cold freshwaters are surprisingly eurythermal; for example, the common carp can live under ice and is farmed in ponds at all temperatures up to about 35 ºC. Others, such as salmonids, are stenothermal, with farming not possible above about 20 ºC. Euryoecious fish species, like weeds, might be less attractive for commercial harvesting, but still have importance as genetic resources, for breeding programmes and related research. For example, the species of tilapia that is arguably the most eurythermal and euryhaline, *Oreochromis mossambicus*, proved to be a bad choice as a farmed fish because of its poor growth and early maturation; but it has been a vital source of genetic material for breeding programmes, especially for the development of salt-tolerant hybrids.

This begs the question of how best to approach the further domestication and genetic improvement of farmed fish, in the face of short-term climate fluctuations and long-term climate change. The key will be to look for variable and highly heritable traits that are indicative of tolerance to lower water quality, especially in terms of more extreme temperature and dissolved-oxygen regimes. Bosynki (1998) showed that genetically improved, and therefore more domesticated, Nile tilapia behaved more quietly and grew faster than controls. Good growth and feed conversion are more measurable than, for example, gill surface area, gill epithelial width and the quiet behaviour that conserves oxygen. Nevertheless, future fish breeders would do well to examine the possibility of selecting for more efficient respiratory structures, respiratory physiology and related behaviour in farmed fish, as further means for adapting them to climate change. In addition, the faming of air-breathing fish and very hypoxia-tolerant fish, such as anguillid eels, catfish and snakeheads, could assume greater importance in areas where climate change reduces an already limited availability of waters for farming more oxygen-demanding species. Air breathing fishes tend to have wide thermal-tolerance ranges. FAO (2008b) in summarizing future uses of genetic resources for adaptation to climate change lists specifically "*Use of fish species and strains adapted to low quality waters*." The most important aspect of that lowered water quality will often be lowered availability of oxygen. Most fish kills on farms, and increasingly fish kills in open waters (e.g. kills of 11 species in the Cocos (Keeling) Islands; Hobbs and McDonald, 2010) are due to lack of dissolved oxygen.

Adaptation to higher or lower temperatures

As emphasized above, one cannot dissociate adaptation of fish to the higher or lower temperatures that they might face from short-term climate fluctuations and long-term climate change without considering the accompanying oxygen regimes. Pörtner and Peck (2010) proposed "oxy*gen and capacity-limited thermal tolerance (OCLT)*" as the key concept for understanding thermally limited aerobic scope in fish. Echoing Pauly (2010), the same authors stated: "*Thermal windows widen in juveniles and young adults in line with rising performance capacity at small body size. Larger individuals then become more thermally sensitive, due to progressively falling oxygen supply capacity in relation to demand*." At their earliest life-history stages, such as eggs and larvae, fish have plenty of highly permeable surface area, relative to their body masses, for absorbing oxygen from the surrounding water and oxygen is then less of a potential limiting factor. For example, Pauly and Pullin (1988) showed that the time to hatching of spherical, pelagic fish eggs is determined mostly by temperature and varies with their diameter. In other words, thermodynamics set the calendars, for fish eggs, fish growth and fish maturation and spawning.

Juvenile, subadult and adult fish have highly evolved mechanisms for responding to extreme temperatures, including anti-freeze proteins and heat shock proteins. Antifreeze proteins are found in a wide range of fished and farmed species, including the Atlantic cod (*Gadus morhua*) where they protect against freezing from the egg stage to adult life (Goddard and Fletcher, 1994) and 37 species of Antarctic fish from highly dissimilar families (Woehrmann, 1997). Heat shock proteins are implicated in general stress resistance and cell protection. Smith *et al*. (1999) described the heat shock protein response of juvenile Atlantic salmon and described it as an "*adaptation to environmental insult*." Heat shock protein indicates hyperosmotic stress in the euryhaline tilapia *Sarotherodon melanotheron* moved to hypersaline environments (Tine *et al*., 2010). Heat shock protein levels are not necessarily indicators of thermal tolerance *per se*. For example, Zakhartsev *et al*. (2005) found that heat shock protein 70 levels in Atlantic cod (*Gadus morhua*) did not change significantly in response to temperature variations within its normal range (4 to 15 °C), confirming similar observations in other species. They concluded that heat shock protein 70s in cod play a secondary role in determining its thermal tolerance limits and that "*the first line of thermal limitation in the cold and warm is a loss in aerobic scope*."

Thermal tolerance in fish is difficult to measure experimentally because of the confounding effects of other stresses. Handling fish can reduce thermal tolerance (e.g. Monirian *et al*., 2010). Linton *et al*. (1998) concluded that, although juvenile trout would probably adapt to small temperature increases, their ability to do so might be compromised by sublethal ammonia, as well as by poor nutritional status. Moreover, as Elliot and Elliot (2010) pointed out, it is easy to come to false conclusions about what seem to be adaptations in wild populations; for example, salmonids living in a geothermal river and seemingly unaffected by summer temperatures of up to 30 °C were later shown in the laboratory to be no more heat-tolerant than two hatchery populations. It was discovered that, in the river, they migrate to a colder tributary to avoid the high summer temperatures. It will often be higher winter temperatures, rather than high summer temperatures, that will determine the natural distributions and geographical limits to the farming of some species. There are many examples of unexpectedly high tolerance to high temperatures in fish that evolved in cooler waters. The common carp, which has become, as an alien species, the most important farmed fish in Indonesia, originated in temperate rivers. Carveth *et al*. (2006) showed that some species that evolved in desert environments were surprisingly less heat tolerant than was previously thought, whereas many species introduced to desert areas from the eastern United States of America had surprisingly high heat tolerances.

Some fish species live in waters that are warm and that can become very warm for short periods of time; for example, rock pool and other shore fishes and fishes associated with tropical shallow reefs and sea grass beds. These species will not be affected directly by higher water temperatures as they live well within their upper thermal tolerance limits, even when exposed on hot days, and sometimes actively seek out the warmest niches. Mora and Espina (2001) found that many reef fish live far below their upper thermal tolerance limits. The risks to such fish from higher temperatures are therefore more likely to come from impacts on the corals upon which the whole reef community depends. Many species of ornamental tropical fish are also capable of withstanding very high temperatures for short periods. For example, Chung (2000) acclimated Venezuelan river tetra (*Astyanax bimaculatus*) juveniles to temperatures from 24 to 33 °C and then subjected them for 10 000 minutes to temperatures from 35 to 39 °C, Those fish showed good heat resistance. as well as rapid acclimation to rising temperatures of only a few days. By comparison, fish shifted from 30 to 24 °C required 14 days acclimation. The conclusion was that tropical freshwater fish acclimate quickly to rising water temperatures during the day and then stay thus acclimated during the onset of a cooler night, and are then ready for the next hot day. Morgan *et al.* (2001) made the important observation that the impacts of higher temperatures on freshwater fish will vary seasonally. For rainbow trout, they found that simulated global warming of 2 °C above the natural regimes, had little effect on appetite and growth for most of the summer, but reduced both in the warmest waters of late summer and increased them by 30–60 percent in winter.

The big question is to what extents do fish populations adapt to temperature fluctuations and to chronic temperature change? There is no clear answer, but the high fecundity of fish in wild populations and in hatcheries means that natural selection can act very rapidly to produce adapted strains even within a few generations. There is evidence that some of the best species of farmed fish can acclimatize rapidly to new temperature regimes. The capacity of farmed fish to adapt to higher temperatures will increasingly set geographical limits for the location hatcheries and growout facilities. For example, Esquer Mendez *et al.* (2010) stated that the maximum average weekly temperature for juvenile California halibut (*Paralichthys californicus*) must not exceed 22.6 °C.

There is, however, abundant evidence for intraspecific variations in the thermal tolerance of fish. For example, Cook *et al.* (2006) showed that the thermal tolerance of a northern population of striped bass (*Morone saxatilis*) was generally broader, in terms of upper and lower limits, than those of southern populations. Molony *et al.* (2004) showed that a domesticated line of rainbow trout (*Oncorhynchus mykiss*) in Western Australia was much better adapted to high temperature (27 °C) than a naturalized line, not only in terms of survival but also as shown by 24 percent higher weight gain, and discussed scope for developing lines that would be tolerant to even higher temperatures. Conversely, Carline and Chung (2001) found that wild strains of brown trout, brook trout and rainbow trout all had critical thermal maxima that exceeded those of equivalent domesticated strains by 0.5 to 1.6 °C.

Breeding for increased tolerance to lower temperatures is also likely to become important in areas where short-term climate fluctuations and long-term climate change expose aquaculture operations to colder conditions. Breeding for cold tolerance has long been a feature of tilapia farming, in order to expand its range beyond the present northern limits in the Near East, mainland China and northern Viet Nam, where many broodstocks and some production stocks are kept in overwintering facilities. Global warming will probably shift the frontiers of tilapia farming significantly northwards, but breeding for cold tolerance will still be needed. The most cold-tolerant tilapia species is the blue tilapia (*Oreochromis aureus*), which can survive down to 8 °C, but is a poor farm fish because it is difficult to harvest by seine net. Female blue tilapia crossed with male Nile tilapia (*Oreochromis niloticus*) produce a fine, cold tolerant, commercial F1 hybrid. Under lower temperature regimes, *Oreochromis aureus* always grows faster than *Oreochromis niloticus* (Behrends *et al.*, 1996). Cnaani *et al.* (2000) reviewed the relative cold tolerances of *Oreochromis aureus*, *Oreochromis mossambicus* and their hybrids. Cross breeding of the European Galicia common carp and the wild Amur common carp was used in the former USSR to produce the low temperature resistant Ropsha carp (Babouchkine, 1987). Ju (2002) concluded that channel catfish (*Ictalurus punctatus*) responds to low temperatures by adjusting the expression of many genes. Ma *et al.* (2007) showed that cold tolerance in red drum

(*Sciaenops ocellatus*) is highly heritable ($H^2 = 0.32 \pm$ SE 0.12) and that selecting for fast growth would not have a negative impact on cold tolerance.

The timing of sexual maturation is of high importance in broodstocks held for aquaculture. The literature shows much variation within a single species; for example, common carp broodstock in tropical South and Southeast Asia can reach first maturity within six months to one year, whereas northern European stocks mature after two to five years. In China, the traditional rule of thumb for estimating age of first maturity of grass carp (*Ctenopharyngodon idella*) was 15 000 °C -days, counting only those days when the water temperature had exceeded 14 °C (Jhingran and Pullin, 1988). As global warming proceeds, such formulae will probably have to be discarded, especially as, following the theory of Pauly (2010), the main controlling factor in fish maturation is the necessity for maturing fish, especially females with huge gonads, to lose body mass by spawning so that their capacity to take up oxygen, relative to their body mass, will allow resumption of growth.

Adaptation to higher or lower salinities

In all fish, stenohaline and euryhaline, osmoregulation consumes energy, requires oxygen and is temperature-dependent. Salinity tolerance in fish interacts strongly with thermal and dissolved oxygen tolerance. For southern flounder (*Paralichthys lethostigmata*) cold-induced death is likely at 10 °C in freshwater and 7 °C in saltwater (Prentice, 1989). Among the tilapias that are of interest for developing salt-tolerant breeds or hybrids, *Oreochromis mossambicus* has been the most widely used, but *Oreochromis spilurus nige*r, from the Athi River above Lugard’s Falls and upper tributaries of the Tana River, Kenya, has probably as much potential and, like *Oreochromis mossambicus*, good cold tolerance as well. The review by Chervinski (1982) and the monograph by Trewavas (1983) remain the best available guides to tilapia species and populations with likely potential for increased salt tolerance and other related attributes of interest for aquaculture. The distribution and availability of some are very limited. For example, among the seven subspecies of Nile tilapia recognized by Trewavas (1983), *Oreochromis niloticus filoa* inhabits the margins of hot alkaline springs (38.5 °C) of the Awash system, Ethiopia.

Adaptation to higher turbidity and siltation

There is a large literature on turbidity and siltation as environmental impacts, but little information on the genetics of tolerance to turbidity and siltation in aquatic species, beyond records of mortalities or of species that prosper, as free living and farmed populations, in more turbid conditions. Short-term climate fluctuations and long-term climate change are likely to increase turbidity and siltation in inland and coastal waters, making them less suitable and productive for aquaculture and fisheries. Increased turbidity and siltation cause rapid, temporary or permanent, degradation of aquatic ecosystems. Storms, flash floods and chronic soil erosion, often exacerbated by deforestation, increase the turbidity and siltation of some inland and coastal waters.

Aquatic species that require very clear water (e.g. giant clams and corals feeding through their symbiotic zooxanthellae) are eliminated by turbidity and siltation. Turbidity can cause abnormalities, including hyperplasia of gill epithelia and fusion of gill filaments, in finfish that require clear water: trout, for example (Pullin, 1971). Increased turbidity lowers light penetration and reduces the abundance and activity of the phytoplankton that produce oxygen and that form the basis of most aquatic food webs. Increased turbidity also compromises fish activities that depend upon clear vision of surroundings, including feeding, reproduction and predator avoidance. Siltation has severe direct effects on aquatic biota, including the physical burial and death of eggs and of adult populations of sessile organisms such as corals and bivalves. Aquatic genetic resources of the farmed and wild-harvested aquatic plants and fish that can withstand higher turbidity and/or siltation will therefore become increasingly important; especially those that can withstand temporary turbidity and siltation problems and still produce adequate yields.

Adaptation to acidification and pollutants

The tolerances of fish to lower water quality in terms of acidification and pollutants is highly interactive with their thermal and dissolved-oxygen tolerances, which will normally determine survival and condition. Most of the concerns about adaptation to acidification relate to marine organisms, but there is also a large literature on acidification of freshwaters as a result of the historical large-scale degradation of watersheds, particularly in northern Europe, by industrial pollution and acid rain. Soil acidification, which will impact some inland waters is continuing; for example in the croplands of China (Guo *et al*. 2010). The rehabilitation of acid-impacted lakes is difficult. Gunn (2002) recounted how native charr (*Salvelinus namaycush*) were eliminated from a shallow lake by air-borne acidification and replaced 20 years later by restocking from a hatchery; but then, after another 18 years an El Niño caused bottom temperatures of 20 °C for several weeks, killing all but a few adults in colder groundwater-seepage areas.

The bulk of the literature on the anticipated acidification of waters as a result of climate change concerns marine biota and ecosystems. Guinotte and Fabry (2008) reviewed the impacts of ocean acidification on marine plants and animals having structures built through biomineralization, including coralline algae, corals and the biological communities that they support, molluscs and echinoderms. The main question is how far such organisms can adapt to CO_2-driven ocean acidification. The extents to which the populations of the main reef-building organisms can adapt to climate change will determine the status of the entire biological communities. Adaptation will depend largely upon the genetic diversity of the corals and of their symbiotic zooanxthellae providing for increased tolerance to higher temperatures and to other interactive environmental changes, including acidification, salinity, turbidity and disease challenges. Recent research on the genetic diversity of corals, including hybrids that colonize marginal habitat (Willis *et al*. 2006), and their zooanxthellae (e.g., Berkelmans and van Oppen 2006) suggests that adaptation is possible, but that less diverse reef systems are to be expected (e.g. Hoegh-Guldberg *et al*. 2007). There is concern over the extents to which marine calcifiers, including coccolithophores and foraminiferans, are capable of adapting to ocean acidification. Acidification will also affect marine plants and animals that lack calcified structures. It will increase the productivity of sea grass beds, but could enable development of algal turfs that would change entire communities: for example, kelp forests (Connell and Russell, 2010). Ocean acidification will also change the behaviour of some larval fish, including their abilities to sense predators, and this might reduce recruitment in some fisheries (Munday *et al*., 2010).

Hall-Spencer *et al*. (2008) made field measurements at volcanic vents that spew carbon dioxide into a shallow benthic community in the Mediterranean. They found that some algae near the vents (*Caulerpa*, *Cladophora*, *Asparagopsis*, *Dictyota* and *Sargassum)* had adapted to waters with pH as low as 7.4 to 7.5, whereas algae such as *Halimeda* and scleractinian corals (*Caryophyllia*, *Cladocora* and *Balanophyllia)* were mostly absent near the vents. It was posited that though such vent systems do not perfectly simulate future acidified oceans owing to temporal variability in pH, spatial proximity of populations unaffected by acidification and the unknown effects of other global changes in parameters such as temperature, currents and sea level, they give snapshots of how some communities might behave in acidified states. Lush stands of sea grass and brown algae can thrive along natural pH gradients where aragonitic and then calcitic calcareous organisms are lost owing to skeletal dissolution (Hall-Spencer *et al*., 2008).

Research on the capacities of marine organisms to adapt to acidification is still at an early stage, with indications that a much wider perspective is needed than a focus on the biomineralization processes alone. Todgham and Hofmann (2009) found broad-scale decreases in gene expression, not only in biomineralization, but also in cellular stress response, metabolism and apoptosis in sea urchin (*Strongylocentrotus purpuratus*) larvae exposed to CO_2-acidified seawater down to pH 7.88, compared with pH 8.01 controls. Based on work in which larvae of the sea urchin *Psammechinus miliaris* were exposed to deep sea waters having high natural CO_2 concentrations, Suarez-Bosche *et al*. (2010) predicted that sea urchin larvae are likely to be able to adapt to predicted ocean acidification scenarios, but found evidence for reduced calcification.

Resistance to diseases, parasites and toxic blooms

There is wide genetic variation among and within wild and farmed populations of aquatic species with respect to their resistance and susceptibility to pathogens and parasites. The resistance of some wild salmonids to microbial diseases and parasites demonstrates well the importance of wild relatives as genetic resources for breeding programmes in aquaculture. For example, Withler and Evelyn (1990) found large and highly heritable resistance to bacterial kidney disease in a riverine race of coho salmon (*Oncorhynchus kisutch*) in British Columbia and referred to similar findings by other authors working on wild salmon and trout populations.

Investigating disease resistance in fish is difficult, because conditions in the laboratory or in microcosms always differ from those in the field and on farm. Experimental challenges with pathogens do not always produce the expected results among susceptible fish. Survival is a complex trait. In the wild, on farms and in experiments, fish die from multiple interactive causes. Nevertheless, there is abundant evidence in farmed fish, principally for catfish, cyprinids and salmonids, of actual and potential genetic improvement in their resistance to pathogenic viruses, bacteria and fungi, and to parasitic protozoans, monogenetic trematodes and crustaceans. Embody and Hyford (1925) improved survival in a population of brook trout with endemic furunculosis from 2 percent to 69 percent after three generations. Okamoto *et al*. (1993) developed an infectious pancreatic necrosis (IPN)-resistant strain of rainbow trout with average mortality of 4.3 percent, compared with 96.1 percent in a highly susceptible strain.

Against such genetic potentials, the environmental factors that increase stress in fish – principally, low dissolved oxygen, poor water quality and inadequate food supply – will usually increase their susceptibility to disease. Therefore, short-term climate fluctuations and long-term climate change are among the determinants of the responses of fish to disease and parasite challenges. Temperature is a very important factor here, because the immune response in fish is depressed by cold. This is particularly serious for fish populations near the geographical limits of their cold tolerance. The farmed tilapias, famous as very disease-resistant tropical species, are a good example. Throughout most of the history of tilapia farming, the relatively few reports of disease problems came mainly from the cold northern and southern limits of its geographical range in Africa, the Near East and subtropical Asia. In recent years, however, the disease problems of tilapia farming have spread throughout the tropics and subtropics, due to intensification and challenges from a wider range of pathogens, such as *Streptococcus* spp.

With climate change, some of the fish that will extend their ranges into waters that are warmer, but that do not get so hot as to induce heat shock or reduce dissolved oxygen to stressful levels, should improve their immune responses to pathogens and parasites. However, they will also face challenges from newly adapted and entirely new pathogens and parasites. For fish in waters that get colder because of climate change, immune responses will be lower and again there will be challenges from new pathogens and parasites.

For aquaculture, as well as for its interactions with fished and other wild populations of aquatic species, the need to control diseases and parasites is likely to increase with short-term climate fluctuations and long-term climate change. The development and distribution of disease- and parasite-resistant fish would then assume greater importance, alongside other countermeasures such as the development of more vaccines against microbial diseases of fish and of specific pathogen-free seed, as available from 1989 for the shrimp *Litopenaeus vannamei* (Wyban *et al*., 1993). This calls for better documentation, conservation and use of disease- and parasite-resistant wild and farmed fish populations in aquaculture and culture-based fisheries.

The application of genetics in aquaculture to develop disease-resistant and specific pathogen-free fish strains has a relatively short history, but will expand rapidly as countermeasures to the pathogens and parasites of farmed fish become increasingly needed, especially in intensive production systems. Subasinghe *et al*. (2004) reviewed surveillance and zoning for fish diseases. Information from this approach could be linked to information updates on the location and uses of aquatic genetic resources. Disease-resistant fish are extremely valuable genetic resources for aquaculture and for restocking depleted waters.

11.2 Roles of aquatic genetic resources for mitigation of climate change

General considerations

Aquatic ecosystems cover about two-thirds of the planet. The aquatic ecosystems, with their resident microorganism, plants and fish that are adapting successfully to climate change, are already contributing much to its mitigation, particularly through their roles as carbon sinks, and will continue to do so. Improving the management of aquatic ecosystems, and especially the conduct of aquaculture and fisheries, so that their contributions to climate change are lessened and their mitigations of climate change are increased requires new thinking and well-targeted research, as reviewed by Cochrane *et al*. (2009). Erwin (2009), citing various authors, stated that wetlands (listed as comprising floodplains, mangroves, sea grasses, salt marshes, arctic wetlands, peatlands, freshwater marshes and forests) cover 6 percent of the world's land surface area, contain about 12 percent of the global carbon pool, are diverse in their responses to restoration at different scales. As restorations are planned, there is a need for more information on the roles of wetlands as emitters of greenhouse gasses as well as their roles as carbon sinks. For example, Bastiven *et al*. (2011) asked for more data on greenhouse gas emissions from inland waters to enable better assessment of net continental greenhouse gas fluxes. Their main point was that total methane emissions from freshwaters might offset some of their roles as carbon sinks.

Theses complexities and others aside, the main shift in human behaviour that will be required to maximize mitigation can be summarized as a transition towards greater responsibility in all aspects of the use of aquatic ecosystems and aquatic genetic resources. This means not only a greater adherence to the FAO Code of Conduct for Responsible Fisheries (FAO, 1995) and its supportive guidelines, but also greater responsibility all along the fish chains. Guidance to policy-makers and to the general public on production, purchasing and consumption of ecofriendly and responsibly sourced fish is becoming increasingly available through web sites and mobile phone applications; for example, www.seafoodguide.org. The FAO Code of Conduct for Responsible Fisheries could be supplemented with a further Technical Guidelines volume on "Meeting climate change challenges in aquaculture and fisheries"; adding to the volumes produced recently on genetic resources for aquaculture and the ecosystem approach (FAO, 2008b; 2010c).

In common with other food and agriculture sectors, aquaculture and fisheries have much scope for reducing their own greenhouse gas emissions, primarily by increasing their efficiency of energy use all along the chains of production from harvests to consumers. The reduction in overcapacity of the world's fishing fleets and the provision for aquaculture and fisheries of more energy-efficient engines, pumps, storage facilities and processing plants can make big contributions to mitigating climate change. In the context of the present study, however, the key to success in understanding and improving the roles of aquatic genetic resources in climate change mitigation will be to take an ecosystem-based approach, based largely upon trophic relationships. In this regard, the farming of fish as herbivores or omnivores and the need to improve feed-conversion efficiency in aquaculture are of paramount importance. Pullin (2011) reviewed trophic relationships in aquaculture and their implications for supportive ecosystems. As in agriculture, the farming of aquatic plants and of herbivorous and omnivorous fish is more ecofriendly than the farming of carnivores. The problem here is that many consumers prefer to eat carnivorous fish.

The aquatic primary production that supports global fisheries has been well studied, including global estimates of its utilization by fish feeding at different trophic levels in different ecosystems. Pauly and Christensen (1995) gave the following global mean percentage uses of primary production, by fisheries ecosystem: open ocean, 1.8; upwellings, 25.1; tropical shelves, 24.2; non-tropical shelves, 35.3; coastal and coastal reef systems, 8.3; and rivers and lakes, 23.6. Heterotrophic activity is also of immense importance in aquaculture (see papers in Moriarty and Pullin, 1987) and can exceed primary production in many freshwater and marine ecosystems (Dodds and Cole, 2007). The foodchains of filtering-feeding and detritivorous fish are short and are highly efficient in carbon sequestration. For example, Pauly *et al*. (1988) estimated a primary production to fish yield efficiency of 0.0117 for the detritivorous tilapia *Sarotherodon* *melanotheron* in the Sakumo lagoon, Ghana; and pointed out that this is at the top of the range of efficiencies, 0.0008 to 0.0100, estimated by Marten and Polovina (1982) for tropical and subtropical lagoons and estuaries. Such tilapias and many other freshwater finfish, particularly bottom-feedings carps and catfish, are very active burrowers into bottom sediments of water bodies, including aquaculture ponds. Those bottom sediments are important sinks for nitrite and nitrate (e.g. Hargreaves, 1998).

Conserving and breeding fish for changing climates and changed ecosystems

In aquaculture and open waters, meeting the challenges of climate change will require re-evaluation, sustainable use and conservation of what can be called ecofriendly fish. Marine aquaculture still lacks domesticated herbivorous and omnivorous finfish species comparable to those that form the basis of most freshwater aquaculture. There are, however, entire families of herbivorous and omnivorous marine fish that browse and graze on coral reefs, on sea grass beds and in estuaries: for example, goatfish, mullets, rabbit fish and surgeon fish. The genetic resources of such fish will be lost progressively as their ecosystems are further damaged. Thrusts to conserve those ecosystems and those possibly more farmable ecofriendly fish, and to explore their greater use in responsible aquaculture and fisheries will therefore become more important as climate change proceeds. This applies particularly in the breeding of eco-friendly fish for aquaculture and for culture-based fisheries. The emphasis must be, as in livestock, on herbivorous and omnivorous fish, with high feed-conversion efficiency. Coincidentally, this will reduce some of the adverse environmental impacts of aquaculture: for example those associated with wastes and with escaped fish. In addition, fish breeders will have to address increasingly the need to breed for assured survival and good performance in waters of variable, and often lower, quality.

Improving watersheds

Watersheds and floodplains and freshwater wetlands have immense importance as carbon sinks and nitrogenous waste processors, but many are under threat worldwide as they are drained for development of intensive agriculture, forestry, human settlements and industry. Mitigation of wetland reclamation is the key to maximizing the contributions of wetland biota to mitigation of climate change. The scope for aquatic genetic resources in freshwaters to contribute to mitigation of climate change depends upon there being a suitable and stable hydrological regime in the ecosystems where the mitigation could take place. Assuring the presence of adequate quantities and quality of freshwater in water bodies and watercourses, additional to that abstracted for agriculture, forestry, human settlements and industry, contributes to mitigation of climate change by increasing terrestrial vegetation and the abundance of aquatic plants. Fishes and forests have mutually beneficial interactions across entire watersheds, though these can easily break down when the ecosystems that they share are mismanaged (Northcote and Hartman, 2004).

Responsible inland fisheries and aquaculture, by their very existence, engender more responsible management of inland waters for their multipurpose use (e.g. Molden, 2007). Guidelines are available for the management of inland fisheries and the rehabilitation of rivers for fish (e.g. Cowx and Welcomme, 1998; Hoggarth *et al*., 1999). In savannah and other dryland ecosystems, for example the African Sahel, the seasonal scarcity and value of water mean that its availability and multipurpose use must be maximized. Seasonal aquaculture and fisheries in the water bodies that are precious “wetlands in drylands” can provide added incentives and resources. Small carps, catfishes, tilapias and miscellaneous small indigenous species can be farmed in cycles as short as three months in areas where water supplies are uncertain.

Across watersheds, floodplains and other freshwater wetlands, natural and artificial small water bodies provide water for agriculture, forestry and associated human settlements, sometimes seasonally and sometimes continuously. Such water bodies also provide and conserve aquatic genetic resources, produce fish harvests and, coincidentally, can mitigate some adverse climate-related impacts. Prein *et al*. (2002) demonstrated the success of small fishponds in improving agro-ecosystems in an upland forest buffer zone that had suffered from slash-and burn farming practices. Pullin and Prein (1995), drawing mainly from experience with development of small, multipurpose farm ponds in Africa, compared hypothetical scenarios for catchments without them and with them (Figure 3). The hypothesis is that watersheds with more stable hydrological regimes and wetlands that are kept wet, not drained, will emit less greenhouse gases.

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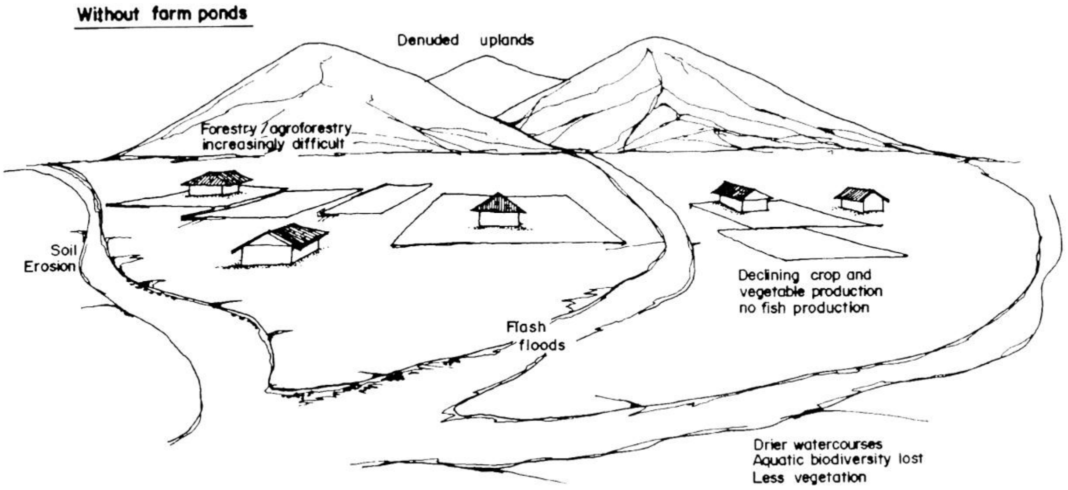
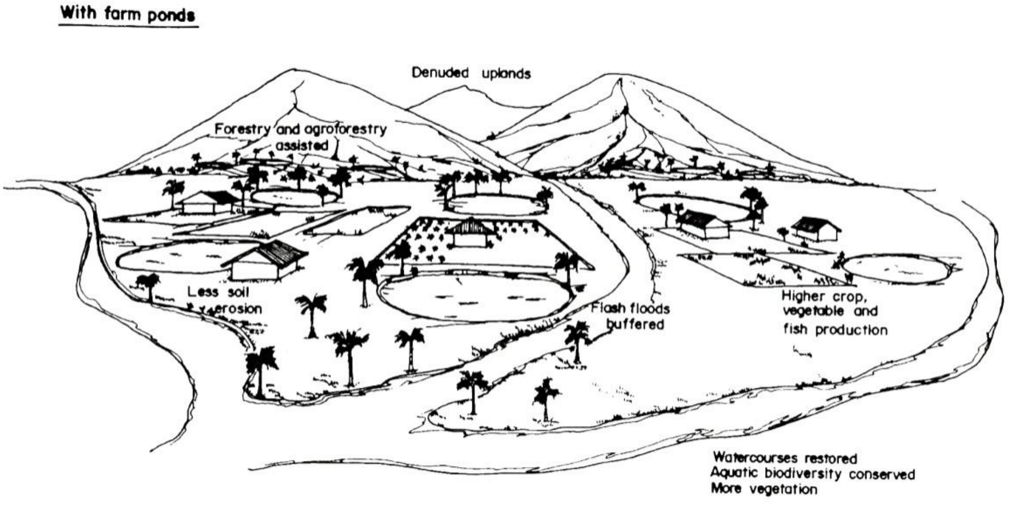
Figure 3. Comparison of catchments without and with small, multipurpose farm ponds, indicating their potential benefits: reduction of soil erosion; improvement of soil structure and fertility; increased production of crops, vegetables, trees and fish; and conservation of aquatic and other biodiversity. Source: Pullin and Prein (1995).





Reappraising integrated farming

The principles and practices of integrated farming and excreta/wastewater-fed aquaculture merit re-examination as potential mitigators of adverse impacts of climate change, because they make the most of locally available nutrients and water. There is a long history of so-called ecological engineering, particularly in China, that could be explored (e.g. Yan *et al*., 1993). Guo and Bradshaw (1993) described a Chinese crop–livestock–fish farming system that increased primary production by 25 percent, increased fish production by 4.7 times, reduced reliance on off-farm nitrogenous fertilizer by 46 percent and provided most of the local food supply. The most successful examples were crop–livestock–fish and wastewater/excreta-fed-pond systems in China and neighbouring countries, with herbivorous and microphagous carps as their key fish species. The historical Chinese rice paddy–reed–fish ecosystem, described by Ma *et al*. (1993) had the following benefits: flood control/water storage; lower radiation of heat than surrounding lands; purification of water; soil improvement; and hosting higher natural biodiversity. With the rapid growth of human populations and the requirements for ever higher production per unit area of farmed land and water, such integrated farming systems have been replaced increasingly since the 1980s with more intensive, separate enterprises, including pellet-fed fishponds, though the dominant fish used is still the grass carp (*Ctenopharyngodon idella*) (Edwards, 2004). Recent attempts to expand rice–fish integrated farming have also failed to prosper, largely because of pesticide use, mismatches in crop cycles and water availability, as well as the small-sized fish that they yield, which makes them more suitable as fish nurseries.

Nevertheless, fish such as Nile tilapia (*Oreochromis niloticus*) have potential for improving the productivity of wetland farming systems and increasing their soil microbial biomass (Lightfoot *et al*., 1990). Lightfoot *et al*. (1993) found that integrated rice–fish systems had potential for increasing rice yields by up to 15 percent, with fish harvests of 500 kg/ha every rice crop. This suggests that integrated farming, using appropriate species and strains of crops and fish, can improve carbon sequestration in wetland agriculture and reduce its greenhouse gas emissions. Moreover, integrated farming systems will require less fossil-fuel energy than intensive feedlot aquaculture and conventional agriculture. For comparison, Haas *et al*. (1995) compared organic farming systems, including rice farming with aquatic nitrogen-fixing cyanobacteria and azolla, and conventional farming systems and found that the former would have 61 percent less CO_2 emissions through their much lower use of fossil-fuel energy. There are obviously trade-offs between the productivity of integrated farming systems, organic agriculture and aquaculture and their environmental benefits, which could now be investigated further with respect to mitigation of climate change. The key questions here are to what extents integrated farming systems can mitigate climate change while, at the same time, produce enough food per unit inputs of land, water, fertilizer, feed, labour, capital, etc. Cross-sectoral, ecosystem-based approaches are needed, providing for sharing of, and synergisms from, the use of scarce resources, especially water and nutrients.

Reservoirs can also have important roles in climate change mitigation. St. Louis *et al*. (2000) pointed to the world’s rapidly increasing area of reservoirs and forecast that greenhouse gas fluxes from hydroelectric reservoirs, comprising 25 percent of the area of all reservoirs, could in future account reach about 15 percent of the global warming potential of all anthropogenic emissions. They estimated reservoir and natural lake greenhouse gas fluxes to the atmosphere, in $mg/m^2/day$, as follows: temperate reservoirs – CO_2, 1 500 and CH_4, 20; tropical reservoirs – CO_2, 3 000 and CH_4, 100; lakes – CO_2, 700 and CH_4, 9. Clearly, there is a need to mitigate the reservoir fluxes as much as possible by designing and managing reservoirs in ways that will maximize their functions as carbon sinks. The prospects for that are unclear, but the prospects for exporting C and N, as fish biomass from reservoir fisheries, including culture-based fisheries and aquaculture, are well proven.

Improving coastal ecosystems

Mangroves sustain a high level of biological productivity from rich biodiversity and play important ecological and economic roles in many countries. The boom in tiger shrimp production in the 1980s triggered the clearing of some mangrove forest area for shrimp ponds. After serious disease problems, however, many shrimp ponds were abandoned, leaving serious problems for coastal ecosystem health, livelihoods and food security (e.g. Stevenson, 1999; Matsui *et al*., 2010). Rehabilitation of these abandoned ponds, back to use as productive fish or shrimp ponds, or to become again mangrove forests, is underway as part of national and regional development plans. Mangroves sequester 1.5 tonnes of carbon per hectare and so can be an important means of mitigating greenhouse gases (Gong and Ong, 1990; Ong, 1993) and for the absorption of nutrients from adjacent aquaculture.

Developing clean biofuels

The Royal Society (2008) reviewed policy options for biofuels and noted the potentials of intensively cultured microalgae having more than 50 percent oil content and of marine macroalgae harvested from open waters, as feedstocks for industrial conversion to biofuels. Mass culture of microalgae to produce biofuel feedstocks is expensive, but the Royal Society (2008) noted the scope for development of genetically modified microalgae for this purpose. From the perspective of mitigation of climate change, it is not yet clear how these aquatic plant feedstocks would compare with cereals or with agricultural and forestry waste feedstocks containing lignocellulose, but reductions in greenhouse gas emissions compared with the use of conventional fuels would be almost certain. Biofuels from lignocellulose feedstocks are likely to show a two-fold or better average greenhouse gas abatement potential compared to biofuels from crop feedstocks (Royal Society, 2008). Coastal harvesting of macroalgae as biofuel feedstocks might have good potential, because it could contribute to mitigation of climate in several ways: directly, as an alternative aquatic feedstock to replace, or complementary to, terrestrial feedstocks, all of which produce cleaner fuels than conventional ones; and indirectly, by contributing to wastewater treatment in coastal waters and by sparing the use of some lands for biofuel production. The Royal Society (2008) quoted data suggesting that production from terrestrially sourced feedstocks of enough biofuels to provide 10 percent of the world’s transport fuel requirements, would require 340 million ha of land, equivalent to about 8 percent of the 5 billion ha of crop and pasture lands in current use. Producing biofuels from wild-sourced marine algal biomass would not compete with land or fertilizer use. Cochrane *et al*. (2009) noted that the farming of seaweeds for other industrial purposes and for food, particularly in the tropics, contributes significantly to carbon sequestration, with harvests of over 2,500 tonnes per ha at approximately three-month intervals: far higher than any yields from terrestrial agriculture.

11.3 Biotechnology for realizing the potentials of aquatic genetic resources in adaptation to, and mitigation of climate change

In situ *conservation*

In situ conservation can be considered as part of biotechnology, in the broadest sense. Conservation of aquatic genetic resources on farms will always be limited because most farmers strive to obtain and then keep only the most productive and profitable species and strains. Formerly used species and strains, some of which can be of further use in breeding programmes and related research, are usually lost. Moreover, farm populations, especially those with low effective breeding numbers, can undergo significant genetic change, including loss and fixation of alleles (Elliot and Evans, 2007). Responsibilities for conserving as much *in situ* on-farm aquatic genetic diversity as possible will rest largely with public- and private-sector breeding programmes and hatcheries. Commercial sources of fish-seed supply dictate largely how much of that genetic diversity is kept or lost. Some government and research-organization breeding programmes and hatcheries, however, will continue striving to maximize whatever can be kept.

Greater uncertainties apply to the *in situ* conservation of aquatic genetic resources in open aquatic ecosystems, especially in waters where stocks are overfished and in the limited aquatic protected areas that have been established, usually with little or no documentation of their populations at the genetic level. Kelleher (1999) provided guidelines for marine protected areas, and the benefits of marine protected areas for conservation of biodiversity and for increasing adjacent fish catches have been widely demonstrated. As Cullis-Suzuki and Pauly (2010) pointed out, however, less than 1 percent of the world's oceans are currently protected areas. Jones (2002) summarized the main issues that can arise from the perspectives of different stakeholders. Large- scale networking, among those managing protected areas, can be highly beneficial across river basins and marine ecosystems by providing key information on specific threats and status (e.g. McCook *et al*., 2009). Information on aquatic protected areas is available through the World Commission on Protected Areas (www.iucn.org).

Freshwater protected areas (for example, in national parks, nature reserves and sacred groves) have received much less attention and investment then marine protected areas, but have high potential to contribute to conservation of aquatic genetic resources for inland aquaculture and fisheries by providing refuges for populations that would otherwise be overfished or eliminated. For example, Reichard (2008) described an undisturbed assemblage of 14 species of fish in the River Gambia. Droughts and floods are now threatening some formerly secure refugia for *in situ* wild populations. For example, Kaufman (2006) pointed to the secure conservation of a reservoir population of a tilapia with high and underutilized potential as a food fish, *Oreochromis esculentus*, but also drew attention to its seriously drought-threatened populations in other refugia that represented significant genetic resources. As short-term climate fluctuations continue, especially droughts and floods, and as long-term climate change takes hold, some important *in situ* aquatic genetic resources in freshwaters will be lost and/or mixed. For diadromous and migratory riverine species, *in situ* conservation requires that all habitats along their migration routes remain accessible and supportive. The need to complement *in situ* conservation of aquatic genetic resources with *ex situ* conservation is certain to increase as threats to open waters, including threats from climate change, intensify. This applies particularly to African inland waters. Overall, the establishment and management of aquatic protected areas has not been accompanied by assessment of their importance and utility in terms of genetic resources. The remedy is to plan aquatic protected areas with conservation of genetic resources as one of their explicit functions and to make updated inventories of aquatic genetic resources in all protected areas.

The concept of *twinning* aquaculture and fisheries development and management with conservation of aquatic genetic resources is important here. It requires that conservation be recognized as a sector in its own right, rather than an occasional optional extra to interventions for increasing food security and livelihoods. Twinning means more than just zoning aquaculture and other uses of lands, and twinning means integrating, in policies and actions, of the conservation of aquatic biodiversity (at gene, population/species and ecosystem levels) with the development and subsequent oversight of agriculture, aquaculture, forestry and all uses of watersheds and coastal zones. Twinning is achieved through co-policymaking, co-planning, co-institution and capacity building, co-financing and co-tracking of progress for the twinned conservation and development objectives (FAO, 2008b). This requires continuous cross-sectoral collaboration, recognition of intersectoral impacts and synergies, and pursuit of long-term conservation and development objectives together.

Twinning links and combines support for *in situ* conservation in aquatic protected areas and on farms with increased production from farming and fishing areas and with *ex situ* conservation. For aquaculture, twinning facilitates responsible farming of the most productive and profitable types of fish in zones where they and their effluent waters will not have adverse environmental impacts, while important wild aquatic genetic resources are conserved elsewhere, in protected areas that are isolated from farmed fish and farm waters and, where no such protected areas are possible, as *ex situ* collections. The farmed fish need not exclude alien species, hybrids, polyploids or any of the products of applications of biotechnology in aquaculture, *provided that* biosafety and biosecurity are assured, with all potentially affected environments and biota adequately safeguarded.

Ex situ *conservation*

Proven technologies exist for *ex situ* cryopreservation of the spermatozoa of about 200 finfish species and of the zygotes and embryos of a few invertebrates (Tiersch and Malik, 2000). Cryopreservation of fish sperm is an important means for conserving important or potentially important fish genetic diversity that is under threat, especially wild types: for example, mahseer (*Tor khudree*) (Basavaraja *et al*., 2002) and Brazilian migratory fish (Carolsfeld *et al*., 2003b). The Frozen Ark Project (www.frozenark.org) includes fish in its activities. Breeding populations of fish in public and private aquaria and in research establishments are also important *ex situ* collections of aquatic genetic resources, though often poorly documented at the genetic level. Moreover, like *in situ* on-farm populations, they are subject to genetic change, especially as their effective breeding numbers are often very small. There are extensive *ex situ* culture collections of the microalgae, rotifers and crustaceans (e.g. cladocerans, copepods and Artemia) that are used in fish hatcheries. The world’s museums contain collections of fish and aquatic-plant specimens from which DNA is recoverable.

Selective breeding, including marker-assisted selection

Selective breeding has been the main route to genetic improvement in aquaculture, following the same approaches used in agriculture and forestry. For example, Henryon *et al*. (2002) showed that additive genetic variation existed for growth rate, feed-conversion efficiency, and disease resistance within a single famed population of rainbow trout (*Oncorhynchus mykiss*). Imsland *et al*. (2000) showed that the most northerly (Norwegian) of three populations of juvenile turbot (*Psetta maxima*) had superior growth and food conversion efficiency compared to populations from France and Scotland. Fast growth and better food-conversion efficiency are often linked in selective breeding of fish. Gjedrem (2005, 2010) reviewed the methods used and much of the historical progress made through selective breeding. FAO (2008b) summarized the main types of selection used, as follows: individual or mass selection; within-cohort selection; within-family selection; and combined selection; with the options of establishing selection indices for multiple traits and the use of marker assisted selection (MAS). Many of the most successful approaches to selective breeding of farmed fish have drawn upon genetic resources from a wide diversity of wild and farmed populations; for example, the genetic improvement of Nile tilapia (*Oreochromis niloticus*) (Eknath *et al*., 1993).

Sonesson (2003) foresaw the potential of MAS in breeding programmes for farmed fish, especially for disease resistance, fillet quality, feed-conversion efficiency and maturation, and noted the limitations posed by small numbers of genetic marker and quantitative trait loci (QTL) maps. Gjedrem (2005) noted that the number of QTLs mapped for farmed fish species was still small and confined to carp, tilapia, rainbow trout and Atlantic salmon, but was beginning to cover a wide range of interesting traits, including cold tolerance in tilapia (Cnaani *et al*. 2003) and carp (Sun and Liang 2004) hybrids. The numbers of QTL maps and their uses in MAS are increasing across a wider range of farmed fish. For example, Fuji *et al*. (2007) used MAS to develop a line of the farmed flatfish *Paralichthys olivaceus* with resistance to lymphocystis disease, a widespread virus affecting many species, and Martínez *et al*. (2009) identified in farmed turbot (*Psetta maxima*) a marker associated with sex that could have wide application. Jackson *et al*. (1998) mapped two QTL, in different linkage groups, that appeared to account for about 13 percent and 9 percent of overall additive genetic variance in upper-temperature tolerance in rainbow trout (*Oncorhynchus mykiss*).

MAS is likely to be used increasingly in fish breeding programmes as the numbers of genetic maps and identified QTL increase and will be an important tool for developing fish that can meet the challenges of short-term climate fluctuations and long-term climate change. Liu (2007) concluded that fine QTL mapping will allow trait-linked markers to be used for MAS, but that MAS should not replace traditional selective breeding but should complement sound selection and provide indicators to breeders that their fish really do have the genes that they are presumed to have. Selective breeding, with or without MAS, is likely to be the mainstay of fish breeders who seek to develop farmed fish that are better able to meet climate challenges. As short-term climate fluctuations and long-term climate change proceed, natural selection in farmed and wild populations, especially those at the geographical limits of environmental tolerance ranges, will provide genetic resources upon which further artificial selection can be applied in breeding programmes.

Cross breeding and hybridization

The terms cross breeding and hybridization are sometimes used loosely and interchangeably in aquaculture and fisheries. FAO (2008) limits the use of cross-breeding to mean the mating of individuals of two different varieties, stocks or strains within the same species, and hybridization to mean the mating of individuals from two separate species. Cross breeding and hybridization have long histories of use in aquaculture and culture-based fisheries. The history of common carp breeding has involved extensive cross breeding among Asian and European riverine races and farmed strains to produce fish with significant heterosis for growth and appearance in terms of body shape and colour (Jhingran and Pullin 1988). Hines *et al.* (1974) found that common carp cross breeds were more disease resistant than inbred strains. However, some recent successes in the genetic improvement of farmed fish have focused more on selective breeding from synthetic base populations that were established from matings among many diverse wild and/or farmed strains, rather than on cross-breeding *per se* between given strains. Before taking this approach, complete diallel crosses can be made among all available strains. This failed to indicate any significant heterosis in Atlantic salmon (Gjerde and Refstie, 1984) and Nile tilapia (Bentsen *et al.*, 1998).

Bartley *et al.* (2001) listed 35 successful hybrid crosses, involving carps, catfish, salmon and trout, and miscellaneous freshwater, diadromous and marine finfish species. They pointed out that contributions from hybrids to world aquaculture and culture-based fisheries production was substantial and growing, but had yet to be documented adequately in statistics. That situation remains largely uncorrected. The most important farmed hybrids include: Nile tilapia (*Oreochromis niloticus*) x blue tilapia (*Oreochromis aureus*), for cold tolerance from female *O. aureus* and for high percentages of male F1 progeny; Mossambique tilapia (*Oreochromis mossambicus*) x Nile tilapia and other *Oreochromis* spp., for tolerance to marine waters; African catfish (*Clarias gariepinus*) x Thai catfish (*Clarias macrocephalus*), for fast growth and flesh quality; and white bass (*Morone chrysops*) x striped bass (*Morone saxatilis*), for fast growth and appearance. Among these four examples, the tilapia and catfish hybrids are all fertile, whereas the bass hybrids are usually, though not always, sterile.

The need for biosecurity precautions with respect to the use of hybrid fish in aquaculture and culture-based fisheries is therefore obvious. Despite that caveat, it seems likely that cross-breeding and hybridization will complement, and in some cases supplant, selective breeding for the development of fish that will be better able to meet climate challenges in aquaculture and culture-based fisheries. If problems with breeding parental lines can be overcome, there will be good prospects for revisiting the potentials of the many hybrids that are known to be possible, but that have not yet seen significant use: for example, the 30 tilapia hybrids reviewed by Wohlfarth and Hulata (1983); the fifteen Indian carp hybrids noted by Selvaraj and Kumar (2004); and the large number of possible catfish hybrids, including those that confer greater tolerance to hypoxia – for example, the channel catfish (*Ictalurus punctatus)* x blue catfish (*Ictalurus furcatus*) hybrid (Dunham *et al.* 1983).

Chromosome set manipulations and monosex populations

The biotechnologies used to manipulate chromosome sets in farmed fish include gynogenesis, the production of all-female populations; androgenesis, the production of all-male populations; and artificially induced polyploidy, to produce triploid or tetraploid populations (FAO, 2008b). Gynogenesis is widely used in fish genetic research but not in commercial aquaculture. Androgenesis has wide potential use in fish breeding, for aquaculture and conservation purposes, when cryopreserved fish sperm is the only extant genetic material available for a species or strain.

About 25 families of fish, including catfish, carps, salmonids and sturgeons, exhibit natural polyploidy at 4n, 6n or 8n (see cytogenetics information available at www.fishbase.org). Triploid fish are sterile. Artificial triploidy has been widely explored for bivalve mollusc and finfish farming, in order to produce higher-quality products and/or to lessen the chances of escapees breeding or interbreeding with wild fish (e.g. Gosling 2003; Tiwary *et al*., 2004). Tetraploid oysters and salmon have been produced experimentally, offering the possibility of crosses with diploids to yield triploid progeny. About 50 percent of the oysters farmed in Europe and the United States of America are triploids (FAO 2008b). Triploid Chinook salmon (*Oncorhynchus tshawytscha*) appear less aggressive than diploids and have been recommended for use in aquaculture (Garner *et al*., 2008).

There are commercial advantages to farming monosex populations in finfish species where either males or females have significantly higher growth and better appearance: for example, all-male populations of tilapias and all-female populations of rainbow trout and flatfish. The principle methods used are hormonal sex reversal, which has been proven as safe for consumers (e.g. Johnstone *et al*., 1983) and, for female heterogametic species, appropriate breeding programmes (FAO, 2008b). F1 hybrids of many tilapias (*Oreochromis* spp.) are usually all-male, or nearly so, but hormonal sex reversal is still applied to most farmed hybrids in order to eliminate all possibilities of females and wild breeding in production stocks. Only one tilapia subspecies (*Oreochromis urolepis hornorum*), from the Wami River, United Republic of Tanzania, always produces 100 percent all-male tilapia F1 hybrid progeny, making its genetic resources potentially very valuable. Genetically all-male stocks of farmed Nile tilapia (*Oreochromis niloticus*), which has male heterogamety, are produced in commercial aquaculture by establishing broodstocks of YY supermales (Mair *et al*., 1997). Genetically male tilapias are being farmed commercially in Asia and the Americas. Their use might increase if future regulations prohibit hormonal sex reversal (on grounds of market image and organic food classification rather than on safety).

There are no clear indications as to whether artificially produced polyploid and monosex fish populations have any significant potential for enabling aquaculture and capture fisheries to meet climatic challenges, but this merits further study, together with further work on the biosecurity aspects of their use and their contact with wild populations. Triploids can have surprising properties, some of which might be relevant with climate change; for example, the gill lamellae of triploid tench (*Tinca tinca*) have a much shorter water–blood diffusion distance for oxygen transfer (1.46 µm) than that of the shorter and thicker lamellae of diploids (2.07 µm) (Flajshans and Piackova, 2006).

Genomics, gene discovery and transgenic fish

Liu (2007) reviewed rapid progress in analytical genetic technologies of relevance for aquaculture and fisheries (DNA markers, genome mapping, microarrays and sequencing) and emphasized that, whereas genomes are fairly stable, transcriptomes and proteomes is highly dynamic and more complex, with environmental factors (temperature, pH, water quality, dissolved oxygen levels, etc.) inducing or suppressing the expression of genes at different life-history stages. Oleksiak (2010) noted that finfish comprise about half of all known vertebrate species and occupy environments from below zero to 46 °C and salinities from zero to above 40 parts per thousand, making them important material for genomic research. The same author noted that less than 0.2 percent of finfish species have documented genomic resources, but was able to list 37 species of teleosts and seven other fishes with large (> 9 000) expressed sequence tag (EST) collections. McAndrew and Napier (2010) have reviewed the present status and future potentials of applied genetics and genomics in aquaculture.

Genetic linkage maps have been constructed for many species of farmed finfish, crustaceans and molluscs, with large DNA libraries established for the most important, including Atlantic salmon, channel catfish, rainbow trout and tilapias (Liu, 2007). This information base is expanding rapidly, especially for the most important farmed and/or fished species. For example, Cerdà *et al*. (2010) listed numbers of ESTs in GenBank’s dbEST database for nine species of commercially important flatfish. Complete genome sequencing has been completed for a few fish species that are important internationally as models in ecotoxicology and other laboratory tests; for example, the sea urchin (*Strongylocentrotus purpuratus*) and the zebrafish (*Danio rerio*). Sequencing of the genomes of important farmed fish genomes is underway (e.g. see http://zfin.org/zf_info/genome.html), with tilapia and other cichlids among the current priorities, through the Cichlid Genome Consortium (http://cichlid.umd.edu). The Ocean Genome Legacy (OGL: www.oglf.org) seeks to provide a public archive of genomic information for marine species, so as to promote conservation and public awareness of the importance of the genetic diversity of marine organisms.

Gene discovery in aquatic organisms will target increasingly the improvement of traits for tolerance of, and good performance in, aquaculture and culture-based fisheries that are challenged by short-term climatic extremes and long-term climate change, especially wider temperature, dissolved oxygen and salinity tolerances and disease resistance. The development of transgenic fish has been focused largely on improving growth rates in farmed finfish in order to shorten production cycles. Nam *et al*. (2008) reviewed progress in growth hormone transgenesis in farmed and fished finfish species, including carps, catfish, charr, flatfish, mud loach, pike and tilapias. They emphasized the shift from allotransgenesis (using readily available constructs from other species) to complete autotransgenesis (developing and using constructs from only the target species) and concluded that the production of growth-enhanced autotransgenic fish has become "*technically simple*" and deserving of consideration "*as a priority choice for improving growth performance of farmed species*."

Despite these research successes and opinions, no transgenic fish has yet been approved for use in aquaculture. The glofish, a transgenic strain of the zebra fish (*Danio rerio*) with a green fluorescent protein gene from jellyfish, is currently the only transgenic fish that is produced and distributed commercially for public use in aquaria (www.glofish.com). Cortemeglia and Beitinger (2005) showed that wild-type zebra fish and red glofish would survive winter temperatures in some waters in the southern United States of America.

As with all genetically modified organisms developed for food and agriculture, there are biosecurity concerns and public resistance to the use of transgenic fish in aquaculture, and a large effort to develop better understanding of the issues and effective regulations and guidelines is ongoing (e.g. Kapuscincki, 2005; Kapuscinski *et al*., 2007). The issues are complex, because farmed fish almost always escape and interact with wild biota. Tymchuk and Abrahams (2005) found that growth hormone transgenic coho salmon (*Oncorhynchus kisutch*) were at least the competitive equals of controls for acquiring food to sustain their enhanced growth in the presence of predators. McKenzie *et al*. (2003) found that growth hormone transgenic tilapia hybrids (*Oreochromis mossambicus* x *Oreochromis urolepis hornorum*) were able to defend the higher demand for oxygen incurred by their superior growth and maintained comparable swimming speeds and tolerance to hypoxia.

The same biosecurity issues apply to all fish that are products of biotechnology, including all hybrids and polyploids, as well as all alien fish species used in aquaculture (Pullin *et al*., 1999). Nevertheless, the special restrictions on release and use of transgenic fish are likely to continue. There have been no clear indications that any experimental transgenic fish have enhanced capabilities to meet the challenges of changing climates, beyond those that are likely to be achievable through selective breeding and hybridization.

XII. GAPS IN INFORMATION, KNOWLEDGE, EDUCATION AND AWARENESS

The gaps described here, for information, knowledge, and education and awareness concerning aquatic genetic resources for adaptation to and mitigation of climate change, all contribute to the ongoing larger gap in policy-making and action on the same fronts. Genetic resources policy and climate change are covered in a parallel Background Study Paper in preparation for the Commission's 13th Session. All of the gaps listed below should be considered as resulting from and contributing to the overall large policy and actions gap.

12.1 Information

Information that relates aquatic genetic resources to climate change remains very limited and scattered, compared to the information that is available for most other genetic resources for food and agriculture. There are many information gaps, but there are also existing sources of valuable information that have yet to be well publicized and linked; for example, Eaton *et al*. (1995) complied a database of over 140 000 matched pairs of weekly mean fish occurences and stream upper water temperatures.

In March 2011, FAO convened a Global Workshop on Improving Collection and Sharing of Information on Aquatic Genetic Resources, which endorsed the urgent need to strengthen information systems for aquatic genetic resources. The proceedings of that workshop, including its recommendations, will be reported to the Commission's 13th Session.

The modelling and forecasting of the likely impacts of climate change on aquatic biota and ecosystems is ongoing and providing useful insights: for example, through Ecopath (www.ecopath.org) and Aquamaps (www.aquamaps.org). Past biophysical relationships can be used as a guide to forecasting probable future impacts of climate change, despite the many uncertainties and data gaps, as Schindler *et al*. (2008) proposed for Pacific salmon. Information about aquatic genetic resources remains the largest and most important gap to be filled. Annex I provides an example of the uneven information that is currently available concerning broad temperature and salinity ranges tolerated by farmed aquatic organisms. In the context of climate change, one important information gap is the paucity of readily accessible data on the pH tolerance ranges of fish, especially in brackishwater and marine waters.

12.2 Knowledge

There are huge knowledge gaps concerning aquatic genetic resources and climate change, including the following major areas: responses and adaptations of aquatic organisms to climate change and other interactive stressors, particularly the degradation and loss of aquatic habitats through eutrophication and destructive fishing; genetic variation in farmed and fished aquatic species for traits relevant to climate change; phenotypic plasticity; scope for improving the roles of aquatic ecosystems in adaptation to and mitigation of climate change; and underdeveloped technology for improving those roles. In addition, there are large knowledge gaps concerning the relative vulnerabilities of not only ecosystems and their biological communities, but also of the human beneficiaries of aquatic ecosystem goods and services, including fishers, farmers, the consumers of aquatic produce, and all who depend upon how the aquatic realm can meet the challenges of climate change. All of these knowledge gaps are exacerbated by limitations in skills and in capacities to learn and apply existing and new knowledge. Capacities for the acquisition of knowledge about aquatic genetic resources and climate, and skills for its application, are very limited in all regions.

12.3 Education and Awareness

The huge ongoing media coverage and public and political debates about climate change have under-emphasized the importance of aquatic organisms and ecosystems, and have made almost no mention of aquatic genetic resources. This is part of the general lack of scientific coverage of genetic resources in educational curricula, at all levels, in government publications and in media messages to the public. This has long been apparent in the generally ill-informed political and public debates over genetically modified organisms. Education and awareness about all such important issues must be based on good science and must be communicated well (Stevens-Smith, 2010). This applies particularly to the ongoing debates about climate change. Unless this is achieved, it is unlikely that adequate investments will be made to maximize the roles of aquatic and other genetic resources for meeting the challenges of climate change.

12.4 Capacity building

Many countries will need to strengthen human resources and financial resources, as well as develop appropriate and well-resourced institutions through which to meet the challenges of climate change. In the context of genetic resources for food and agriculture, this applies particularly to a general lack of capacity to recognize and maximize the roles of aquatic genetic resources for adaptation to and mitigation of climate change. In much of world aquaculture and fisheries, those roles are hardly mentioned. Given the wide importance of aquatic ecosystems for the provision of goods and services to humans, including adaptation to and mitigation of climate change, this lack of capacity poses a serious problem for policy-makers, legislators, technical experts and developers, across the public and private sectors. Building capacity for conservation and sustainable use of aquatic genetic resources will be vital for meeting the challenges of climate change. Because of the many commonalities among different sectors with respect to conservation and sustainable use of genetic resources for food and agriculture, filling this gap could best be seen as an opportunity for cross-sectoral collaboration and action, rising above past sector-specific arrangements and budgetary conflicts.

XIII. PARTNERSHIPS

The interdependence of countries with respect to aquatic genetic resources for food and agriculture has been reviewed by CGRFA (2009b). This interdependence is particularly great for aquatic genetic resources, given the interconnected nature of the world’s aquatic ecosystems and the many transboundary issues. Therefore, the most important partnerships to maximize the roles of aquatic genetic resources for adaptation to and mitigation of climate change are regional, subregional and country partnerships. These can be built to some extent on existing arrangements and networks, such as those for regional development, river basins and seas, but new partnerships can also be explored.

In pursuing realization of the potentials of aquatic genetic resources for adaptation to and mitigation of climate change, FAO can benefit from cooperation and synergy with global programmes and organizations, such as the Convention on Biological Diversity (CBD), the Millennium Development Goals and the Millennium Ecosystem Assessment, the Ramsar Convention on Wetland and Wetlands International, the UN Environment Programme (UNEP), the Convention on International Trade in Endangered Species (CITES), the UN Convention on the Law of the Sea, the UN Fish Stocks Agreement, the UN Framework Convention on Climate Change (UNFCCC), the Consultative Group on International Agricultural Research (CGIAR), the International Union for the Conservation of Nature and Natural Resources (IUCN) and the World Wildlife Fund (WWF), the Marine Stewardship Council, the Marine Aquarium Council and Ornamental Fish; organizations and consortia that manage biological databases (e.g. AlgaeBase, FishBase and SealifeBase) with links to genomic and other relevant genetic databases, such as GenBank; international networks that maintain *ex situ* collections of aquatic genetic resources (e.g. the Frozen Ark; public and private aquaria; culture collections of microalgae and other aquatic microorganism; and research groups); and the regional aquaculture and fisheries organizations that emphasize aquatic genetic resources in their activities: for example, the Network of Aquaculture Centers in Asia-Pacific (NACA) and the Network of Aquaculture Centres in Eastern Europe (NACEE).

It will also be important to establish and strengthen partnerships with organizations and consortia that are spearheading ecological and biodiversity forecasting related to climate change, as proposed by Clark *et al.* (2001). In this dynamic and fast-developing field, the many partner organizations in Aquamaps (www.aquamaps.org) are forecasting aquatic biodiversity scenarios with climate change, based on a suite of environmental parameters (bottom depth, temperature, salinity, primary production, sea ice concentration, and distance to land), with equivalents for inland waters and linked to other consortia working in aquaculture, fisheries and aquatic ecology; including the Sea Around Us (www.seaaroundus.org) and Ecopath with Ecosim (www.ecopath.org).

XIV. CONCLUSIONS, RECOMMENDATIONS AND PRIORITY ACTIONS

At its Twenty-ninth Session, January 31 to February 4, 2011, The FAO Committee on Fisheries (COFI) discussed fisheries and aquaculture in changing climates, and made recommendations, among which the following concern aquatic genetic resources:

> "*(a) that Members should intensify their efforts to assess environmental and anthropogenic factors affecting aquatic ecosystems including changes in migratory patterns of fish species and other adverse impacts including ocean acidification, and should consider these in management aprroaches;*
>
> *(b) that FAO should continue to keep Members informed about the implications of climate change for fisheries and aquaculture, based on the best available scientific information and the needs of vulnerable nations and developing countries;*
>
> *(c) that emphasis should be placed on the ecological and economic resilience of fisheries and aquaculture operations and the communities that depend upon them; and…*
>
> *(e) taking note of the urgent need of many members for technical assistance, that FAO should continue and strengthen support to Members and especially developing countries, particularly in relation to adaptation, including facilitating access of these countries to UN adaptation funds for fisheries and aquaculture* (FAO 2011)."

Noting these important recommendations, the present authors' general conclusions and recommendations are as follows:

- Better information on the potential impacts of climate change and the interaction of these impacts with other important factors that influence the health and productivity of natural and human systems is essential for providing the lead time necessary to take full advantage of opportunities for minimizing or adapting to impacts, as well as for allowing adequate opportunity for the development of the necessary institutional and financial capacity to manage change.
- This aquatic planet will not be able to adapt to and mitigate climate change successfully without greatly increased investment for research on aquatic biodiversity at all levels (gene, species/population and ecosystem), as well as for policy-making and for building the institutions and human capacities to implement the best science available.
- The keys to maximizing the roles of aquatic genetic resources for adaptation to climate change and mitigation of climate change are to take care of aquatic ecosystems and to conserve aquatic gene pools.
- Aquatic food production has many comparative advantages in terms of energy use and efficiency, as reviewed for FAO by Bartley *et al*. (2007b) and by Brown (2006) who quoted FAO as supporting the perspective that aquaculture of herbivorous species "*is where the great growth potential for efficient animal protein production lies.*"
- Inland aquaculture and fisheries should become greater partners in the multipurpose use of scarce freshwaters, occupying parts of them but not substantially consuming them.
- FAO could consider adding to its series of Technical Guidelines in support of its Code of Conduct for Responsible Fisheries a volume on "Meeting the Challenges of Climate Change", including in that volume appropriate emphasis on responsible conduct to maximize the roles of aquatic genetic resources for adaptation to and mitigation of climate change.
- In pursuit of its coverage of all biodiversity for food and agriculture and for a cross-sectoral and ecosystem approach to genetic resources and climate change, the Commission could now consider further how best to assign its MYPOW responsibilities for aquatic plant genetic resources and aquatic microorganism genetic resources, as well as for the genetic resources of any aquatic vertebrates and invertebrates that are used for food and agriculture but not yet covered as aquatic genetic resources.

In addition, the authors wish to state the following specific conclusions, recommendations and suggested priority actions concerning aquatic genetic resources and climate change for the following areas: adaptation; mitigation; conservation; cross-sectoral collaboration and ecosystem approaches; biotechnology and biosecurity; education and awareness; and partnerships.

Adaptation

Conclusions

- Climate change impacts are interactive with many other stressors of aquatic organisms and ecosystems; therefore, fostering and improving their adaptation to climate change will require a holistic approach: in particular, moves towards responsible aquaculture and fisheries, in collaboration with other food and agriculture sectors, should be accelerated.
- Wild aquatic organisms are already adapting to climate change through natural selection and movement to new areas.
- There is large scope for screening, further domesticating and breeding aquatic plants and fish that can adapt well to climate change, using all available biotechnology, provided that biosecurity is assured.
- Aquatic farmers and fishers can pursue effective adaptation measures, but some measures are beyond their financial and technical scope and must therefore be undertaken by government institutions, science and technology organizations, and the private sector, in partnerships where possible.

Recommendations

- Recognize and invest in research so as to understand more fully and utilize the capacity of aquatic organisms to adapt to climate change and the current and likely future importance of particular aquatic genetic resources towards that end.
- Encourage, equip and train aquatic farmers and fishers to pursue effective adaptation measures themselves, while ensuring that measures beyond their financial and technical scope, such as provision of information and extension services, coastal defences, extreme-event forecasting and early warning systems, are undertaken by government institutions and science and technology organizations.
- Investigate further and encourage the use of innovative, productive and profitable aquaculture and fisheries operations that can reduce climate change and other stressors on aquatic ecosystems: for example, integrated multi-trophic level aquaculture.

Priority actions

- Encourage and facilitate the establishment and strengthening of institutions for furthering research on the adaptation of aquatic organisms to climate change and for implementing its findings in aquaculture, fisheries and conservation of aquatic genetic resources.
- Monitor, document and, where necessary, take steps to increase the ongoing adaptation to climate change by aquatic organisms and by the parties who use and conserve aquatic genetic resources.

Mitigation

Conclusions

- Aquatic ecosystems and their biota contribute to climate change, but are also its most important current and potential mitigators, and their roles must be fostered and not diminished.
- Aquatic genetic resources underpin the contributions aquatic ecosystems, responsible aquaculture and responsible fisheries to the mitigation of climate change, in concert with those of other sectors for food and agriculture.

Recommendations

- Investigate thoroughly and maximize the ongoing and potential roles of aquatic genetic resources in mitigation of climate, through sound management of aquatic ecosystems, responsible aquaculture and responsible fisheries.
- Improve watersheds, coastal zones and the open sea as mitigators of climate change, through conservation and sustainable use of their natural resources for food and agriculture, including responsible aquaculture and inland fisheries.
- Reappraise integrated farming and wastewater-fed aquaculture in terms of energy efficiency and production, linked to carbon fluxes and possible reductions of methane and other greenhouse gas emissions.

Priority actions

- Research further the flows of carbon and nitrogen in the ecosystems that host and support aquaculture and fisheries, from the perspectives of maximizing their carbon storage and minimizing greenhouse gas emissions.
- Rehabilitate degraded watersheds through improving and sustaining their hydrological regimes, including conservation of wetlands and development of responsible inland aquaculture
- Rehabilitate degraded coastal zones through mangrove reforestation, conversion of abandoned or unproductive aquaculture ponds to more ecofriendly productive use and through cessation of overfishing and destructive fishing methods.

Conservation

Conclusions

- Climate change is a major threat, additional to those from the degradation and elimination of aquatic ecosystems, overexploitation and the impacts of alien species and diseases, to the availability of aquatic genetic resources upon which future adaptation and mitigation depend.
- *In situ* conservation of aquatic genetic resources is ongoing, in marine and other aquatic protected areas as well as on some farms and in some well managed fisheries, but is very limited and not yet widely recognized as an important goal.
- *Ex situ* conservation of aquatic genetic resources is very limited, scattered, under-resourced, and largely unable yet to play an adequate complementary role to *in situ* conservation of aquatic genetic resources that are of particular importance for the future and are threatened.

Recommendations

- Invest in the expansion of *in situ* and complementary *ex situ* conservation of aquatic genetic resources, emphasizing those that have the greatest potential to increase and sustain the contributions of aquatic organisms and ecosystems to food and agriculture as well as to climate change adaptation and mitigation.
- Establish and manage, from a genetic resources perspective, more aquatic protected areas and especially, given the extremely threatened status of many aquatic species and ecosystems, more freshwater protected areas.
- Improve genetic management in aquaculture and fisheries, so as to lessen or avoid the loss of aquatic genetic resources for their current and future contributions to adaptation to and mitigation of climate change.

Priority actions

- Review national, regional and international coverage, status and needs of *in situ* conservation of aquatic genetic resources, in open waters and on farms.

- Review national, regional and international coverage, status and needs of *ex situ* conservation of aquatic genetic resources, in gene banks, research collections and aquaria.
- Build capacity for, and initiate actions to make and continue to update, aquatic genetic resources inventories for all existing and new aquatic protected areas.

Cross-sectoral collaboration and ecosystem approaches

Conclusions

- Genetic resources institutions and their activities are still largely sector specific, underdeveloped and under resourced for effective cross-sectoral collaboration and ecosystem approaches.
- This is changing with the increase in genomic studies across diverse taxa and the realization that different sectors share the same ecosystems, but a more proactive approach is needed for cross-sectoral synergies and ecosystem approaches to be realized.
- Given the importance of water, aquatic ecosystems and aquatic genetic resources for all food and agriculture sectors, as well as their interdependence for adaptation to and mitigation of climate change, the time is ripe for more substantial cross sectoral collaboration and ecosystem approaches, with adaptation to and mitigation of climate change as a catalyst.
- Such cross-sectoral collaboration and ecosystem approaches are important throughout food and agriculture supply chains, from ecosystems to consumers.

Recommendations

- Build and strengthen cross-sectoral collaboration for maximizing the roles of all genetic resources for food and agriculture concerning adaptation to and mitigation of climate change.
- Promote and implement cross-sectoral collaboration and ecosystem approaches in policy-making and interventions for food and agriculture.
- For the mutual benefit of all sectors, increase the resilience and adaptive capacities of aquatic ecosystems and the communities that depend on their goods and services, through good cross-sectoral governance and sound, ecosystem-based management.
- Seek common cross-sectoral and ecosystem-based policies to meet the challenges of climate change, respecting national needs and priorities and addressing transboundary issues, particularly for shared watersheds and water bodies.
- The widespread application of the Ecosystem Approach for Fisheries/Ecosystem Approach for Aquaculture as the strategy to contribute to maintaining biodiversity, preserve the resilience of aquatic and human systems to change and improve capacity to anticipate and adapt to climate-induced changes in aquatic ecosystems and related fisheries and aquaculture production systems.

Priority actions

- Prepare proposals for widening cross-sectoral collaboration and the ecosystem approach for the long-term conservation and sustainable use of genetic resources for food and agriculture, using cross-sectoral interdependence for adaptation to and mitigation of climate change and interdependence on shared ecosystems as the main rationales.

Biotechnology and biosecurity

Conclusions

- Biotechnology will be increasingly developed and applied to improve the productivity and sustainability of aquaculture and capture fisheries, as well as the conservation and fullest possible use of their genetic resources, including farm and research populations and their wild relatives.

- Biosecurity provisions will become increasingly important as these efforts proceed and should encompass all methods by which aquatic organisms are genetically altered and can impact ecosystems and wild populations, not only the use of transgenesis, as well as all potential impacts of alien species.

Recommendation

- Recognize the high potentials of biotechnology to improve and sustain the roles of aquatic organisms, aquatic ecosystems, aquaculture and fisheries in adaptation to and mitigation of climate change.

Priority action

- Review current and potential applications of biotechnology in improving and sustaining the roles of aquatic organisms, aquatic ecosystems, aquaculture and fisheries for adaptation to and mitigation of climate change, and make proposals for increasing such applications, with assurance of biosecurity.

Education and awareness

Conclusions

- Public awareness and understanding of climate change science and climate change impacts have increased, but are not yet addressed well in many educational curricula and media communications.
- The roles of aquatic ecosystems and aquatic genetic resources for adaptation to and mitigation of climate change have been greatly underemphasized, compared to those of terrestrial ecosystems and plant and forest genetic resources.
- Improving awareness and understanding of climate change, and creating solutions to facilitate access to accurate and up-to-date information are keys to winning public support for climate-related policies.
- Communication and information processes that reach all stakeholders will be essential elements in sectoral and cross-sectoral responses to proposals for climate change adaptation and mitigation measures.

Recommendations

- Develop, at all levels, curricula that integrate conservation and sustainable use of aquatic genetic resources.
- Utilize communication specialists to ensure that the information is accessible and usable, presenting diverse and complex issues in a form that is targeted and understandable for each audience.
- Share experiences, lessons learned and best practices in developing and implementing education and outreach activities, including practical examples of such activities, and develop options and strategies for strengthening and expanding these activities.

Priority actions

- Target policy-makers, young people and the media to promote public awareness of climate change issues using a wide range of communication channels, including press conferences, print advertisements, online media and short films.
- Develop holistic solutions to improving climate change and genetic resources education, including approaches that are based on needs and that aim at making an impact by changing behaviour.
- Include climate change and genetic resources materials and teaching in formal educational curricula and in non-formal education.

Partnerships

Conclusions

- Partnerships for investigating, documenting, improving and sustaining the roles of aquatic genetic resources for adaptation to and mitigation of climate change are under-resourced and under-developed.
- In particular, there are limited partnerships among institutions and organizations having sector-specific responsibilities and between the public and private sectors.
- Climate change concerns are catalysts for establishing new partnerships and strengthening existing ones, with global interest in and dependence upon aquatic ecosystems and genetic resources as the broad scope.

Recommendations

- Establish and strengthen partnerships for investigating, documenting, improving and sustaining the roles of aquatic genetic resources for adaptation to and mitigation of climate change.
- Encourage and provide resources for closer partnerships among sector-specific institutions and organizations and between the public and private sectors.
- Utilize climate change concerns as catalysts for establishing new partnerships and strengthening existing ones, citing mutual dependence on aquatic ecosystems and genetic resources.

Priority actions

Review the existing partnerships of FAO for investigating, documenting, improving and sustaining the roles of aquatic genetic resources for adaptation to and mitigation of climate change and explore new ones.

REFERENCES

Abery, N., Sukadi, F., Budhiman, A., Kartamihardja, E., Koeshendrajana, S. and S.S. De Silva. 2005. Fisheries and cage culture of three reservoirs in West Java, Indonesia: a case study of ambitious development and resulting interactions. Fisheries Management and Ecology 12 (5): 315-330.

ACECRC. 2008. Position Analysis: CO2 and Climate Change: Ocean Impacts and Adaptation Issues. http://www.acecrc.org.au/uploaded/117/797619_20pa02_acidification_0805.pdf

ACIA. 2004. Impacts of Warming Arctic: Arctic Climate Impact Assesment. Cambridge: Cambridge University Press.

Adams, S.M. 2005. Assessing cause and effect of multiple stressors on marine systems. Marine Pollution Bulletin 51: 649–657.

ADB 2001. Tuna: A Key Economic Resource in the Pacific. Manila, Philippines: Asian Development Bank. Available at: www.adb.org/documents/reports/tuna/prelims.pdf

Adrian R. 1998. The timing of warming - an important regulator of change in lake plankton communities, p. 205-222. In: D.G. George D.G (ed) Management of Lakes and Reservoirs During Global Climate Change. Dordrecht, Netherlands: Kluwer Academic Publishers. 323p.

Agnèse, J-F. Editor. 1998. Genetics and Aquaculture in Africa. Paris: Editions de l'Orstom. 328p.

Akcaalan, R., Koeker, L., Soezer, B., Oguz, B. and M. Albay. 2009. N/P ratio or allelopathy is effecting microcystin production of *Microcystis aeruginosa*. Phycologia 48 (4): Suppl. np.

Allan, J.D., Abell, R., Hogan, Z., Revenga, C. Taylor, B.W., Welcomme, R.L. and K. Winemiller. 2005. Overfishing of inland waters. Bioscience 55 (12): 1041- 1051.

Allison, E.H. and F. Ellis, F. 2001. The livelihoods approach and management of small-scale fisheries. Marine Policy 25(5): 377–388.

Allison, E.H., Adger, W.N., Badjeck, M-C., Brown, K., Conway, D., Dulvy, N.K., Halls, A., Allison, P., and J.D. Reynolds. 2004. Effects of climate change on the sustainability of capture and enhancement fisheries important to the poor: analysis of the vulnerability and adaptability of fisherfolk living in poverty. Fisheries Management Science Programme Department for International Development. Project No. R4778J.

Allison, E.H., Adger, W.N., Badjeck, M-C., Brown, K., Conway, D., Dulvy, N.K., Halls, A., Perry A. and J.D.Reynolds. 2005. Effects of climate change on the sustainability of capture and enhancement fisheries important to the poor: analysis of the vulnerability and adaptability of fisher folk living in poverty. London, Fisheries Management Science Programme MRAG/DFID, Project no. R4778J. Final Technical Report. 164 p.

Allison, E.H., N.L. Andrew and J. Oliver, J. 2007. Enhancing the resilience of inland fisheries and aquaculture systems to climate change. Journal of Semi-Arid Tropical Agricultural Research 4(1): 38p. Available at: http://www.icrisat.org/Journal/SpecialProject/sp15.pdf

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

Anderson, G.T. and G.A. Rose. 2001. Offshore spawning and year-class strength of northern cod (2J3KL) during the fishing moratorium. 1994-1996. Canadian Journal of Fisheries and Aquatic Sciences 58: 1386-1394.

Andrews, J.D. 1973. Effects of tropical storm Agnes on epifaunal invertebrates in Virginia estuaries. Chesapeake Science 14: 223-234.

Anthony, A., J. Atwood, P. August, C. Byron, S. Cobb, C. Foster, C. Fry, A. Gold, K.

Anthony, S.P. and R. Philip. 2008. Probiotics in aquaculture. World Aquaculture 39: 59-63.

APHA, AWWA and WPCF. 1981. Standard Methods for the Examination of Water and Wastewater. Fifteenth Edition. Washington DC: American Public Health Association. 1,134p. + supplements.

Ask, E.I. 1999. *Kappaphycus cottonii* and *K. spinosum* cultivation handbook. FMC Corporation, Philadelphia, PA, USA.

Arntz, W.E. 1986. The two faces of El Niño 1982 to 1983. Meeresforschung 31: 1–46.

Azanza, R.V., Fukuyo, Y., Yap, L.G. and H. Takayama. 2005. *Prorocentrum minimum* bloom and its possible link to a massive fish kill in Bolinao, Pangasinan, Northern Philippines. Harmful Algae 4: 519–524.

Azanza, R., Baula, I., and Y. Fukuyo. 2006. Seasonal changes in phytoplankton composition in an extensive fish culture area in Bolinao, Pangasinan Philippines. Coastal and Marine Science 30: 85–87.

Babouchine, Y.P. 1987. The selection of a winter carp. Schriften der Bundesforschungsanstalt für Fischerei Hamburg. 1987. np.

Badjeck, M.C. 2008. Vulnerability of coastal fishing communities to climate variability and change: implications for fisheries livelihoods and management in Peru. Ph.D Thesis.University of Bremen, Bremen, Germany. Available at http://elib.suub.uni-bremen.de/diss/docs/00011064.pdf.

Baltz D.M. and P.B. Moyle. 1993. Invasion resistance to introduced species by a native assemblage of California stream fishes. Ecological Applications 3: 246–255.

Bartley, D.M. 1996. Conservation of biological diversity in hatchery enhancement programmes, p. 424- 428. In F. di Castri and T. Younès (eds.) Biodiversity, Science and Development: Towards a New Partnership. Wallingford, UK: CABI International.

Bartley, D.M., Rana, K. and A.J. Immink. 2001. The use of inter-specific hybrids in aquaculture and fisheries. Reviews in Fish Biology and Fisheries 10: 325-337.

Bartley, D.M., B.J. Harvey and R.S.V. Pullin, Editors. 2007a. Workshop on Status and Trends in Aquatic Genetic Resources: A Basis for International Policy. FAO Fisheries Proceedings 5. Food and Agriculture Organization of the United Nations, Rome, Italy. 179p.

Bartley, D.M., Brugère, C., Soto, D., Gerber, P. and B. Harvey, Editors. 2007b. Comparative Assessment of the Environmental Costs of Aquaculture and Other Food Production Sectors. FAO Fisheries Proceeedings 10. 241p.

Basavaraja, N., Hegde, S.N., Akash, N. and K.S. Udupa. 2002. The fertility of cryopreserved Deccan mahseer, *Tor khudree* (Sykes) spermatozoa. Asian Fisheries Science 15: 193-202.

Bastiven, D., Tranvk, L.J., Downing, J.A. Crill, P.M. and A. Enrich-Prast. 2011. Frehswater methane emissions offset the continental carbon sink. Science 331: p.50.

Bates, B.C., Kundzewicz, Z.W., Wu, S. and J.P. Palutikof, Editors. 2008: Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 p.

Bays, J.S. and T.L. Crisman. 1983. Zooplankton and trophic state relationships in Florida lakes. Canadian Journal of Fisheries and Aquatic Sciences 40: 1813-1819.

BBC. 2011. Climate secrets of Marianas Trench probed. Report by R. Morelle on the work of R. Glud and co-workers. British Broadcasting Corporation News; Scienec and Environment; January 17, 2011. Available at: www.bbc.co.uk/news/science-environment

Beare, D., Burns, F., Jones, E., Peach, K., Portilla, E., Greig, T., McKenzie, E. and D. Reid. 2004. An increase in the abundance of anchovies and sardines in the north-western North Sea since 1995. Global Change Biology 10 (7): 1209-1213.

Beaugrand, G., Reid, P.C., Ibanez, F., Lindley, J.A. and M. Edwards. 2002. Reorganization of North Atlantic marine copepod biodiversity and climate. Science 296: 1692–1694.

Beaugrand, G., Brander, K.M., Lindley, J.A. and M. Edwards. 2003. Plankton effect on cod recruitment in the North Sea. Nature 426: 661-614.

Behrends, L.L., Kingley, J.B. and M.J. Bull. 1996. Cold tolerance in mouthbrooding tilapias: heritability estimates and correlated growth responses at suboptimal temperatures, p. 257-265 In: R.S.V. Pullin, J. Lazard, M. Legendre, J-B. Amon Kothias and D. Pauly (eds.) The Third International Symposium on Tilapia in Aquaculture. ICLARM Conference Proceedings 41, 574p.

Bentsen, H.B., Eknath, A.E., Palada-de Vera, M.S., danting, J.C., Bolivar, H.L., Reyes, R.A., Dionisio, E.E., Longalong, F.M., Circa, A.V. , Tayamen, M.M. and B. Gjerde. 1998. Genetic improvement of farmed tilapias: growth performance in a complete diallel cross experiment with eight strains of *Oreochromis niloticus*. Aquaculture 160: 145-173.

Benzie, J.A.H. 1998. Penaeid genetics and biotechnology. Aquaculture 164: 23-47.

Benzie, J.A.H. *et al.* (in press). Promoting responsible use and conservation of aquatic biodiversity for sustainable aquaculture development, p. 00-00. In Proceedings of the Global Conference on Aquaculture 2010, September 22-25 2010, Phuket, Thailand.

Berkelsman, R. and M.J.H. van Oppen. 2006. The role of zooanxthellae in the thermal tolerance of corals: a ‘nugget of hope’ for coral reefs in an era of climate change. Proceedings of the Royal Society B 273 No. 1599: 2305-2312.

Bertahas, I., Dimltriou E., Laschou S. and I. Zacharias. 2006. Climate change and agricultural pollution effects on the trophic status of a Mediterranean lake. Acta Hydrochimica et Hydrobiologica 4:349–359.

Beveridge, M.C.M., Baird, D.J., Rahmatullah, S.M., Lawton, L.A., Beattie, K.A. and G.A. Codd. 1993. Grazing rates on toxic and non-toxic strains of cyanobacteria by *Hypophthalmichthys molitrix* and *Oreochromis niloticus*. Journal of Fish Biology 43: 901-907.

Bilio, M. 2008. The future of capture and culture fisheries – keeping and creating diversity in fish production. Plenary lecture delivered at the 7th International Symposium on Innovative Marine Life Science for the Three E’s, Edibles, Environment and Education, in 21st Century, 17-19 November, Hokkaido University, Hokkaido, Japan. 19p.

Bindoff, N.L., Willebrand, J., Artale, V., Cazenave, A., Gregory, J., Gulev, S., Hanawa, K. Le Quéré, C., Levitus, S., Nojiri, Y., Shum, C.K., Talley, L.D. and A. Unnikrishnan. 2007. Obervations: Oceanic Climate Change and Sea level. In S. Solomon, D. Qin. M. Manning, Z. Chen, M. Marquis, K.B. Avery, M. Tignor and H.L. Miller (eds.) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessement Report of the Intergovernmental Panel on Climate Change. Cambridge UK: Cambridge University Press.

Bondad-Reantoso, M.G., Arthur, J.R. and R.P. Subasinghe, Editors. 2008. Understanding and Applying Risk Analysis in Aquaculture. FAO Fisheries and Aquaculture Technical Paper 519. 304p.

Bootsma H.A. and R.E. Hecky. 2003. A comparative introduction to the biology and limnology of the African Great Lakes. Journal of Great Lakes Research 29 (Supplement 2): 3–18.

Bosynski, C.C. 1998. Interactions between growth, sex, reproduction, and activity levels in control and fast-growing strains of Nile tilapia (Oreochromis niloticus). Master of Science Thesis. Vancouver B.C. University of British Columbia. 108p.

Brander, K.M. 2007. Global fish production and climate change. Proceedings of the National Academy of Sciences of the United States of America 104: 19709-19714.

Brander, K.M. 2010. Cod, *Gadus morhua* and climate change: processes, productivity and prediction. Journal of Fish Biology 77 (8): 1899-1911.

Brander, K. and Mohn, R. 2004. Effect of the North Atlantic Oscillation on recruitment of Atlantic cod (*Gadus morhua*). Canadian Journal of Fisheries and Aquatic Science 61: 1558-1564.

Bregnaballe, J. 2010. A Guide to Recirculation Aquaculture. Copenhagen and Rome: Eurofish and FAO. 64p.

Brown B. R. 2003 Sensing temperature without ion channels. Nature 421: 495-495.

Brown, L.R. 2006. Plan B 2.0: Rescuing a Planet Under Stress and a Civilization in Trouble. New York: W.W. Norton and Company. 365p.

Burkholder, J.M., Noga, E.J., Hobbs, C.W., Glasgow Jr., H.B. and S.A. Smith. 1992. New "phantom" dinoflagellate is the causative agent of major estuarine fish kills. Nature 358: 407–410.

Byrne M., Ho, M., Selvakumaraswamy, P., Nguyen, H.D., Dworjanyn, S.A. and A.R. Davis. 2009. Temperature, but not pH, compromises sea urchin fertilization and early development under near-future climate change scenarios. Proceedings of the Royal Society B 276: 1883–1888.

CAF. 2000. Las lecciones del El Niño: Memorias del fenómeno El Niño 1997 to 1998: retos y propuestas para la región Andina, volumen V: Perú. Corporación Andina de Fomento.

Cai, R-S., Chen, J-L and R-H Huang. 2006. The response of marine environment in the offshore area of China and its adjacent ocean to recent global climate change. PICES XV. Book of Abstracts, p. 239.

Caldeira, K. 2007. What corals are dying to tell us about CO2 and ocean acidification. Oceanography 20: 188–195.

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

Capili E.B., Ibay, A.C.S and J.R.T. Villarin, 2005. Climate change impacts and adaptation on Philippine coasts, p.1-8 In Proceedings of the International Oceans 2005 Conference. 19-23 September 2005, Washington D.C.

Cardoso, P.G., Brandao, A., Pardal, M.A., Raffaelli, D., and J.C. Marques. 2005. The resilience of *Hydrobia ulvae* populations to anthropogenic and natural disturbances. Marine Ecology Progress Series 289: 191–199.

Cardoso, P.G., Raffaelli, D., Lillebø, A.I., Verdelhos, T., and M.A. Pardala. 2008. The impact of extreme flooding events and anthropogenic stressors on the macrobenthic communities dynamics. Estuarine, Coastal and Shelf Science 76: 553–565.

Carline, R.F. and J.F. Machung. 2001. Critical thermal maxima of wild and domestic strains of trout. Transactions of the American Fisheries Society 130 (6): 1211-1216.

Carolsfeld, J., Harvey, B., Ross, C. and A. Baer. Editors. 2003a. Migratory Fishes of South America: Biology, Fisheries and Conservation Status. Victoria BC, Canada: World Fisheries Trust. 372p.

Carolsfeld, J., Godinho, H.P., Filho, E.Z. and B.J. Harvey. 2003b. Cryopreservation of sperm in Brazilian migratory fish. Journal of Fish Biology 63: 472-489.

Carveth, C.J., Widmer, A.M. and S.A. Bonar. 2006. Comparison of upper thermal tolerances of native and nonnative fish species in Arizona. Transactions of the American Fisheries Society 135 (6): 1433-1440.

Castilho, R. and Y. Cifti. 2005. Genetic differentiation between close eastern Mediterranean *Dicentrachus labrax* (L.) populations. Journal of Fish Biology 67: 1746-1752.

Cerdà, J., Douglas, S. and M. Reith. 2010. Genomic resources for flatfish research and their applications. Journal of Fish Biology 77: 1045-1070.

CGRFA. 2007a. Genomics and Genetic Resources for Food and Agriculture. Background Study Paper No. 34. Commission on Genetic Resources for Food and Agriculture. Rome: FAO. 47p.

CGRFA. 2007b. Status and Trends in Aquatic Genetic Resources: A Basis for International Policy. Background Study Paper No. 37. Commission on Genetic Resources for Food and Agriculture. Rome: FAO. 22p.

CGRFA. 2009a. Climate Change and Biodiversity for Food and Agriculture: Taking Systemic and Second Order Effects into Account. Background Study Paper No. 41. Commission on Genetic Resources for Food and Agriculture. Rome: FAO. 28p.

CGRFA. 2009b. The Use and Exchange of Aquatic Genetic Resources for Food and Agriculture. Background Study Paper No. 45. Commission on Genetic Resources for Food and Agriculture. Rome: FAO. 40p.

CGRFA. 2009c. Background Study Paper No. 48. The Impact of Climate Change on Countries' Interdependence on Genetic Resources for Food and Agriculture. Preliminary Version. Commission on Genetic Resources for Food and Agriculture. Rome: FAO. 79p.

Chamberlain, T. 2001. Histamine levels in longlined tuna in Fiji: a comparison of samples from two different body sites and the effect of storage at different temperatures. The South Pacific Journal of Natural Sciences 19 (1): 30-34.

Chervinski, J. 1982. Environmental physiology of tilapia, p. 119-128 In: R.S.V. Pullin, and R.H. Lowe-McConnell (eds.) The Biology and Culture of Tilapia. Manila, Philippines: International Center for Living Aquatic Resources Management.

Cheung, W.W.L., Lam, V.W.Y., Sarmiento, J.L., Kearney, K. Watson, R. and D. Pauly. 2009. Projecting global marine biodiversity impacts under climate change scenarios. Fish and Fisheries 10: 235-251.

Chisholm, J.R.M. 2000. Calcification by crustose coralline algae on the northern Great Barrier Reef, Australia. Limnology and Oceanography 45: 1476–1484.

Chopin T. 2006. Integrated multi-trophic aquaculture. What it is, and why you should care... and don't confuse it with polyculture. Northern Aquaculture 12 (4) July/August: p4.

Chung, K.S. 2000. Heat resistance and thermal acclimation rate in tropical tetra *Astynax bimaculatus*. Environmental Biology of Fishes 57 (4): 459-463.

Clark, J.S., Carpenter, S.R., Barber, M., Collins, S., Dobson, A., Foley, J.A., Lodge, D.M., Pascual, M., Pielke Jnr, R., Pizer, W., Pringle, C. Reid, W.V., Rose, K.A., Sala, O., Sclesinger, W.H., Wall, D,H. and D. Wear. 2001. Ecological forecasts: an emerging imperative. Science 293: p.657.

Cnaani, A., Gall, G.A.E. and G. Hulata. 2000. Cold tolerance of tilapia species and hybrids. Aquaculture International 8 (4): 289-298.

Cnaani, A., Hallerman, E.M., Ron, M., Weller, J.L., Indelman, M., Kahi, Y., Gall, G.A.E., and G. Hulata. 2003. Detection of a chromosomal region with two quantitative trait loci, affecting cold tolerance and fish size, in an F2 tilapia hybrid. Aquaculture 223: 117-128.

Coates, D. 2002. Inland Capture Fishery Statistics of Southeast Asia: Current Status and Information Needs. Bangkok, Thailand: FAO Regional Office for Asia and the Pacific. 114p.

Cochrane, K., De Young, C., Soto, D. and T. Bahri, Editors. 2009. Climate Change Implications for Fisheries and Aquaculture. RAP Publication 2002/11. FAO Fisheries and Aquaculture Technical Paper 530. 212p.

Cohen, J. 2010. Book Review. The Biologist 57 (4): p.222. Review of: Evolution, the Extended Synthesis by Pigliucci, M. and G.B. Müller, Editors. 2010. Cambridge MA: MIT Press. 495p.

Colman, J.A. and P. Edwards. 1987. Feeding pathways and environmental constraints in waste-fed aquaculture, p. 240-281. In: D.J.W. Moriarty and R.S.V. Pullin (eds.) Detritus and Microbial Ecology in Aquaculture. ICLARM Conference Proceedings 14, 420p.

Connell, S.D. and B.D. Russell. 2010. The direct effects of increasing CO2 and temperature on non-calcifying organisms: increasing the potential for phase shifts in kelp forests. Proceedings of the Royal Society B 277:1409-1415.

Cook, A.M., Duston, J. and R.G. Bradford. 2006. Thermal tolerance of a northern population of striped bass Morone saxatilis. Journal of Fish Biology 69: 1482-1490.

Corkum, C.P. and A.K. Gamperl. 2009. Does the ability to metabolically downregulate alter the hypoxia tolerance of fishes? A comparative study using cunner (*T. adspersus*) and Greenland cod (*G. ogac*). Journal of Experimental Zoology, Part A: Ecological Genetics and Physiology. Vol. 311A (no. 4): 231-239.

Cortemeglia, C. and T. Beitinger. 2005. Temperature tolerances of wild-type and red transgenic zebra danios. Transactions of the American Fisheries Society 134 (6): 1431-1437.

Cowx. I.A. and R.L. Welcomme. Editors. 1998. Rehabilitation of Rivers for Fish. Oxford: Fishing News Books Ltd. 260p.

Cotton, P.A., Sims, D.W., Fanshawe, S. and M. Chadwick. 2005. The effect of climate variability on zooplankton and basking shark (*Cetrorhinus maximus*) relative abundance off soutwest Britain. Fisheries Oceanography 14: 151-155.

Cruz, R.V., Harasawa, H., Lal, M., Wu, S., Anokhin, Y., Punsalmaa, B., Honda. Y., Jafari, M., Li, C. and N. Huu Ninh. 2007. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, p. 469-506. In M.L. Parry, O.F. Canziani, J.P. Palutikov, P.J. van der Linden ans C.E. Hanson (eds.). Asia Climate Change 2007: Impacts, Adapatation and Vulnerability. Cambridge UK: Cambridge University Press.

Csirke, J. and M. Vasconcellos. 2005. Fisheries and long-term climate variability, p. 201-211. In FAO's Review of the State of World Marine Fishery Resources. FAO Fisheries Technical Paper 457. 235p.

Cullis-Suzuki, S. and D. Pauly. 2010. Marine protected area costs as "beneficial" fisheries subsidies: a global evaluation. Coastal Management 38 (2): 1 13-121.

Daskalov, G.M., Grishin, S., Rodionov, S. and V. Mihneva. 2007. Trophic cascades triggered by overfishing reveal possible mechanisms of ecosystem regime shifts. Proceedings of the National Academy of Science of the USA 104: 10518-10523.

Daszak, P., Cunningham, A.A. and A.D. Hyatt. 2000. Emerging infectious diseases of wildlife-threats to biodiversity and human health. Science 287: 443–449.

De Casablanca, M-L., Laugier, T. and E. Marinho-Soriano. 1997. Seasional chages of nutrients in water and sediment in a Mediterranean lagoon with shellfish fartming activity (Thua Lagoon, France). ICES Journal of Marine Science 54: 905-916.

De Jesús, M.J. and C.C. Kohler. 2004. The commercial fishery of the Peruvian Amazon. Fisheries 29 (4):10-16.

De Silva, S.S., Amarasinghe, U.S. and T.T.T. Nguyen. 2006. Better-Practice Approaches for Culture-Based Fisheries in Asia. ACIAR Monograph 120. 96p.

De Silva, S.S. and D. Soto. 2009. Climate change and aquaculture: potential impacts, adaptation and mitigation. P. 151-212. In K. Cochrane, C. De Young, D. Soto and T. Bahri (eds.) Climate change implications for fisheries and aquaculture: overview of current scientific knowledge. FAO Fisheries and Aquaculture Technical Paper. No. 530.

De Silva, S.S., Yu, Z. and L. H. Xiang. 1991. A brief review of the status and practices of the reservoir fishery in mainland China. Aquaculture and Fisheries Management 22: 73-84.

De Silva, S.S. and M.J. Phillips. 2007. A Review of Cage Aquaculture: Asia (Excluding China), p. 18-48. In M. Halwart, D. Soto and J.R. Arthur (eds.) Cage Aquaculture – Regional Reviews and Global Overview. FAO Fisheries Technical Paper No. 498.

Dodds, W.K. and J.J. Cole. 2007. Expanding the concept of trophic state in aquatic ecosystems: it’s not just the autotrophs. Aquatic Science 69:427-439.

Duarte, C.M., Marbá, N, and M. Holmer. 2007. Rapid domestication of marine species. Science 316: 382-383.

Dudgeon, D. 2000. Large-scale hydrological changes in tropical Asia: prospects for riverine biodiversity. Bioscience 50 (9): 793-806.

Dungan, M., Miller, T. and D. Thomson. 1982. Catastrophic decline of a top carnivore in the Gulf of California rocky intertidal zone. Science 216: 989–91.

Dunham, R.A., Smitherman, R.O. and C. Webber. 1985. Relative tolerance of channel x blue hybrid and channel catfish to low oxygen concentrations. Progressive Fish Culturist 45: 55-56.

Eaton, J.G., McCormick, J.H., Stefab, H.G. and M. Hondzo. 1995. Extreme value analysis of a fish/temperature field database. Ecological Engineering 4 (4): 289-305.

Edwards, P. 1980. Food Potential of Aquatic Macrophytes. ICLARM Studies and Reviews 5. 51p. (reprinted 1984, 1987).

Edwards, P. (2004) Traditional Chinese aquaculture and its impact outside China. World Aquaculture 35 (1), 24-27.

Eknath, A.E., Tayamen, M.M., Palada-de Vera, M.S., Danting, J.C., Reyes, R.A., Dionisio, E.E., Capili, J.B., Bolivar, H.L., Abella, T.A., Circa, A.V., Bentsen, H.B., Gjerde, B., Gjedrem, T. and R.S.V. Pullin. 1993. Genetic improvement of farmed tilapias: the growth performance of eight strains of *Oreochromis niloticus* tested in eleven different farm environments. Aquaculture 111:171-188.

Elliot, J.M. and J.A. Elliot. 2010. Temperature requirements of Atlantic salmon *Salmo salar*, brown trout *Salmo trutta* and Arctic charr *Salvelinus alpinus*: predicting the effects of climate change. Journal of Fish Biology 77: 1793-1817.

Elliot, N. and B. Evans. 2007. Genetic change in farm stocks: should there be concern? World Aquaculture 38 (1): 6-8.

Embody, G.C. and D.C. Hyford, 1925. The advantage of rearing brook trout fingerlings from selected breeders. Transactions of the American Fisheries Society 55:135-138.

Erwin, K.L. 2009. Wetlands and global climate change: the role of wetland restoration in a changing world. Wetlands Ecology and Management 17: 71-84.

Estay. F., Araneda, C. and N. Colihueque. 2010. A twice-annually spawning rainbow trout strain in Chile. World Aquaculture 41 (3): 26-28.

Esquer Mendez, J.L., Hernandez Rodriguez, M. and L. F. Bueckle Ramirez. 2010. Thermal tolerance and compatibility zones as a tool to establish the optimum culture condition of the halibut *Paralichthys californicus*. Aquaculture Research 41 (7): 1015-1021.

Fabry, V.J., Seibel, B.A., Feely, R.A., and J.C. Orr. 2008. Impacts of ocean acidification on marine fauna and ecosystem processes. ICES Journal of Marine Science 65: 414–432.

FAO. 1995. Code of Conduct for Responsible Fisheries. Rome: FAO. 41p.

FAO. 1999a. Global Characterization of Inland Fishery Enhancements and Associated Environmental Impacts. FAO Fisheries Circular 945. 89p.

FAO 1999b. Management Guidelines for Asian Floodplain Rivers. Part 1: A Spatial, Hierarchical ans Integrated Strategy for Adaptive Co-management. FAO Fisheries Technical Paper 384/1.63p.

FAO. 2003a. Review of the State of World Fishery Resources: Inland Fisheries. FAO Fisheries Circular 942. 60p.

FAO. 2005a. Review of the State of World Marine Fishery Resources. FAO Fisheries Technical Paper 457. 235p.

FAO. 2005b. Increasing the contribution of small-scale fisheries to poverty alleviation and food security. FAO Technical Guidelines for Responsible Fisheries No. 10. Rome: FAO. 79 p.

FAO. 2007a. Fishery and Aquaculture Statistics 2007. Rome: FAO.

FAO. 2007b. 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. 08. Rome. 16 p. Available at: http://www.sflp.org/briefs/eng/policybriefs.html

FAO. 2008a. State of World Fisheries and Aquaculture. Rome: FAO. 176p.

FAO. 2008b. Aquaculture Development 3. Genetic Resource Management. FAO Technical Guidelines for Responsible Fisheries 5. Suppl. 3. 125p.

FAO. 2008c. Climate Change and Biodiversity for Food and Agriculture. Technical Background Document from the Expert Consultation Held on 13 to 14 February, 2008. Rome: FAO. 10p. Available at: ftp://ftp.fao.org/docrep/fao/meeting/013/ai787e.pdf

FAO. 2010a. State of World Fisheries and Aquaculture 2010. Rome: FAO. 197p.

FAO. 2010b. Fishstat. Rome: FAO. Available at: http://www.fao.org/fishery/statistics/software/fishstat/en.

FAO. 2010c. Aquaculture Development 4. Ecosystem Approach to Aquaculture. FAO Technical Guidelines for Responsible Fisheries 5. Suppl. 4. 53p.

FAO. 2011. Committee on Fisheries. Twenty-ninth Session, 31 January to 4 February, Rome. Report Recommendations: p. 10-11.

Feely, R.A., Doney, S.C. and S.R. Cooley. 2009. Ocean acidification: present conditions and future changes in a high-CO2 world. Oceanography 22: 36–47.

Feely, R.A., Sabine, C.L., Hernandez-Ayon, J.M., Lanson D., Hales B. 2008. Evidence for upwelling of corrosive “acidified” water on to the continental shelf. Science 320: 1490-1492.

Fernand, L. and P. Brewer. Editors. 2008. Changes in surface CO2 and ocean pH in ICES shelf sea ecosystems. In ICES Cooperative Research Report No. 290. 35 p.

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

Fisheries Research Services. 2010. Climate Change, Scottish Waters and Fishing Grounds. Available at: http://www.frs-scotland.gov.uk

Flajshans, M. and V. Piackova. 2006. Difference in blood and water diffusion distance in gill lamellae of diploid and triploid tench *Tinc tinca* (L.). Journal of Fish Biology 69: 1870-1873.

Friedland K.D., Reddin, D.G., McMenemy, J.R. and K.F Drinkwater. 2003. Multidecadal trends in North American Atlantic salmon (*Salmo salar*) stocks and climate trends relative to juvenile survival. Canadian Journal of Fisheries & Aquatic Science, 60, 563-583.

Froese, R and A. Torres. 1999. Fishes under threat: an analysis of the fishes in the 1996 IUCN Red List, p. 131-144 in R.S.V. Pullin, D.M. Bartley and J. Kooiman (eds.) Towards Policies for Conservation and Sustainable Use of Aquatic Genetic Resources. ICLARM Conference Proceedings 59, 277p.

Fuij, K., Hasegawa, O., hinda, K., Kumasaka, K., Sakamoto, T. and N. Okamoto. 2007. Marker-assisted breeding of a lymphocystis disease-resistant Japanese flounder (*Paralichthys olivaceus*). Aquaculture 272: 291-295.

Gaedke, U., Ruhenstroth-Bauer, M., Wiegand, I., Tirok, K., Aberle, N., Breithaupt, P., Lengfellner, K., Wohlers, J., and U. Sommer. 2010. Biotic interactions may overrule direct climate effects on spring phytoplankton dynamics. Global Change Biology 16 (3): 1122-1136.

Garner, S.R., Madison, B.N., Bernier, N.J., and B.D. Neff. 2008. Juvenile growth and aggression in diploid and triploid Chinook salmon *Oncorhynchus tshawytscha* (Walbaum). Journal of Fish Biology 73: 169-185.

Gazeau, F., Quiblier, C., Jansen, J. M., Gattuso, J.P., Middelburg, J.J., and C.H.R. Heip. 2007. Impact of elevated CO2 on shellfish calcification, Geophysical Research Letters 34: L07603. doi:10.1029/2006GL028554.

Gilles, S., Amon-Kothias, J-B. and J-F Agnèse.1998. Comparison of brackish water growth performances of *Sarotherodon melanotheron* (Cichlidae) from three West African populations, p 199-210. In: J-F Agnèse (ed.) Genetics and Aquaculture in Africa. Paris: Editions de l’Orstom. 328p.

Gilman, E. L., J. Ellison, N.C. Duke and C. Field. 2008. Threats to mangroves from climate change and adaptation options. Aquatic Botany 89: 237–250.

Gjedrem, T. 2005. Selection and Breeding Programs in Aquaculture. Dordrecht, the Netherlands: Springer. 364p.

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

Gjerde, B. and T. Refstie. 1984. Complete diallel cross between five strains of Atlantic salmon. Livestock Production Science 11: 207-226.

Glynn P.W. 1988. Coral bleaching and mortality in the tropical eastern Pacific during the 1982-83 El Niño warming event, p. 42-45 In: J. Ogden and R. Wicklund (eds.) Mass Bleaching of Coral Reefs in the Caribbean: a Research Strategy. NOAA’s Undersea Research Program; St Croix, US Virgin Islands, Research Reportt 88-2.

Goddard, S.V. and G.L. Fletcher. 1994. Antifreeze proteins: their role in cod survival and sitribution from egg to adult, p. 676-683. In: J. Jakobsson, O.S. Asthorsson, R.J.H. Beverton, B. Bjoernsson, N. Daan, K.T. Frank, J. Meincke, B. Rothschild, S. Sundby and S. Tilseth (eds) Cod and Climate Change: Proceedings of a Symposium Held in Reykjavik. Copenhagen: International Council for the Exploration of the Sea.

Gong, W.K.and J.E. Ong. 1990. Plant biomass and nutrient flux in a managed mangrove forest in Malaysia. Estuarine, Coastal and Shelf Science 31: 519-530.

Gopal, B. 2003. Does inland aquatic biodiversity have a future in Asian developing countries? Hydrobiologia 542: 69-75.

Goreau, T.J. 1990. Coral bleaching in Jamaica. Nature 343: p. 417.

Gosling, E.M. 2003. Bivalve Molluscs. Oxford: Fishing News Books (Blackwell Science). 369p.

Graham, N.A.J., Wilson, S.K, Jennings, S., Polunin, N.V.C., Bijoux, J.P. and J. Robinson. 2006. Dynamic fragility of oceanic coral reef ecosystems. Proceedings of the National Academy of Sciences of the United States of America, 103: 8425–8429.

Graham, N.A.J., Wilson, S.K., Jennings, S., Polunin, N.V.C., Robinson, J., Bijoux, J.P. and T.M. Daw. 2007. Lag effects in the impacts of mass coral bleaching on coral reef fish, fisheries and ecosystems. Conservation Biology 21: 1291–1300.

Grant, W.S. 2007. Status and trends in genetic resources of capture fisheries, p. 29-80 In: D.M. Bartley, B.J. Harvey and R.S.V. Pullin (eds.) Workshop on Status and Trends in Aquatic Genetic Resources: A Basis for International Policy. FAO Fisheries Proceedings 5. 179p.

Griffiths, S.P., Fry, G.C., Manson, F.J. and R.D. Pillans. 2007. Feeding dynamics, consumption rates and daily ration of longtail tuna (*Thunnus tonggol*) in Australian waters, with emphasis on the consumption of commercially important prawns. Marine and Freshwater Research 58: 376-397.

Gregory, S. and G. Jones. 2010. Bats and Allee effects: when social behaviours go batty. The Biologist 57 (4): 198-203.

Gross, M.G., Karweit, M., Cronin, W.B. and J.R. Scubel. 1978. Suspended sediment discharge of the Susquehanna River to northern Chesapeake Bay. Estuaries 1: 106-110.

Guinotte, J.M. and V.J. Fabry. 2008. Ocean acidification and its potential effects on marine ecosystems. Annals of the New York Academy of Sciences 1134: 320–342. doi: 10.1196/annals.1439.013.

Gunn, J.M. 2002. Impact of the 1998 El Nino event on a lake charr, *Salvelinus namaycush*, population recovering from acidification. Environmental Biology of Fishes 64 (1-3): 343-351.

Guo, J.Y. and A.D. Bradshaw. 1993. The flow of nutrients and energy through a Chinese farming system. Journal of Applied Ecology 30: 86-94.

Guo, J.H., Liu, X.J., Zhang, Y., Shen, J.L., Han, W.X., Zhang, W.F., Christie, P., Goulding, K.W.T., Vitousek, P.M. and F.S. Zhang. 2010. Significant acidification in major Chinese croplands. Science 327: 1008-1010.

Haas, G., Geier, U., Schulz, D. and U. Köpke. 1995. CO_2 balance: can the CO_2 effiency of organic farming be used as a guide for developing agricultural production systems in the Third World? Plant Science Rsearch and Development 41/42: 15-25.

Hales, S., Weinstein, P. and A. Woodward. 1999. Ciguatera (fish poisoning), El Niño, and Pacific sea surface temperatures. Ecosystem Health 5(1): 20- 25.

Hall-Spencer, J.M., Rodolfo-Metalpa, R., Martin, S., Ransome, E., Fine, M., Turner, S.M., Rowley, S.J., Tedesco, D., and M.C. Buia. 2008. Volcanic carbon dioxide vents show ecosystem effects of ocean acidification. Nature 454: 96–99.

Halwart M. and D. M. Bartley, Editors. 2005. Aquatic biodiversity in rice-based aquatic ecosystems. Studies and reports from Cambodia, China, Lao Democratic Republic and Viet Nam. CD-ROM. Rome: FAO.

Halwart, M. 2008. Biodiversity, nutrition and livelihoods in aquatic rice-based systems. Biodiversity 9 (1 and 2): 36-40.

Halwart, M. and M.V. Gupta. Editors. 2004. Culture of Fish in Rice Fields. Rome and Penang, Malaysia: FAO and the WorldFish Center. 83p.

Halwart, M., D. Soto, D. and J.R. Arthur. Editors. 2007. Cage Aquaculture – Regional Rviews and Global Overview. FAO Fisheries Technical Paper No. 498.

Handyside, N.T., Ross, L.G. Badjeck, M-C and E.H. Allison. 2006. The Effects of Climate Change on World Aqauculture: A Global Perspective. London: Department for International Development. 151p.

Hansen, J., Sato, M., Ruedy, R., Lo, K., Lea, D. and M. Medina-Elizade. 2006. Global temperature change. Proceedings of the National Academy of Science USA. 103:14288–14293.

Hargreaves, J.A. 1998. Nitrogen biogeochemistry of aquaculture ponds. Aquaculture 166:181-212.

Harvell, C.D., Kim, K., Burkholder J.M., Colwell, R.R., Epstein, P.R., Grimes, D.J., Hofmann, E.E., Lipp, E.K., Osterhaus, A.D.M.E., Overstreet, R.M., Porter, J.W., Smith, G.W., and G.R. Vasta. 1999. Emerging marine diseases – climate links and anthropogenic factors. Science 285: 1505–1510.

Harvell, C.D., Mitchell, C., Ward, J.R., Altizer, S., Dobson, A.P., Ostfied, R.S., and M.D. Samuel. 2002. Climate warming and disease risks for terrestrial and marine biota. Science 296: 2158–62.

Hasan, M.R. and R. Chakrabati. 2009. Use of Algae and Aquatic Macrophytes as Feed in Small-Scale Aquaculture. FAO Fisheries and Aquaculture Technical Paper 531. 123p.

Hawksworth, D.L. and M.T. Kalin-Arroyo. 1995. Magnitude and distribution of biodiversity, p. 107-191. In V.H. Heywood (ed.) Global Biodiversity Assessment. Cambridge: Cambridge University Press.

Henryon, M., Jokumsen, A., Berg, P., Lind, I., Pedersen, P.B., Olesen, N. and W.J. Slerendrecht. 2002. Genetic variation for growth rate, feed conversion efficiency, and disease resistance exists within a farmed population of rainbow trout. Aquaculture 209: 59-76.

Hines, R.S., Wohlfarth, G.W., Moav, R. and G. Hulata. 1974. Genetic differences in susceptibility to two diseases among strains of the common carp. Aquaculture 3: 187-197.

Hobbs, J-P. A., and C.A. McDonald. 2010. Increased seawater temperature and decreased dissolved oxygen triggers fish kill at the Cocos (Keeling) Islands, Indian Ocean Journal of Fish Biology 77: 1219-1229.

Hobday, A. J., E. S. Poloczanska, and R. J. Matear, Editors. 2008. Implications of Climate Change for Australian Fisheries and Aquaculture: a Preliminary Assessment. Report to the Department of Climate Change, Canberra, Australia. August 2008.

Hodgson, G., 1999. A global assessment of human effects on coral reefs. Marine Pollution Bulletin 38: 345-355.

Hoegh-Guldberg, O. 1999. Climate Change, Coral Bleaching and the Future of the World’s Coral Reefs. Marine and Freshwater Research 50: 839-866.

Hoegh-Guldberg, O., Mumby, P.J., Hooten, A.J., Steneck, R.S., Greenfield, P., Gomez, E., Harvell, C.D., Sale, P.F., Edwards, A.J., Caldeira, K., Knowlton, N., Eakin, C.M., Iglesias-Prieto R., Muthiga, N., Bradbury, R.H., Dubi, A., and M.E. Hatziolos. 2007. Coral reefs under rapid climate change and ocean acidification. Science 318: 1737-1742.

Hofmann M and H.J. Schellnhuber. 2009. Oceanic acidification affects marine carbon pump and triggers extended marine oxygen holes. Proceedings of the National Academy of Science of the USA 106: 3017–3022.

Hoggarth, D.D., Cowan, V.J., Halls, A.S., Aeron-Thomas, M., McGregor, J.A., Garaway, C.A., Payne, A.I. and R.L. Welcomme. 1999. Management Guidelines for Asian Floodplain Rivers. Part 1: A Spatial, Hierarchical and Integrated Strategy for Adaptive Co-management. Part 2. Summary of DFID Research. FAO Fisheries Technical Papers Nos. 384/1 and 384/2. 63p. and 117p.

Hook, S.E. 2010. Promise and progress in environmental genomics: a status report on the applications of gene expression-based microarray studies in ecologically relevant fish species. Journal of Fish Biology 77: 1999-2022.

Hori, H. 2000. The Mekong: Environment and Development. New York: United Nations University. 398p.

Hughes, T.P., Baird, A.H., Bellwood, D.R., Card, M., Connolly, S.R., Folke, C., Grosberg, R., Hoegh-Guldberg, O., Jackson, J.B.C., Kleypas, J., Lough, J.M., Marshall, P., Nystrom, M., Palumbi, S.R., Pandolfi, J.M., Rosen, B. and J. Roughgarden. 2003. Climate change, human impacts, and the resilience of coral reefs. Science 301: 929–933.

Hughes, T.P., Bellwood, D.R., Hoegh-Guldberg, O., Moltschaniwskyj, N., Steneck, R.S., Rodrigues, M.J., Ceccarelli, D., Laurence, M. L., Pratchett, M.S. and W.B. Bette. 2007. Phase shifts, herbivory, and the resilience of coral reefs to climate change. Current Biology 17:1–6.

Hughes, S.L. and N.P. Holliday. 2007. ICES Cooperative Research Report No. 289. ICES Report on Ocean Climate 2006. 55p.

Hughes, A.R., Williams S.L., Duarte C.M., Heck K.L. and M. Waycott. 2009. Associations of concern: declining seagrasses and threatened dependent species. Frontiers in Ecology and Environment 7: 242–246.

Humphreys, J. 2010. The introduction of Manila clam to British coastal waters. The Biologist 57(3):134-138.

Hunt, G.L. and S. McKinnell. 2006. Interplay between top-down, bottom-up, and wasp-waist control in marine ecosystems. Progress in Oceanography 68: 115-124.

Imsland, A.K., Foss, A., Naevdal, G., Cross, T., Bonga, S.W., Ham, E.V. and S.O. Stefansson. 2000. Countergradient variation in growth and food conversion efficiency of juvenile turbot. Journal of Fish Biology 57 (5): 1213-1226.

IPCC. 2001. Climate Change 2001: The Scientific Basis. Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge, U.K: Cambridge University Press.

IPCC. 2005. IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Integovernmental Panel on Climate Change; Metz, B.O., Davidson, H.C., de Coninck, M. Loos, and L.A. Meyer (eds.). Cambridge, U.K: Cambridge University Press. 442 p.

IPCC 2007a. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to 20 the Fourth Assessment. Report of the Intergovernmental Panel on Climate Change; Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L. (eds.). Cambridge, U.K: Cambridge University Press.996 pp.

IPCC. 2007b. 4th Assessment: Summary for Policy Makers. Intergovernmental Panel on Climate Change. Available at: http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_spm.pdf

IPCC 2007c. Special Reports on Climate Change. The Regional Impacts of Climate Change. Accessed January 2011. Avaialable at: http://www.grida.no/publications/other/ipcc_sr/?src=/climate/ipcc/regional/index.htm

ISRS, 1998. ISRS statement on global coral bleaching in 1997-98. International Society for Reef Studies. Avaailble at: http://www.uncwil.edu/isrs/

Jackson, J.B.C. 2001.What was natural in the coastal oceans? Proceedings of the National Academy of Sciences USA 98: 5411-5418.

Jackson, J.B.C., Kirby, M.X., Berger, W.H., Bjorndal, K.A., Botsford, L.W., Bourque, B.J., Bradbury, R.H., Cooke, R., Erlandson, J., Estes, J.A., Hughes, T.P., Kidwell, S., Lange, C.B., Lenihan, H.S., Pandolfi, J.M., Peterson, C.H., Steneck, R.S., Tegner, M.J. and R.R. Warner, R.R. 2001. Historical overfishing and the recent collapse of coastal ecosystems. Science 293: 629–638.

Jackson, T.R., Ferguson, M.M., Danzmann, R.G., Fishback, A.G. Ihssen, P.E., O’Connell, M. and T.J. Crease. 1998. Identification of two QTL-influencing upper temperature tolerance in three rainbow trout (*Oncorhynchus mykiss*) populations. Heredity 80 (2): 143-151.

Jacobson, L.D., De Oliveira, J.A.A., Barange, M., Cisneros-Mata, M.A., Felix-Uraga, R., Hunter, J.R., Kim, J.Y., Matsuura, Y., Niquen, M., Porteiro, C., Rothschild, B., Sanchez, R.P., Serra, R., Uriarte, A. and T. Wada. 2001. Surplus production, variability, and climate change in great sardine and anchovy fisheries. Canadian Journal of Fisheries and Aquatic Science 58: 1891-1903.

Jacoby, J.M. and J. Kann. 2007. The occurrence and response to toxic cyanobacteria in the Pacific Northwest, North America. Lake and Reservoir Management 23 (2): 1213-143.

Jang, Min-Ho, Jung, Jong-Mun and N. Takamura. 2007. Changes in microcystin production in cyanobacteria exposed to zooplankton at different densities and infochemical concentrations. Limnology and Oceanography 52 (4): 1454-1466.

Jeney, Z., and J. Zhu. 2009. The use and exchange of aquatic resources relevant for food and agriculture: common carp (*Cyprinus carpio* L.). FAO/NACA Expert Meeting on the Use and Exchange of Aquatic Genetic Resources for Food and Agriculture, March 31 - April 2, 2009, Chonburi, Thailand.

Jhingran, V.G. and R.S.V. Pullin. 1988. A Hatchery Manual for the Common, Chinese and Indian Major Carps. Second Revised Edition. Manila, Philippines: Asian Development Bank and the International Center for Living Aquatic Resources Management. 191p.

Jiang, Y., Ji, B., Wong R.N.S. and M.H. Wong. 2008. Statistical study of environmental factors on the growth and microcystins production of bloom-forming cyanobacterium- *Microcystis aeruginosa*. Harmful Algae 7 (2): 127-136.

Johnstone, R., Mckintosh, D.J. and R.S. Wright. 1983. Elimination of orally administered 17 alpha- methyltestosterone by *Oreochromis mossambicus* (tilapia) and *Salmo gairdneri* (rainbow trout) juveniles. Aquaculture 35: 249-257.

Jones, P. 2002. Marine protected area strategies: issues, divergences and the search for middle ground. Reviews in Fish Biology and Fisheries 11:197-216.

Ju, Z. 2002. Development of expressed sequence tags (ESTs) and CDNA microarrays for analysis of differentially expressed genes in the channel catfish (*Ictalurus punctatus*) brain. Dissertation Abstracts International Part B – Science and Engineering Vol 62, no. 10: p.4375.

Jung, M., Reichstein, M., Ciais, P., Seneviratne, S.L., Sheeld, J., Goulden, M.L., Bonan, G., Cescatti, A., Chen, J., de Jeu, R., Dolman, A.J., Eugster, W., Gerten, D. Gianelle, D., Gobron. N., Heinke, J., Kimball, J. , Law, B.E., Montagnani, L., Mu, Q., Mueelr, B., Oleson, K., Papale, D., Richardson, A.D., Roupsrad, O., Running, S., Tomelleri, E. Viovy, N., Weber, U., Willimas, C. Wood, E. onke, Zachle, S. and K. Zhang. 2010. Recent decline in the global land evapotranspiration trend due to limited moisture supply. Nature 467 No. 7318: 951-954.

Kalff, J. 2000. Limnology. Upper Saddle River, New Jersey: Prentice Hall. 592p.

Kapuscinski, A.R. 2005. Current scientific understanding of the environmental biosecurity of transgenic fish and shellfish. Revue scientifique et technique (International Office of Epizootics) 24 (1): 309-372.

Kapuscinski, A.R., Li, SiFa, Hayes, K.R. and G. Dana. Editors. 2007. Environmental Risk Assessment of Genetically Modified Organisms. Methodology for Transgenic Fish. Wallingford, Oxford: CABI. 95p.

Kaufman, L. 2006. The situation for live material is desperate. Communication to the Tilapia E-mail list; available at: tilapia@lists.unh.edu

Kelleher, G. Editor. 1999. Guidelines for Marine Protected Areas. World Commission on Protected Areas. Best Practice Guidelines No. 3. Gland, Switzerland: IUCN. World Conservation Union, xxiv + 107p.

Kim, S.S., Moon, D.Y. and W.S. Yang. 2000. Mitochondrial DNA analysis for stock identification of walleye Pollock *Theragra chalcogramma,* form the north Pacific Ocean. Bulletin of the National Fisheries Research Development Insitute Korea 58: 22-27.

Kinch, J., S. Purcell, S. Uthicke and K. Friedman.(2008. Population status, fisheries and trade of sea cucumbers in the western Pacific, p. 7-56 In: V. Toral-Granda, A. Lovatelli and M. Vasconcellos (eds.). Sea Cucumbers: A Global Review of Fisheries and Trade. FAO Fisheries Technical Paper 516.

Kitagawa T., Sartimbul A., Nakata H., Kimura S., Yamada H. and A. Nitta . 2006. The effect of water temperature on habitat use of young Pacific bluefin tuna *Thunnus orientalis* in the East China Sea. Fisheries Science 72: 1166-1176.

Knights, B. 2003. A review of the possible impacts of long-term oceanic and climate changes and fishing mortality on recruitment of anguillid eels of the Northern Hemisphere. Science of the Total Environment 310: 237-244.

Kurki H., Mannini P., Vuorinen I., Aro E., Mo¨lsa¨ H. and O.V. Lindqvist. 1999. Macrozooplankton communities in Lake Tanganyika indicate food chain differences between the northern part and the main basins. Hydrobiologia 407:123–129.

Kurihara, H., Kato, S., and Ishimatsu, A. 2007. Effects of increased seawater CO2 on early development of the oyster *Crassostrea gigas*. Aquatic Biology 1: 91–98.

Laurs R.M., Fiedler P.C. and Montgomery D.R. 1984. Albacore tuna catch distributions relative to environmental features observed from satellites. Deep-Sea Research 31: 1085-1099.

Lebrato, M., *et al.*, 2010 'Global contribution of echinoderms to the marine carbon cycle: a re-assessment of the oceanic CaCO3 budget and the benthic compartments', Ecological Monographs e-view, January 2010.

Leemans, R. and A van Vliet. 2004. Extreme Weather. Does Nature Keep Up? World Wildlife Fund Report. Available at: www.worldwildlife.org/climate/Publications/WWFBinaryitem

Lehodey P., Bertignac M., Hampton J. Lewis A. and J. Picaut. 1997. El Niño Southern Oscillation and tuna in the western Pacific. Nature 389: 715-718.

Lester, S.E., Toblin, E.D., and M.D. Behrens. 2007. Disease dynamics and the potential role of thermal stress in the seaurchin, *Strongylocentrotus purpuratus*. Canadian Journal of Fisheries and Aquatic Sciences 64: 314–323.

Lévêque, C., Balain, E.V. and K. Martens. 2005. An assessment of animal species diversity in continental waters. Hydrobiologia 542: 39-67.

Lightfoot, C., Roger, P.A., Cagauan, A. and C.R. Dela Cruz. 1990. A fish crop may improve rice yields and ricefields. Naga. The ICLARM Quarterly 13 (4): 12-13.

Lightfoot, C., Roger, P.A., Cagauan, A. and C.R. Dela Cruz. 1993. Preliminary steady-state nitrogen models of a wetland ricefield ecosystem with and without fish, p. 56-64. In V. Christensen and D. Pauly (eds.) Trophic Models of Aquatic Ecosystems. ICLARM Conference Proceedings 26, 390p.

Linton, T.K., Morgan, I.J., Reid, S.D. and C.M. Wood. 1998. Long-term exposure to small temperature increase and sublethal ammonia in hardwater acclimated rainbow trout: does acclimation occur? Aquatic Toxicology 40 (2-3): 171-191.

Litaker, R.W. and P.A. Tester. 2003 . Extreme events and ecological forecasting, p. 85-91. In N. Valette-Silver and D. Scavia (eds.) Ecological Forecasting: New Tools for Coastal and Marine Ecosystem Management. Silver Spring MD:NOAA/National Ocean Service/National Centers for Coastal Ocean Science.

Little, D, and J. Muir. Editors. 1987. A Guide to Integrated Warm Water Aquaculture. Stirling, Scotland: Institute of Aquaculture. 238p.

Littler, M.M. and D.S. Littler. 1984. Models of tropical reef biogenesis: the contribution of algae. Progress in Phycological Research 3:323–364.

Liu, Z-J. 2007. Fish genomics and analytical genetic technologies, with examples of their potential applications in management of fish genetic resources, p. 145-179 In: D.M. Bartley, B.J. Harvey and R.S.V. Pullin (eds.) Workshop on Status and Trends in Aquatic Genetic Resources: A Basis for International Policy. FAO Fisheries Proceedings 5. 179p.

Lodge, D.M., Taylor., C.A., Holdich, D.M. and J. Skurdal. 2000. Nonindigenous crayfishes threaten North American Freshwater Biodiversity: Lessons from Europe. Fisheries 25 (8): 7-20.

Lofgren B.M. 2002. Global warming influences on water levels, ice, and chemical and biological cycles in lakes: some examples, p. 15-22 in N.A.McGinn (ed.) Fisheries in a Changing Climate. Bethesda, MD: American Fisheries Society.

Lorenzen, K., Amarasinghe, U.S., Bartley, D.M., Bell, J.D., Bilio, M., De Silva, S.S., Garaway, C.J., Hartmann, W.D., Kapetsky, J.M., Laleye, P., Moreau, J., Sugunan, V.V. and D.B. Swar. 2001. Strategic review of enhancements and culture-based fisheries, p. 221-237 In: R.P. Subasinghe, P.Bueno, M.J. Phillips, C. Hough, S.E. McGladdery and J. R. Arthur (eds.) Aquaculture in the Third Millenium.. Technical Proceedings of the Conference on Aquaculture in the Third Millenium, Bangkok, Thailand, 20-25 February, 2000. Bangkok and Rome: Network of Aquaculture Centres in Asia-Pacific and FAO.

Lowe-McConnell, R.H., 1987. Ecological Studies in Tropical Fish Communities. Cambridge University Press, Cambridge, United Kingdom. 400p.

Ma, Liang, Saillant, E., Gatlin, D.M. III, Neill, W.H., Vega, R.R. and J.R. Gold. 2007. Heritability of cold tolerance in red drum. North American Journal of Aquaculture 69 (4): 381-387.

Ma, X-C., Liu, X-T., and R-F Wang. 1993. China's wetlands and agro-ecological engineering. Ecological Engineering 2:291-301.

MacKenzie, B.R. and A.W. Visser. 2001. Fish and fisheries under climate change scenarios: the Danish perspective. Chapter 19. In A. M. Jorgensen and J. Fenger (eds.) Impacts of Climate Change in Denmark. Copenhagen: Danish Meteorological Institure and Danish Environment Ministry.

Mackenzie, B.R., Gislason, H.m Mollmann, C. and F.W. Koster. 2007. Impact of 21st century climate change on the Baltic Sea fish community and fisheries. Global Change Biology 13 (7): 1348-1367.

Maclean. J. L. 1993. Developing-country aquaculture and harmful algal blooms, p. 252-284. In: R.S.V. Pullin, H. Rosenthal and J.L. Maclean (eds.) Environment and Aquaculture in Developing Countries. ICLARM Conference Proceedings 31, 359p.

Macleod, D. 2002. Red tides on the march. Fish Farmer 25 (3): 45-46.

McAndrew, B. and J. Napier. 2010. Application of genetic and genomics to aquaculture development: current and future directions. Journal of Agricultural Science.. Cambridge University Press: doi 10.1017/S002185961000152. 9p.

Mair, G.C., Abucay, J.S., Skibinski, D.O.F., Abella, T.A. and J.A. Beardmore. 1997. Genetic manipulation of sex ratio for the large-scale production of all-male tilapia *Oreochromis niloticus* L. Canadian Journal of Fisheries and Aquatic Sciences 54: 396-404.

Marcogliese, D.J. 2001. Implications of climate change for parasitism of animals in the aquatic environment. Canadian Journal of Zoology 79: 1331-1352.

Marten, G.G. and J.J. Polovina. 1982. A comparative study of fish yields from various tropical ecosystems, p. 255-289. In D. Pauly and G.I Murphy (eds.) Theory and Manaagement of Tropical Fisheries. ICLARM Conference Proceedings 9.

Martínez, P., Bouza, C., Hermida, M., Fernandez, J., Toro, M.A., Vera, M., Pardo, B.G., Millán, A., Fernandez, C., Vilas, R., Vinas, A.M., Sanchez, L., Felip, A., Piferrer, F., Ferreiro, I., and S. Cabaleiro. 2009. Identification of the major sex determining region of turbot (*Scophthalmus maximus*). Genetics 183: 1443-1452.

Matsui, N, J Suekuni, M Nogami, S Havanond, and P Salikui. 2010. Mangrove rehabilitation dynamics and soil organic carbon changes as a result of full hydraulic restoration and regarding of a previously intensively managed shrimp pond. Wetlands Ecological Management 18 : 233-242.

Mauget SA (2003) Multidecadal regime shifts in US streamflow, precipitation, and temperatures at the end of the twentieth century. Journal of Climatology 16:3905–3916.

Mazur-Mardec, H., Browarczyk-Matiusak, G., Forychka, K., Kobos, J., and M. Plinski. 2010. Morphological, genetic, chemical and ecophysiological characterization of two *Microcystis aeruginosa* isolated from Vistula Lagoon, southern Baltic Sea. Oceanologia 52 (1): 127-46.

McCauley, R. and T. Beitinger. 1992. Predicted effects of climate warming on the commercial culture of the channel catfish (*Ictalurus punctatus*). Geojournal 28 (1): 61-66.

McCook, L.J., Ayling, T., Capo, M., Choat, J.H., De Freitas, D.M., Heupel, M., Hughes, P.H., Jones, G.P., Mapstone, B., Marsh, H., Miils, M., Molloy, F.J., Pitcher, R.L., Russ, G.R., Sutton, S., Sweatman, H., Tobin, R., Wachenfeld, D.R. and D.H. Williamson. 2009. Adaptive management of the Great Barrier Reef: a globally significant demonstration of the benefits of networks of marine reserves. Proceedings of the National Academy of Sciences of the USA 107(43):1 8278-18285.

McCormick, S.D., Hansen L.P., Quinn, T.P. and R.L. Saunders. 1998. Movement, migration and smolting of Atlantic salmon (*Salmo salar*). Canadian Journal of Fisheries and Aquatic Science 55 (S1): 77-92.

McHugh, D.J. 1987. Production and Utilization of Products from Commercial Seaweeds. FAO Fisheries Technical Paper 288. 189p.

McHugh, D.J. 2005. A Guide to the Seaweed Industry. FAO Fisheries Technical Paper 441. 105p.

McKenzie, D.J.M., Martínez, R., Morales, A., Acosta, J., Morales, R., Taylor, E.W., Steffenson, J.F. and M.P. Estrada. 2003. Effects of growth hormone transgenesis on metabolic rate, exercise performance and hypoxia tolerance in tilapia hybrids. Journal of Fish Biology 63: 398-409.

MEA. 2005a. Ecosystems and Human Well-Being: Wetlands and Water Synthesis. Washington DC: Millenium Ecosystem Assessment.

MEA. 2005b. Ecosystems and Human Well-Being: Scenarios, Volume 2.. Washington DC: Millenium Ecosystem Assessment.

Metzger, R., Sartoris, F.J., Langenbuch, M. and H.O. Pörtner. 2007. Influence of elevated CO_2 concentrations on thermal tolerance of the edible crab *Cancer pagurus*. Journal of Thermal Biology 32: 144–151.

Miller, A.W., Reynolds, A.C., Sobrino, C.and G.F. Riedel, 2009. Shellfish Face Uncertain Future in High CO2 World: Influence of Acidification on Oyster Larvae Calcification and Growth in Estuaries. PLoS ONE 4(5): e5661. doi:10.1371/journal.pone.0005661

Miller, K.A. 2000. Pacific salmon fisheries: climate, information and adaptation in a conflict-ridden context. Climate Change 45(1): 37–61.

Miller, K.A. 2007. Climate variability and tropical tuna: management challenges for highly migratory fish stocks. Marine Policy 31: 56–70

Molden, D. Editor. 2007. Water for Food and Life: A Comprehensive Assessment of Water Management in Agriculture. London: Earthscan and Colombo, Sri Lanka: International Water Management Institute. 40p.

Molony, B.W., Church, A.R. and G.B. Maguire. 2004. A comparison of the heat tolerance and growth of a selected and non-selected line of rainbow trout, *Oncorhynchus mykiss*, in Western Australia. Aquaculture 241: 655-665.

Monirian, J., Sutphin, Z. and C. Myrick. 2010. Effects of holding temperature and handling stress on the upper thermal tolerance of threadfin shad *Dorosoma petense*. Journal of Fish Biology 76: 1329-1342.

Mooney, H., Larigauderie, A., Cesario, M., Elmquist, T., Hoegh-Guldberg, O., Lavorel, S., Mace, G.M., Palmer, M., Scholes, R. and T. Yahara. 2009. Biodiversity, climate change, and ecosystem services. Current Opinion in Environmental Sustainability 1: 46–54.

Mora, C. and A.F. Ospina. 2001. Tolerance to high temperatures and potential of sea warming on reef fishes of Gorgona Island (tropical eastern Pacific). Marine Biology 139: (4): 765-769.

Morgan, I..J., McDonald, D.G. and C.M. Wood. 2001. The cost of living for freshwater fish in a warmer, more polluted world. Global Change Biology 7 (4): 345-355.

Moriarty, D,J.W. and Pullin, R.S.V. Editors. 1987. Detritus and Microbial Ecology in aquaculture. ICLARM Conference Proceedings 14, 420p.

Moyle, P.B. and J.J. Cech. 2004. Fishes: an Introduction to Ichthyology, 5th Edition. Englewood Cliffs, NJ: Prentice Hall. 774p.

Munday, P.L. 2004. Habitat loss, resource specialization, and extinction on coral reefs. Global Change Biology 10(10): 1642-1647.

Munday, P.L., Jones, G.P., Pratchett, M.S. and A.J. Williams. 2008. Climate change and the future for coral reef fishes. Fish and Fisheries 9 (3): 261-285.

Munday, P.L., Dixson, D.L., McCormick, M.I., Meekan, M., Ferrari, M.C.O. and D.P. Chivers. 2010. Replenishment of fish populations is threatened by ocean acidification. Proceedings of the National Academy of Sciences of the United States of America 107 (29): 12930-12934.

Murty, T.S. and R.A. Flather. 1994. Impact of storm surges in the Bay of Bengal. Journal of Coastal Research 12:149–161.

Murty, A.S. 1986. Toxicity of Pesticides to Fish. Volume 2. Boca Raton: CRC Press.

Mustafa, S. 2003. Stock enhancement and sea ranching: objectives and potential. Reviews in Fish Biology and Fisheries 13: 141-149.

Mydlarz, L.D., McGinty, E.S. and C. Drew Harvell. 2010. What are the physiological and immunological responses of coral to climate warming and disease? Journal of Experimental Biology 213:934-945.

Myers, R.A. and B. Worm. 2003. Rapid worldwide depletion of predatory fish communities. Nature 423: 280–83.

Nam, Y.K., Maclean, N., Hwang, G. and D.S. Kim. 2008. Autotransgenic and allotransgenic manipulation of growth traits in fish for aquaculture: a review. Journal of Fish Biology 72: 1-26.

Nellemann, C., Hain, S. and J. Alder. Editors. 2008. In Dead Water, Merging of Climate Change with Pollution, Overharvest and Infestations in the World’s Fishing Grounds. Arendal, Norway: UNEP Rapid Response Assessment.

Neori, A., Chopin, T., Troell, M., Buschmann, A.H., Kraemer, G.P., Halling, C., Shpigel, M. and C. Yarish. 2004. Integrated aquaculture: rationale, evolution and state of the art emphasizing seaweed biofiltration in modern mariculture. Aquaculture 231: 361-391.

New, M.B. 2002. Farming Freshwater Prawns: A Manual for the Culture of the Giant River Prawn (*Macrobrachium rosenberghii*). FAO Fisheries Technical Paper 428. 212p.

Nicholls, R.J. 2004. Coastal flooding and wetland loss in the 21st century: changes under the SRES climate and socio-economic scenarios. Global Environmental Change 14: 69–86.

Nicholls, R.J., Wong, P.P., Burkett, V.R., Codignotto, J.O., Hay, J.E., McLean, R.F., Ragoonaden, S. and C.D. Woodroffe. 2007. Coastal systems and low-lying areas, p. 315-356 In: M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van den Linden and C.E. Hanson, eds. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK, Cambridge University Press.

Northcote, T.G. and G.F. Hartman. Editors. 2004. Fishes and Forestry. Oxford: Blackwell Science. 653p.

Okamoto, N., Tayaman, T., Kawanobe, M., Fujiki, N., Yasuda, Y. and T. Sano. 1993. Resistance of a rainbow trout strain to infectious pancreatic necrosis. Aquaculture 117: 71-76.

Olafsson, J., Olafsdottir, S.R., Benoit-Cattin, A., Danielsen, M., Arnason, T.S. and T. Takahashi. 20009. Rate of Iceland Sea acidification from time series measurements. Biogeosciences Discussions 6: 5251-5270. www.biogeosciences-discuss.net/6/5251/2009/

Oleksiak, M.F. 2010. Genomic approaches with natural fish populations. Journal of Fish Biology 76: 1067-1093.

Ong, J.E. (1993). Mangroves – a carbon source and sink. Chemosphere 27: 1097-1107.

Orr, J.C, Fabry, V.J., Aumont, O., Bopp, L., Doney, S.C., Feely, R.A., Gnanadesikan, A., Gruber, N., Ishida, A., Joos, F., Key, R.M., Lindsay, K., Maier-Reimer, E., Matear, R., Monfray, P., Mouchet, A., Najjar, R.G., Plattner, G.K., Rodgers, K.B., Sabine, C.L., Sarmiento, J.L., Schlitzer, R., Slater, R.D., Totterdell, I.J., Weirig, M.F., Yamanaka, Y. and A. Yool. 2005. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. Nature 437: 681–686.

Ottersen G, Alheit J, Drinkwater KF, Friedland KD, Hagen E. and N.C. Stenseth. 2004. The response of fish populations to ocean climate fluctuations, p. 73-94 In: N.C. Stenseth, G. Ottersen, J.W. Hurrell and A. Belgrano (eds.) Marine Ecosystems and Climate Variation. Oxford: Oxford University Press.

OXFAM .2007. Climate alarm: disasters increase as climate change bites. In Weather Alert to Climate Alarm, Oxfam Briefing Paper 108. 28p.

Padiñas, A.F., Campo, D., Pola, I., Miralles, G., Juanes, F. and E. Garcia-Vaquez. 2010. Climate change and ocean barriers: genetic differentiation in *Pomatomus saltatrix* (Pisces: Pomatomidae) in the North Atlantic Ocean and the Mediterranean Sea. Journal of Fish Biology 77 (8): 1993-1998.

Paerl, H.W., Pinckney, J.L., Fear, J.M. and B.L. Peierls. 1998. Ecosystem responses to internal and watershed organic matter loading: consequences for hypoxia in the eutrophying Neuse River Estueary, North Carolina., USA. Marine Ecology Progress Series 166: 17-25.

Pane, E.F. and J.P. Barry. 2007. Extracellular acid-base regulation during short-term hypercapnia is effective in a shallow water crab, but ineffective in a deep-sea crab. Marine Ecology Progress Series 334: 1-9.

Parmesan, C. and G. Yohe. 2003. A globally coherent fingerprint of climate change impacts across natural systems. Nature 421: 37-42.

Pauly, D. 1995. Ocean Ecology. In Encyclopedia of Environmental Biology Volume 3. London: Academic Press. 17p. reprint.

Pauly, D. 2010. Gasping Fish and Panting Squids: Oxygen, Temperature and the Growth of Water-Breathing Animals. Excellence in Ecology 22. Oldendorfe/Luhe, Germany: International Ecology Institute. 216p.

Pauly, D., Moreau, J. and M.L.D. Palomares. 1988. Detritus and energy consumption and conversion efficiency of *Sarotherodon melanotheron* (Cichlidae) in a West African lagoon. Journal of Applied Ichthyology 4: 190-193.

Pauly, D. and V. Christensen. 1995. Primary production required to sustain global fisheries. Nature 374:255-257.

Pauly, D. and R.S,V. Pullin. 1988. Hatching time in spherical, pelagic, marine fish eggs in response to temperature and egg size. Environmental Biology of Fishes 22 (4): 261-271.

Penman, D.J., Gupta, M.V. and M.M. Dey. Editors. 2005. Carp Genetic Resources for Aquaculture in Asia. WorldFish Center Technical Report 65. 152p.

Pereira, E., Teles, F.O. and V. Vasconcelos. 2008. Variation of environmental parameters and dynamics of phytoplankton in a temperate eutrophic reservoir (Torrao, Taamega River, Portugal). Fresenius Environmental Bulletin 17 (12b): 2193-2199.

Perry, A.L., Low, P.J., Ellis, J.R. and J.D. Reynolds. 2005. Climate change and distribution shifts in marine fishes. Science 308 No. 5730: 1912-1915.

Persson, L., Diehl, S., Johansson, L., Andersson, G. and S.F. Hamrin. 1991. Shifts in fish communities along the productivity gradient of temperate lakes – patterns and importance of size-sructured interactions. Journal of Fish Biology 38: 281-293.

Pickering, A.D. Editor. 1981. Stress and Fish. London: Academic Press. 367p.

Pigliucci, M. and G.B. Müller, Editors. 2010. Evolution, the Extended Synthesis by Cambridge MA: MIT Press. 495p.

Pinnegar, J.K., D. Viner, D. Hadley, S. Dye, M. Harris, F. Berkout and M. Simpson. 2006. Alternative Future Scenarios for Marine Ecosystems.
Available at: http://www.cefas.co.uk/our-science/climate-impacts-and-adaptation.aspx

Poff, N.L and J.D. Allan. 1995. Functional-organization of stream fish assemblages in relation to hydrological variability. Ecology 76: 606–62.

Pörtner, H. O., Langenbuch, M. and A. Reipschlager. 2004. Biological impacts of elevated ocean CO2 concentrations: lessons from animal physiology and earth history. Journal of Oceanography. 60: 705–718.doi:10.1007/s10872-004-5763-0.

Pörtner, H.O. and R. Knust. 2007. Climate change affects marine fishes through the oxygen limitation of thermal tolerance. Science (Washington) 315, No. 5808: 95-97.

Pörtner, H.O. and M.A. Peck. 2010. Climate change effects on fishes and fisheries: towards a cause-and-effect understanding. Journal of Fish Biology 77 (8): 1745-1779.

Precht, W.F. and R.B. Aronson. 2004. Climate change flickers and range shifts of reef corals. Frontiers in Ecology and the Environment 2: 307-314.

Prein, M., Oficial, R., Bimbao, M.A. and T. Lopez. 2002. Aquaculture for diversification within forest buffer zone management: an example from the uplands of Quirino Province, Philippines, p. 97-110. In: P.Edwards, D.C. Little and H. Demaine (eds.) Rural Aquaculture. Wallingford, U.K: CABI International.

Prentice, J.A. Low-temperature tolerance of southern flounder in Texas. Transactions of the American Fisheries Society 118 (1): 30-35.

Primavera, J. H. 1995. Mangroves and brackishwater pond culture in the Philippines. Hydrobiologia 295: 303–309.

Primavera, J.H. 2005. Global voices of science: mangroves, fishponds, and the quest for sustainability. Science 310: 57–59.

Primavera, J.H., Sadaba, R.B., Lebata, M.J.H.L. and J.P. Altamirano. 2004. Handbook of Mangroves in the Philippines -Panay. Iloilo, Philppines: SEFDEC Aquaculture Department. 106p.

Pullin, R.S.V. 1971. Silt discharge into a Manx river and its effect on trout. Report of the Marine Biological Station, Port Erin 84: 23-30.

Pullin, R.S.V. Editor. 1988. Tilapia Genetic Resources for Aquaculture. ICLARM Conference Proceedings 16, 108p. (Also available in French).

Pullin, R.S.V. 2000. Management of aquatic biodiversity and genetic resources. Reviews in Fisheries Science 8(4): 379-393.

Pullin, R.S.V. 2007. Genetic resources for aquaculture: status and trends, p. 109-143 In: D.M. Bartley, B.J. Harvey and R.S.V. Pullin (eds.) Workshop on Status and Trends in Aquatic Genetic Resources: A Basis for International Policy. FAO Fisheries Proceedings 5. 179p.

Pullin, R.S.V. 2011. Aquaculture up and down the food web, p. 89-119 In: V. Christensen and J.L. Maclean (eds.) Ecosystem Approaches to Fisheries: a Global Perspective. Cambridge University Press, Cambridge, UK.

Pullin, R.S.V. and M. Prein. 1995. Fishponds facilitate natural resources management on small-scale farms in tropical developing countries, p. 169-186 In: J.J. Symoens and J.C. Micha (eds.) The Management of Integrated Freshwater Agro-Piscicultural Ecosystems in Tropical Areas. Technical Centre for Agricultural and Rural Co-operation (CTA) and Royal Academy of Overseas Sciences, Brussels. (Also available in French).

Pullin, R.S.V., D.M. Bartley and J. Kooiman, Editors. 1999. Consensus Statement (p. 253) In: Towards Policies for Conservation and Sustainable Use of Aquatic Genetic Resources. ICLARM Conference Proceedings 59, 277p.

Pullin, R.S.V., Williams, M.J. and N. Preston. 1998. Domestication of crustaceans. Asian Fisheries Science 11: 59-62.

Rahmstorf, S., Cazenave, A., Church, J.A., Hansen, J.E., Keeling, R.F., Parker, D.E. and R.C.J. Somerville. 2007. Recent climate observations compared to projections. Science 316: p.709.

Rainbow, P., Robbins, R. and P. Clark. 2003. Alien invaders: Chinese mitten crabs in the Thames and spreading. The Biologist 50 (5): 227-230.

Reichard, M. 2008. Microhabitat use by fishes in the middle course of the River Gambia in the Niokolo Koba National park, Sénégal: a unique example of an undisturbed West African assemblage. Journal of Fish Biology 72: 1815-1824.

Reiskind, J.B., Seamon, P.T., and G. Bowes. 1989. Photosynthetic responses and anatomical features of two marine macroalgae with different C02 compensation points. Aquatic Botany 33:71–86.

Reist. J.D., Wrona, F.J., Prowse, T.D., Power, M., Dempson, J.B., Beamish, R.J., King, J.R., Carmichael, T.J. and C.D. Sawatzky. 2006. General effects of climate change on Arctic fishes and fish populations. Ambio 35: 370–380.

Reusch, T.B.H., Ehlers, A., Hämmerli, A. and B. Worm. 2005. Ecosystem recovery after climatic extremes enhance by genotypic diversity. Proceedings of the National Academy of Sciences of the USA 102: 2826-2831.

Rice, M.A., Mmoche, A.J., Zuberi, L. and M. Savoie. 2006. Aquaculture in Tanzania. World Aquaculture 37 (4): 50-57.

Ribbink, A.J. 1987. African lakes and their fishes: conservation scenarios and suggestions. Environmental Biology of Fishes 19:3–26.

Rodriguez, C.F., Bécares, E. and M. Fernández-Aláez. 2003. Shift from clear to turbid phase in Lake Chosas (NW Spain) due to the introduction of American red swamp crayfish (*Procambarus clarkii*). Hydrobiologia 506-509: 421-426.

Royal Society. 2005. Ocean acidification due to increasing atmospheric carbon dioxide. Policy Document 12/05. London and Cardiff: The Royal Society and Clarendon Press Ltd. 57p..

Royal Society. 2008. Sustainable Biofuels: Prospects and Challenges. Policy Document 01/08. London: The Royal Society. 82p.

Ruane, J. and A. Sonnino. 2006. Results from the FAO Biotechnology Forum: Background and Dialogue on Selected Issues. FAO Research and Technology Paper 11. 152p.

Ruhk, H.A. and K.L. Smith Jr. 2004. Shifts in deep-sea community structure linked to climate and food suplly. Science 305 No. 5683: 513-515.

Sabine, C.L., Feely, R.A., Gruber, N., Key, R.M., Lee, K., Bullister, J.L., Wanninkhof,R., Wong, CS., Wallace, D.W.R., Bronte Tilbrook, B., Millero, F.J., Peng, T.H., Kozyr, A., Ono, T. and A.F. Rios. 2004. The oceanic sink for anthropogenic CO2. Science 305: 367–371.

Schindler, D. W. 2001. The cumulative effects of climate warming and other human stresses on Canadian freshwaters in the new millennium. Canadian Journal of Fisheries and Aquatic Sciences 58: 18–29.

Schindler, D.E., Augerot, X., Fleishman, E., Mantua, N.J., Riddell, B., Ruckelhuas, M. Seeb, J. and M. Webster. 2008. Climate change, ecosystem impacts and management for Pacific salmon. Fisheries 33 (10): 502-506.

Schreck, C.B. 1981. Stress and compensation in teleostean fishes: response to social and physical factors, p. 295-321 In: A.D. Pickering (ed.) Stress and Fish. London: Academic Press. 367p.

Schuster, U. and A. J. Watson. 2007. A variable and decreasing sink for atmospheric CO2 in the North Atlantic. Journal of Geophysical Research doi:10.1029/2006JC003941

Science Council Secretariat. 2005. Conservation of Livestock and Fish Genetic Resources. Joint Report of Two studies Commissioned by the CGIAR Science Council. Rome: Science Council Secretariat. 89p.

ScienceDaily. 2010. Echinoderms contribute to global carbon sink: impact of marine creatures underestimated. Available at: www.sciencedaily.com/releases/2010/01/100108101425.htm

Selvaraj, S. and J.S.S. Kumar, 2004. Hybrid carps – production and scope in Indian aquaculture. World Aquaculture 35 (1): 21-22.

Semmler, T., Varghese, S., Mcgrath, R., Nolan, P., Wang, S., Lynch, P. and C. O'Dowd. 2006. Global warming impacts on storminess, p. 20-27. In C.D. O'Dowd (ed.) Proceedings of the SOLAS Ireland Workshop 2006. Galway: National University of Ireland.

Shankar, B., Halls, A. and J. Barr. 2004. Rice versus fish revisited: on the integrated management of floodplain resources in Bangladesh. Natural Resources Forum, 28(2): 91–101.

Sharp, G.D. 2003. Future Climate Change and Regional Fisheries: A Collaborative Analysis. FAO Fisheries Technical Paper 452. 75p.

Sims D.W., Wearmouth, V.J., Genner, M.J., Southward, A.J. and J. Hawkins. 2004. Low-temperature-driven early migration of a temperate marine fish. Journal of Animal Ecology 73: 333-341.

Sims D.W. and V.A.Quayle.1998. Selective foraging behaviour of basking sharks on zooplankton in a small-scale front. Nature, 393, 460-464.

Smit, B., Burton, I., Klein, R.J.T. and J. Wandel. 2000. An anatomy of adaptation to climate change and variability. Climatic Change 45: 223–251.

Smith, P.J.. 2007. Issues, status and trends in deep-sea genetic resources, p. 81 – 108 In: D.M. Bartley, B.J. Harvey and R.S.V. Pullin (eds.) Workshop on Status and Trends in Aquatic Genetic Resources: A Basis for International Policy. FAO Fisheries Proceedings 5. 179p.

Smith, T.R., Tremblay, G.C. and T.M. Bradley. 1999. Characterization of the heat shock protein response of Atlantic salmon (*Salmo salar*). Fish Physiology and Biochemistry 20 (3): 279-292.

Smock, L.A., Smith, L.C., Jones, J.B. Jr. and S.M. Hopper. 1994. Effects of drought and a hurricane on a coastal headwater stream. Archiv für Hydrobiologie 131: 25-38.

Solomon, D. J. and H.T. Sambrook. 2004. Effects of hot dry summers on the loss of Atlantic salmon, *Salmo salar*, from estuaries in South West England. Fisheries Management and Ecology, 11: 353-363.

Sonesson, A.K. 2003. Possibilities for Marker-Assisted Selection in Fish Breeding Schemes. Available at: www.fao.org/biotech/docs/Sonesson.pdf .

Song, L., Chen, W., Wan, N. and L. Peng. 2009. Mechanism study on the frequent variations of cell-bound microcystins in cyanobacterial blooms in Lake Taihu: implications for water quality monitoring and assessments. Phycologia 48 (4): Suppl. np.

Soto, D., Aguilar-Manjarrez, J. and N. Hiishamunda, Editors. 2008. Building an Ecosystem Approach to Aquaculture. FAO Fisheries and Aquaculture Proceedings 14. 221p.

Spicer, J.I., Raffo, A. and S. Widdicombe. 2007. Influence of CO2-related seawater acidification on extracellular acid-base balance in the velvet swimming crab *Necora puber.* Mar. Biol. 151: 1117–1125.

Steinacher, M., Joos, F., Frolicher, T.L., Plattner, G.K. and S.C. Doney. 2009. Imminnet acidification in the Arctic projected with the NCAR global coupled carbon cycle model. Biogeoscience 6: 515-533.

Stevenson, N.J., Lewis, R.R. and P.R. Burbridge. 1999. Disused shrimp ponds and mangrove rehabilitation, p. 277-297 In: W. J. Streever (ed.) An International Perspective on Wetland Rehabilitation. Dordrecht, the Netherlands: Kluwer Academic Publishers.

Stevens-Smith, J. 2010. For science's sake – it's good to talk. Biologist 57(4): 204-205.

St. Louis, V., Kelly, C.A., Duchemin, E, Rudd, J.W.M., and D.M. Rosenberg. 2000. Reservoir surfaces as sources of greenhouse gases to the atmosphere: a global estimate. Bioscience 50(9): 766-775.

Suarez-Bosche, N.E., Lebrato, M., Tyler, P.A. and D. Iglesias-Rodriguez. 2010. The effect of CO2-enriched deep ocean waters on echinoderm larvae. Abstract of Paper Presented at the 14th Biennial Challenger Conference for Marine Science, September 6-9, 2010, National Oceanography Centre, Southampton, U.K. Book of Abstracts, p.65. Available at: www.challenger2010.org.uk

Subasinghe, R.P., McGladdery, S.E. and B.J. Hill, Editors. 2004. Surveillance and Zoning for Aquatic Animal Diseases. FAO Fisheries Technical Paper 451. 73p.

Sun, X. and L. Liang. 2004. A genetic linkage map of common carp (*Cyprinus carpio* L.) and mapping of a locus associated with cold tolerance. Aquaculture 238 (1-4): 165-172.

Tanhua, T., Kortzinger, A., Friis, K. and D.W.R. Waugh. 2007. An estimate of anthropogenic CO2 inventory from decadal change in oceanic carbon content. Proceedings of the National Academy of Sciences U.S.A. 104 (9) : 3037-3042.

ACECRC. 2008. Position Analysis: CO2 and Climate Change, Ocean Impacts and Adaptation Issues. The Antarctic Climate and Ecosystems Cooperative Research Centre. PA02-080516.ISSN: 1835-7911.

Thilsted, S.H., Roos, N. and N. Hassan. 1997. The role of small indigenous fish species in food and nutrition security in Bangladesh. NAGA. The ICLARM Quarterly. Supplement (July-December): 13-15.

Thomas, C.D., Cameron, A., Green, R.E., Bakkenes, M., Beaumont, L.J., Collingham, Y.C., Erasmus, B.F.N., de Siqueira, M.F., Grainger, A., Hannah, L., Hughes, L., Huntley, B., van Jaarsveld, A.S., Midgley, G.F., Miles, L., Ortega-Huerta, M.A., Peterson, A.T., Phillips, O.L. and S.E. Williams. 2004. Extinction risk from climate change. Nature 427: 145–148.

Thorpe, A., Johnson, D. and M. Bavinck. 2005. Introduction, p. 41-69 In: J. Kooiman, M. Bavinck, S. Jentoft and R. Pullin (eds.) Fish for Life: Interactive Governance for Fisheries. Amsterdam: Amsterdam University Press. 427p.

Thorpe, J.P., Solé-Cava, A.M. and P.C. Watts. 2000. Exploited marine invertebrates: genetics and fisheries. Hydrobiologia 420: 165-184.

Timmermann, A., Oberhuber, J., Bacher, A., Esch, M., Latif, M. & E. Roeckner (1999) Increased El NinÄ frequency in a climate model forced by future greenhouse warming. Nature 398: 694-697.

Tiersch, T.R. and P.M. Malik. 2000. Cryopreservation in Aquatic Species. Baton Rouge, Louisiana: the World Aquaculture Society. 439p.

Tine, M., Bonhomme, F., McKenzie, D. and J-D. Durand. 2010. Differential expression of the heat shock protein Hsp70 in natural populations of the tilapia *Sarotherodon melanotheron*, acclimatised to a range of environmental salinities. BMC Ecology 2010 10: 11. 8p.

Tiwary, B.K., Kirubagaran, R and A.K. Ray. 2004. The biology of triploid fish. Reviews in Fish Biology and Fisheries 14: 391-402.

Todgham, A.E. and G.E. Hofmann. 2009. Transcriptomic response of sea urchin larvae *Strongylocentrotus purpuratus* to CO2-driven seawater acidification. Journal of Experimental Biology 212: 2579-2594.

Trenberth, K.E., Jones, P.D., Ambenje, P., Bojariu, R., Easterling, D., Klein Tank, A., Parker, D., Rahimzadeh, F., Renwick, J.A., Rusticucci, M., Soden B. and P. Zhai. 2007. Observations: surface and atmospheric climate change, In: S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Avery, M. Tignor and H.L. Miller (eds.). Climate Change 2007: The Physical Science Basis. Cambridge UK: Cambridge University Press.

Trewavas, E. 1983. Tilapiine Fishes of the Genera Sarotherodon, Oreochromis and Danakilia. London: British Museum (Natural History): 583p.

Tringali, M.D. and T.M. Bert. 1998. Risk to genetic effective population size should be an important consideration in fish stock-enhancement programs. Bulletin of Marine Science 62(2): 641-659.

Tucker, C.S. 2000. Off-flavor problems in aquaculture. Reviews in Fisheries Science 8(1): 45-88.

Tymchuk, W.E.V. and M.V. Abrahams..2005. Comparative ability and mortality of growth-enhanced transgenic coho salmon fry and parr when foraging for food. Transactions of the American Fisheries Society 124: 381-389.

UNEP/WorldFish. 2010. Blue Harvest: Inland Fisheries as an Ecosystem Service. Nairobi and Penang: United Nations Environment Programme and the WorldFish Centre. 63p.

UNFCCC. 2006 and 2010. Climate Change: Impacts, Vulnerabilities and Adaptation in Developing Countries. IV. Regional Aspects of and Vulnerabilities to Climate Change. Bonn, Germany: UNFCCCC. www.unfccc.int/resource/docs/publications/impacts.pdf

UNEP. 2006. African Environment Outlook 2. Our Environment, Our Wealth. Chapter 5. Coastal and Marine Environments. Lead Authors: Athurton, R. and K. Korateng. http://www.unep.org/dewa/Africa/publications/AEO-2/contenet/pdf/aco2_ch5.pdf

UNEP. 2010. UNEP Emerging Issues: Environmental Consequences of Ocean Acidification: A Threat to Food Security. Nairobi: United Nations Environment Programme.

US Climate Change Science Program and the Subcommittee on Global Change Research (USCCSP) .2008a. Weather and Climate Extremes in a Changing Climate (Regions of Focus: North America, Hawaii, Caribbean and US Pacific Islands). In: T.R. Karl, G.A. Meehl, C.D. Miller, S.J. Hassol, A.M. Waple and W.L. Murray, W.L.(eds) US Climate Change Science Program Synthesis and Assessment Product 3.3. Available at: www.climatescience.gov

US Climate Change Science Program and the Subcommittee on Global Change Research (USCCSP). 2008b. Abrupt Climate Change: Final Report, Synthesis and Assessment Product3.4. Available at: www.claimatescience.gov

Vance, D.J., Haywood, M.D.E., Heales, D.S., Kenyon, R.A. and Loneragan, N.R. (1998) Seasonal and annual variation in abundance of postlarval and juvenile banana prawns, *Penaeus merguiensis*, and environmental variation in two estuaries in tropical northeastern Australia: a six-year study. Marine Ecology Progress Series 163: 21-36.

Vinebrooke, R.D., Cottingham, K.L., Norberg, J., Scheffer, M., Dodson, S.I.,Maberly, S.C. and U. Sommer. 2004. Impacts of multiple stressors on biodiversity and ecosystem functioning: the role of species co-tolerance. Oikos 104: 451–457.

Vitousek, P.M., Mooney, H.A., Lubchenco, J. and J.M. Melillo. 1997. Human domination of earth's ecosystems. Science 277: 494-499.

Wagner, C. and R. Adrian. 2009. Cyanobacteria dominance: quantifying the effects of climate change. Limnology and Oceanography 54 96): 2460-2468.

Warbitz, C., Taylor, M., Green, E. and T. Razak (2003). From Ocean to Aquarium. Cambridge, UK: UNEP- World Conservation Monitoring Centre.

Ward, J.R., and K.D. Lafferty. 2004. The elusive baseline of marine disease: are diseases in ocean ecosystems increasing? PLoS Biol. 2: 542–47.

Ward, R.D., Skibinski, D.O.F. and M. Woodmark, 1992. Protein heterozygosity, protein structure, and taxonomic differences. Evolutionary Biology 26: 73-159.

Watson, R.T., Zinyowera, M.C. Moss, and R.H. 2000. IPCC Special Report on the Regional Impacts of Climate Change: An Assessment of Vulnerability. http://www.grida.no/publications/other/ipcc_sr/?src=/climate/ipcc/regional/153.htm

Waycott, M., Duarte, C., Carruthers, T., Orttth, B., Dennison, B., Olyarnik, S., Calladine, A., Forqureau, J., Heck, K., Hughes, R., Kendrick, G., Kenworthy, J., Short, F. and S. Williams. 2009. Accelerating loss of seagrasses across the globe threatens coastal ecosystems. Proceedings of the National Academy of Sciences. June 29, 2009.

Welcomme, R.L. 1979. The Inland Fsheries of Africa. CIFA Occasional Paper 7. 77p.

Wernberg T., Campbell A., Coleman M.A., Connell S.D., Kendrick G.A., Moore P.J., Russell B.D., Smale D. and P.D. Steinberg. 2009. Macroalgae and temperate rocky reefs. In: E.S. Poloczanska, A.J. Hobday and A.J. Richardson (eds.) A Marine Climate Change Impacts and Adaptation Report Card for Australia 2009. NCCARF Publication 05/09, ISBN 978-1-921609-03-9.

Whalen, K.G., Parrish, D.L. and S.D. McCormick. 1999. Migration timing of Atlantic salmon smolts relative to environmental and physiological factors. Transactions of the American Fisheries Society, 128: 289-301.

Wilderbuer, T.K., Hollowed, A.B., Ingraham, Jr., W.J., Spencer, P.D., Conners, M.E., Bond, N.A. and G.E. Walters. 2002. Flatfish recruitment response to decadal climatic variability and ocean conditions in the eastern Bering Sea. Progress in Oceanography 55: 235–247.

Willis, B.L., van Oppen, M.J.H., Miller, D.J., Vollmer, S.V. and D.J. Ayre. 2006. The role of hybridization in the evolution of reef corals. Annual Review of Ecology, Evolution and Systematics 37: 489-517.

Wilson, R.W., Millero, F. J., Taylor, J.R. Walsh, P.J., Christensen, V., Jennings, S. and M. Grosell. 2009. Contribution of fish to the marine inorganic carbon cycle. Science 323, no. 5912: 359-362.

Winfield, I.J. and J.F. Craig. Editors. 2010. Fishes and Climate Change. Special Issue FSBI Symposium. Journal of Fish Biology 77 (8): 1731-1998.

Withler, R.E. and T.P.T. Evelyn. 1990. Genetic variation in resistance to bacterial kidney disease within and between two strains of coho salmon from British Columbia. Transactions of the American Fisheries Society 119:1003-1009.

Wood, C.C and L.B Holtby. 1998. Defining conservation units for Pacific salmon using genetic survey data, p. 233-250. In B. Harvey, C. Ross, D. Greer and J. Carolsfeld (eds.) Action Before Extinction: an International Conference on Conservation of Fish Genetic Diversity. Victoria BC: World Fisheries Trust.

Woerhrmann, A.P.A. 1997. Freezing resistance in Antarctic fish, p. 209-216 In: B. Battaglia, J. Valencia and D.W.H. Walton (eds.) Antarctic Communities: Species, Structure and Survival. Cambridge: Cambridge University Press.

Wohlfarth, G.W. and G. Hulata. 1983. Applied Genetics of Tilapias. ICLARM Studies and Reviews 6, 26p.

Wood, R.J., Boesch, D.F. and V.S Kennedy. 2002. Future consequences of climate change for the Chesapeake Bay ecosystem and its fisheries, p.171-184 In: N.A. McGinn NA (ed.) Fisheries in a Changing Climate. Bethesda, MD: American Fisheries Society.

World Bank. 2000. Managing change in Pacific Island economies. In: Volume IV Adapting to Climate Change – Cities, Seas, and Storms. Washington, D.C: The World Bank, Papua New Guinea and Pacific Country Unit.

Worm, B., Barbier, E.B., Beaumont , N. *et al.* 2006. Impacts of biodiversity loss on ecosystem services. Science 314: 787-790.

WWF. 2010. Climate Change: Impacts of Climate Change on Habitat and Species in Florida. www.wwf.org

Wu, R-Z and Y. Ma. 2008. Analysis on spatial and temporal distribution and cause of red tides over past 20 years in South China Sea. Marine Environmental Science/ Haiyang Huanjing Kexue. Dalian 27 (1): 30-32.

Wyban, J.A., Swingle, J.S., Sweeney, J.N. and G.D. Pruder. 1993. Specific pathogen free *Penaeus vannamei*. World Aquaculture 24 (1): 39-45.

Xenopoulos, M.A., Lodge, D.M., Alcamo, J., Marker, M., Schukze, K and D.P. Van Vuuren. 2005. Scenarios of freshwater fish extinctions from climate change and water withdrawal. Global Change Biology 11: 1557-1564.

Xu, Yao, Wang Guo-Xiang, Yang, Wen-Bin and Renhui Li. 2010. Dynamics of the water bloom-forming Microcystis and its relationship with physicochemical factors in Lake Xuanwu (China). Environmental Science and Pollution Research 17 (9): 1581-1590.

Yan, J.S., Zhang, Y.S. and X.Y. Wu. 1993. Advances of ecological engineering in China. Ecological Engineering 2: 193-215.

Yap, L. G., Azanza, R. V. and L. Talaue-McManus. 2004. The community composition and production of phytoplankton in fish pens of Cape Bolinao, Pangasinan: a field study. Marine Pollution Bulletin 49: 819–832.

Yarish, C., Wilkes, R., Chopin, T., Fei, X.G., Mathieson, A.C., Klein, A.S., Neefus, C.D., Mitman, G.G. and I. Levine. 1998. Domestication of indigenous porphyra (nori) species for commercial cultivation in Northeast America. World Aquaculture 29 (4): 26-29 and 55.

Zakhartsev, M., De Wachter, B., Johansen, T., Pörtner, H.O. and R. Blust. 2005. Hsp70 is not a sensitive indicator of thermal limitation in *Gadus morhua*. Journal of Fish Biology 67 (3): 767-778.

Zimba, P.V., Khoo, L., Gaunt, P.S., Brittain, S. and W. Carmichael. 2001. Confirmation of catfish, *Ictalurus punctatus* (Rafinesque) mortality from Microcystis toxins. Journal of Fish Diseases 24 (1): 41-47.

Zou, D. 2005. Effects of elevated atmospheric CO2 on growth, photosynthesis and nitrogen metabolism in the economic brown seaweed, *Hizikia fusiforme* (Sargassaceae, Phaeophyta). Aquaculture 250:726–73.

ANNEX I

TEMPERATURE AND SALINITY TOLERANCES OF FARMED AQUATIC SPECIES, AS PUBLISHED BY FAO AND IN BIOLOGICAL DATABASES

The following table summarizes some of the most readily available information and data for the temperature and salinity tolerances of some major and minor farmed aquatic species: seaweeds; crustaceans; molluscs and finfish. The data given are assumed to indicate limits or climatic zones beyond which these species could not survive sufficiently well to be farmed. Coverage is somewhat uneven and not fully standardized. There are gaps and, for a causal searcher seeking only summary data and descriptors, some potentially misleading entries marked*; most of which derive from attempts to include single climatic zone descriptors, or examples from a single study, while providing much more detailed information, including maps and scientific references. The sources used were:

FAO FACTS, meaning the FAO Cultured Aquatic Fact Sheets (www.fao.org);

ALGAEBASE (www.algaebase.org);

SEALIFEBASE (www.sealifebase.org);

FISHBASE I, meaning an upfront Fishbase species page, with links to multiple tables and references (www.fishbase.org);

FISHBASE II, meaning a FishBase Aquaculture Species Profile (www.fishbase.org).

The abbreviations used are: BR = brackishwater; ET = eurythermal; EH = euryhaline, including diadromous species and strains; FW= freshwater; GR = growout; HA = harvesting); MA = marine; NA = not applicable; ND = no data; NL = not listed; T = temperature; TE = temperate; TR = tropical; ST = subtropical; S= salinity; SS = seed supply.

SEAWEEDS	**FAO FACTS**		**ALGAEBASE**	
	T (0C)	S (ppt)	T (0C)	S (ppt)
Eucheuma alvarazii /spp.	27 – 30 (GR)	30 – 35	ND	MA
Laminaria japonica	> 21 (HA)	ND	ND	MA
Porphyra spp.	22 – 27 (SS)	ND	Over 200 related species listed; ND, MA	

CRUSTACEANS	**FAO FACTS**		**SEALIFEBASE**	
	T (0C)	S (ppt)	T (0C)	S (ppt)
Eriocheir sinensis	ND	7 – 33 (SS)	TE	BR, FW
Macrobrachium rosenberghii	28 – 31 (SS)	ND	TR	ND
Penaeus indicus	ND	5 – 40 (SS)	TR	BR
Penaeus monodon	ND	1 – 30	TR	ND
Penaeus (Litopenaeus) vannamei	>20	ND	ST*	BR
Procambarus clarkii	ND	NA	TR*	FW

MOLLUSCS	**FAO FACTS**		**SEALIFEBASE**	
	T (0C)	S (ppt)	T (0C)	S (ppt)
Crassostrea gigas	-1.8 – 35	<10 – >35	15 – 20	ND
Crassostrea virginica	<30	ND	ST	ND
Mercenaria mercenaria	>5 – 30	12 – 30	ST	ND
Mytilus edulis	> 0 – 29	4 – 30	ST*	BR
Mytilus galloprovincialis	10 – 20 (GR)	34 (GR)	TR	ND
Ostrea edulis	>0 – 25	>15 (SS)	ST	ND
Patinopecten yessoensis	2neg – 30	32 – 34	ST	MA
Perna canaliculus	ND	ND	TE	ND
Ruditapes philippinarum	0 – 35	ND	TR*	BR
Saccostrea commercialis	> 20 (SS)	ND	NL	NL
Venerupis pullastra	10 – 26 (SS)	ND	TE	ND

FINFISH	**FAO FACTS**		**FISHBASE I (II)**	
	T (0C)	S (ppt)	T (0C)	S (ppt)
Acipenser baerii	1 – 26	ND	10 – 20	EH
Anguilla Anguilla	18 – 25 (GR)	ND	4 – 20	EH
Argyrosomus regius	14 – 23 (GR)	ND	ST	MA
Carassius auratus	ND	NA	? – 41	FW
Catla catla	>14	NA	18 – 28 (17 – 40)	FW (<5)
Chanos chanos	ND	EH	15 – 43 (14 – 41)	EH
Cirrhinus molitorella	>7	NA	22 – 26	FW
Cirrhinus mrigala	>14	NA	TR	FW
Clarias gariepinus	>24 (SS)	NA	8 – 35	FW
Cyprinus carpio	ET	<5	3 – 35	FW
Dicentrarchus labrax	5 – 28	3 – 30	8 – 24	EH
Epinephelus coioides	30 (SS)	30 (SS)	ST*	BR, MA
Hippocampus comes	26 – 28 (SS)	NA	TR	MA
Hypophthalmichthys molitrix	6 – 28	NA	6 – 28	FW

Hypophthalmitrix nobilis	0.5 – 38	NA	4 – 26	FW
Ictalurus punctatus	26 – 30 (GR)	NA	10 – 32	FW
Labeo rohita	14 – >30	NA	TR	FW, BR
Lates calcarifer	ND	EH	15 – 28	EH
Mugil cephalus	20 – 24 (SS)	30 – 32 (SS)	8–24	EH
Oncorhynchus kisutch	9 – 15 (GR)	NA	? – 25	EH
Oncorhynchus mykiss	0 – 27	NA	10 – 24, ST*	EH
Oreochromis niloticus	11 – 42	NA	14 – 23	FW, BR
Oreochromis shiranus	NL	NL	TR (10 –40)	FW, BR (FW)
Psetta maxima	11 – 23	NA	TE	BR, MA
Rachycentron canadum	20 – 37 (GR)	NA	TR, ST	BR, MA
Salmo salar	6 – 16 (GR)	33 – 34 (GR)	2 – 9*	EH
Sarotherodon melanotheron	NL	NL	23 – 25*, TR (17 – 33)	FW, BR (EH)
Sciaenops ocellatus	17 – 28 (SS)	NA	ST	BR, MA
Seriola quinqueradiata	20 – 29 (GR)	30 – 36	ST	MA
Sparus auratus	4 – >26	NA	ST	BR, MA
Tilapia rendalli	NL	NL	24 – 28*, TR (10 – 40)	FW, BR* (FW)