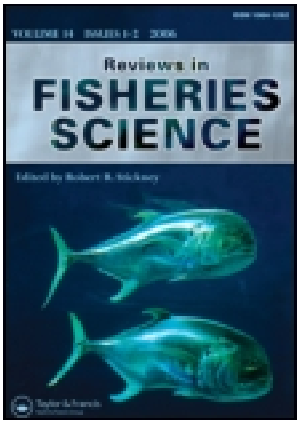


Reviews in Fisheries Science
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/brfs20

Marine Fisheries Management in a Changing Climate: A Review of Vulnerability and Future Options

Johanna E. Johnson [a] & David J. Welch [b c]

[a] C_2O-coasts climate oceans, Townsville, Australia

[b] Queensland Primary Industries and Fisheries, Townsville, Australia

[c] Fishing and Fisheries Research Centre, School of Earth and Environmental Sciences, James Cook University, Townsville, Australia

Version of record first published: 21 Jan 2010

To cite this article: Johanna E. Johnson & David J. Welch (2009): Marine Fisheries Management in a Changing Climate: A Review of Vulnerability and Future Options, Reviews in Fisheries Science, 18:1, 106-124

To link to this article: http://dx.doi.org/10.1080/10641260903434557

Reviews in Fisheries Science, 18(1):106–124, 2010
Copyright © Taylor and Francis Group, LLC
ISSN: 1064-1262 print
DOI: 10.1080/10641260903434557

Marine Fisheries Management in a Changing Climate: A Review of Vulnerability and Future Options

JOHANNA E. JOHNSON[1] and DAVID J. WELCH[2,3]
[1]C_2O–coasts climate oceans, Townsville, Australia
[2]Queensland Primary Industries and Fisheries, Townsville, Australia
[3]Fishing and Fisheries Research Centre, School of Earth and Environmental Sciences,
James Cook University, Townsville, Australia

Marine capture fisheries are an important source of protein globally, with coastal and oceanic fish providing a rich source of essential fatty acids, vitamins, and minerals. Fisheries also support economies and important social structures in many nations, particularly developing nations (Allison et al., 2009). Marine fisheries are under increasing threat from climate change, with climate change now identified as the latest threat to the world's fast declining fish stocks (UNEP, 2008; Cochrane et al., 2009). Marine fisheries will be exposed to increasing sea surface temperatures, ocean acidification, sea level rise, increasing storm intensity and altered ocean circulation, and rainfall patterns that will affect target species through a range of direct and indirect mechanisms. The sensitivity of fish stocks to these changes will determine the range of potential impacts to life cycles, species distributions, community structure, productivity, connectivity, organism performance, recruitment dynamics, prevalence of invasive species, and access to marine resources by fishers. Many fisheries are already experiencing changes in target species diversity and abundance, species distribution, and habitat area, as well as loss of fishing effort due to intensifying storms (Johnson and Marshall, 2007; Hobday et al., 2008; UNEP, 2008). Using a vulnerability assessment framework, we examine the level of vulnerability of marine fisheries to climate change and the factors that will temper vulnerability, such as adaptive capacity. Assessing fisheries vulnerability to climate change is essential to prioritize systems in greatest need of intervention, understand the drivers of vulnerability to identify future research directions, and more importantly, to review current fisheries management with the view to develop management responses that will be effective in securing the future sustainability of marine fisheries.

Keywords vulnerability, adaptation, climate change, marine ecosystems, marine fisheries

INTRODUCTION TO VULNERABILITY

Almost 80% of the world's fisheries species are currently considered to be beyond or close to their harvest capacity (UNEP, 2008), and the proportion of overexploited, depleted, and recovering stocks globally remains unchanged over the past 10–15 years (FAO, 2008a). Overall, global marine fisheries catches decreased by 2.6 million tons between 2005 and 2006, supplying the world with approximately 82 million tons of food fish, with a per capita supply of 8.9 kg (live weight equivalent; FAO, 2008a). This represents about 53% of total fisheries production globally (FAO, 2008a). Coastal ecosystems are particularly important, producing more than 90% of the food provided by marine ecosystems (Garcia and Grainger, 2005), with half the world's marine fisheries catch captured in less than 10% of the ocean (UNEP, 2008).

Overexploitation is even more serious for fishery resources that are exploited solely or partially in the high seas (deep water fisheries), for straddling stocks and for highly migratory oceanic species. The FAO summarized the status of world fisheries in the statement: "*This confirms earlier observations that the maximum wild capture fishery potential from the world's oceans has been reached and reinforces the calls for more cautious and effective fisheries management to rebuild depleted stocks and*

Address correspondence to Johanna Johnson, 9 Coral Sea Crescent, Wulguru 4811, Australia. E-mail: j.johnson@c2o.net.au

prevent the decline of those being exploited at or close to their maximum potential" (FAO, 2006).

Stressors on marine fisheries extend beyond overexploitation and include other major environmental threats, such as habitat loss, invasive species, and pollution (UNEP, 2008). Changes to global climate, however, are now considered to pose the greatest long-term threat to terrestrial and marine ecosystems (IPCC, 2007). The Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC, 2007) states that warming of the climate system is unequivocal and it is highly probable (greater than 99%) that observed changes are the result of anthropogenic activities. As a result, increasing atmospheric carbon dioxide concentrations are causing global climatic changes, which are having, and will continue to have, great influence on marine ecosystems (IPCC, 2007).

Growing national and international efforts have produced a number of substantial bodies of work documenting the implications of climate change for marine fisheries, and discussing the need for new directions in fisheries management (Hobday et al., 2006, 2008; FAO, 2007; Poloczanska et al., 2007, 2008; FAO, 2008b; UNEP, 2008; Allison et al., 2009). Despite these efforts there still exists a dearth of knowledge on the direct effects of climate-induced changes on marine populations, with a consequential high level of uncertainty in predictions of ecosystem and marine fisheries responses. This also equates to barriers in fisheries management responsiveness.

In this review, we broadly assess the vulnerability of global marine fisheries to climate change and use this information to identify key focus areas for fisheries management in the face of a changing and uncertain future. We have used an approach that determines vulnerability as a function of the exposure, sensitivity, and adaptive capacity of marine fisheries to climate change (Figure 1). This type of approach is a form of integrated assessment that assimilates social, ecological, and economic information and can be applied broadly to marine fisheries globally, or more specifically to individual fishery regions and/or sectors. The benefit of assessing vulnerability this way is that it highlights the key elements that combine to amplify (or alleviate) the risks that climate change can impose on a system. Understanding these elements can help identify highly vulnerable areas, the potential source of vulnerability, and management actions that can help minimize the threat. In addition, this type of approach does not rely on extensive datasets and can incorporate expert judgments and local knowledge to assess vulnerability and ultimately assist management.

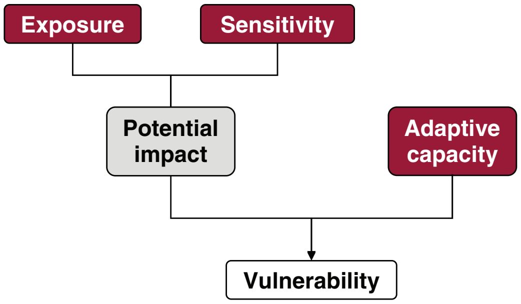


Figure 1 Framework for assessing vulnerability to climate change adopted by the IPCC. Exposure relates to the influences or stimuli that impact on a species or system, and represents the background climate conditions, and any changes in those conditions. Sensitivity reflects the responsiveness of a species or system to climatic influences, and the degree to which changes in climate affect current form. Together these determine the potential impacts a species or system experiences, which will be tempered by its adaptive capacity. That is, the ability to adapt to increase the capacity of a species or system to cope with (or avoid) the consequences of climate change (adapted from Schroter and the ATEAM Consortium, 2004).

We summarize the emerging changes in the Earth's ocean climate that marine fisheries will be exposed to, review the implications for marine fish based on known sensitivities, and the links with current stressors, and potential impacts on marine fisheries. We discuss the ability of fisheries to adapt to or cope with future climate change and the key areas of vulnerability for marine capture fisheries. We then perform a semi-quantitative assessment of vulnerability to climate change using an indices-derived approach for three example fisheries. The factors that limit adaptive capacity and heighten vulnerability are used to identify key targets for action that will facilitate effective management of marine fisheries under a future regime of climate change and uncertainty.

Exposure: Predicted Changes in Ocean Climate

Average global surface air temperatures have increased by 0.74°C under the 100-year trend from 1906 to 2005, and are projected to increase by 1.8 to 4.0°C by 2100 depending on the emission scenario (IPCC, 2007). The oceans have absorbed approximately 80% of the additional heat in the global climate system and observations show that the average global ocean temperature has increased by approximately 0.5°C since 1961 (IPCC, 2007). Global sea surface temperatures are projected to continue to increase over the 21st century, with tropical oceans experiencing the greatest increases of 1 to 3°C in some regions (IPCC, 2007; Lough, 2007). Exposure of marine fishes to small increases in temperature can have a direct effect on their physiology (Brander, 2007; Munday et al., 2008), distribution (Scavia et al., 2002; Soto, 2002; Sabates et al., 2006; Stenevik and Sundby, 2007; Boyce et al., 2008), life cycle events (Soto, 2002; Brander, 2007), and biodiversity (Cheung et al., 2009; Brierley and Kingsford, 2009).

Atmospheric carbon dioxide concentration increased to 379 ppm in 2005, which exceeds the natural range of the past 850,000 years (Luthi et al., 2008). The world's oceans are a natural sink for atmospheric carbon dioxide, absorbing increasing amounts since 1750. This additional dissolved carbon dioxide reacts with seawater to form weak carbonic acid with a consequent decline in seawater pH (McNeil and Matear, 2007). Oceanic pH is estimated to have decreased by 0.1 units since pre-industrial times and is predicted to fall a further 0.14 to 0.35 units by 2100 (Royal Society, 2005; Kleypas et al., 2006; IPCC, 2007). This would make the ocean more acidic than at any time in the past 300 million years (Caldeira et al., 2003). Reduced pH has direct implications for the reproductive performance of many marine fishes (Harley et al., 2006; Munday et al., 2009) and for food webs, and will indirectly affect marine fisheries by modifying habitats important to fish (Kurihara et al., 2004; Kingsford and Welch, 2007; Munday et al., 2007).

Average global sea level is rising due to thermal expansion of the oceans and contributions of water from melting continental ice sheets and glaciers. Global average sea level has risen since 1961 at an average rate of 1.8 mm per year, and since 1993 at an average rate of 3.1 mm per year (IPCC, 2007). Future predictions are that global average sea level will continue to rise by at least 0.18 to 0.59 m above the 1980–1999 baseline by 2100 (Church and White, 2006; IPCC, 2007), with larger rises of up to 1.4 m possible (Hansen, 2007; Rahmstorf, 2007). Sea level rise will be in the order of meters if there is rapid melting of glaciers and ice-caps (Schneider, 2009), although there is uncertainty about the likelihood of this occurring. This rate and magnitude of sea level rise would affect coastal habitats important for many fish species, coastal fisheries infrastructure, as well as the 250 million people living within 5 meters of high tide (UNEP, 2007), many of whom rely on coastal fisheries for subsistence and livelihoods.

Recent global climate models indicate that the wind speed of tropical cyclones will increase by 5 to 12% with global warming (IPCC, 2007). Observational evidence from the North Atlantic indicates an increase in tropical cyclone intensity since 1970. Temperate storms are likely to shift poleward with consequential changes in wind, rainfall, and temperature patterns (IPCC, 2007). More extreme droughts and floods are predicted in a warmer world, and the total area affected by drought worldwide has already increased since the 1970s (IPCC, 2007). Stronger storms will increase disturbance regimes, affecting coastal and shallow fish habitats, access to fish stocks and, therefore, fishing effort (FAO, 2007). More extreme rainfall patterns will lead to greater variability in terrestrial nutrient enrichment of marine ecosystems, affecting coastal productivity and distribution and abundance of fish stocks (Kennedy et al., 2002; Garcia and Grainger, 2005).

Ocean currents transport heat and nutrients throughout the global oceans and influence the location and intensity of upwellings, pelagic hotspots, and large-scale water exchange mechanisms. Such water exchange mechanisms that ‘flush’ continental shelves are found near approximately 75% of all major marine fishing grounds worldwide (UNEP, 2008). Climate models predict a general weakening of global circulation in the 21st century, and the possibility of an abrupt transition if an as yet unquantified threshold is crossed (IPCC, 2007). Any ‘slowing down’ of coastal exchange mechanisms will affect nutrient and larval transport and increase the risks to coastal fisheries from pollution and dead zones (Schmittner, 2005; Harley et al., 2006; UNEP, 2008). Dead zones (hypoxic waters) tend to occur in coastal environments and are associated with urban and agricultural pollutants. The number of known dead zones increased from 149 to over 200 worldwide from 2003 to 2006 (UNEP, 2008), coinciding with important primary coastal fishing grounds with the potential to influence fish distribution and abundance.

Sensitivity: Response of Marine Fish

Marine fish communities will be directly exposed to changing climate variables as well as a range of direct and indirect ecosystem responses to climate change. Known environmental dependencies and sensitivities provide excellent predictors of how fish populations are likely to respond, with anticipated changes in species richness, abundance, reproductive success, and shifts in distribution and community structure (Hobday et al., 2006, 2008; Brander, 2007; Poloczanska et al., 2007, 2008; Munday et al., 2008; Brierley and Kingsford, 2009).

Oceanic plankton productivity is strongly influenced by periodic events that alter nutrient availability, such as freshwater inputs, sediment re-suspension from storms, and upwelling of nutrient-rich waters (Richardson and Schoeman, 2004; McKinnon et al., 2007). Climate change will affect all of these events to some degree, with corresponding changes in plankton community dynamics and their biogeographic ranges (McKinnon et al., 2007; Brierley and Kingsford, 2009). Ultimately this will have flow-on effects to higher trophic levels (McKinnon et al., 2007; UNEP, 2008). Despite their ability to rapidly respond to environmental change (due to short generation times and functional redundancies; Richardson and Schoeman, 2004; McKinnon et al., 2007), changes in plankton communities due to changes in climate have already been observed at high latitudes (Hays et al., 2005). The Continuous Plankton Recorder in the northeast Atlantic has recorded evidence of warmer water copepods moving northward by 10 degrees of latitude—or about 1,000 km—in the 40 years up to 1999 (SAHFOS, 2006). It is predicted that increased spatial and temporal variability of plankton productivity as a result of more frequent climate and oceanography extremes could destabilize existing trophic links, ultimately favoring shorter lived, rapid turnover fish species at higher trophic levels (Soto, 2002; Brierley and Kingsford, 2009).

A key issue is how changes to plankton communities might affect the pelagic larvae of important fisheries target species. The larvae of fish spend days to months in the plankton while the larvae of important fishery invertebrates, such as crustaceans, spend months in the plankton before settling (Kingsford and Welch, 2007; Hobday et al., 2008). Starvation is thought to be a major contributor to mortality during the larval period, particularly with increased larval duration, and shifts between low-nutrient and high-nutrient plankton communities might have significant impacts on survival of fish larvae. Such a shift is likely to generate increased variability in the dynamics of population recruitment, with extreme high and low cohort strengths becoming more common and intervening cohort strength less abundant. A mismatch between the timing of fish reproduction and periods of high plankton productivity could impact significantly on fish population replenishment (Edwards and Richardson, 2004; Kingsford and Welch, 2007). For example, a rapid response by plankton communities to changes in sea temperature and nutrients may not coincide with the reproductive peaks of fish species if those species' reproduction is strongly cued by day length rather than temperature (Poloczanska et al., 2007).

Changes in local and meso-scale currents are likely to affect the retention and dispersal of larval fish, due to their importance for larval dispersal (James et al., 2002; Cowen et al., 2006; Burgess et al., 2007). Therefore, the dynamics of fish larval supply and the degree of connectivity between regions will be affected as ocean circulation patterns and upwelling are affected by climate change. Synergistic interactions between changing circulation patterns and changes to sea temperature and productivity could also affect how many larvae survive the pelagic stage and their condition at settlement (Kingsford and Welch, 2007).

Temperature has been found to directly affect the metabolism of marine fish species, increasing growth rates and reducing egg incubation time plus other physiological effects (Soto, 2002; Hobday et al., 2008; Munday et al., 2008). Increased metabolic rates as a consequence of elevated ocean temperatures can result in increased demand for oxygen as well as food. However, increases in temperature will decrease dissolved oxygen availability and, due to alterations in the mixed-layer depth, changes in plankton productivity may cause food to be limited also, further compromising larval survival and exacerbating recruitment variability (Brierley and Kingsford, 2009). There is also a positive correlation between larval growth and development, and ocean temperature (Ray et al., 1992; Soto, 2002; Wilson and Meekan, 2002; Green and Fisher, 2004; O'Connor et al., 2007; Munday et al., 2008). A study by Meekan et al. (2003) observed that water temperature had a greater influence on larval growth than food supply. This may reduce the time larvae spend in the plankton or hasten the onset of active swimming and settlement behavior, both of which would tend to reduce dispersal distances (Armsworth, 2000; Cowen et al., 2006). Small increases in temperature, therefore, may also improve the survival prospects of larval fish in the short-term with improved growth rates; however, large sea temperature increases are likely to have negative effects on the reproductive performance of adults. Importantly, mobile species can shift their distributions and ranges in response to changes in temperature gradients and spatial patterns of plankton productivity (Soto, 2002; Sabates et al., 2006; Boyce et al., 2008; Munday et al., 2008).

Changing climate regimes are expected to influence species' distributions (Brander, 2007; Worldfish, 2007; Cheung et al., 2009), which are set by physiological tolerances to temperature, precipitation, dissolved oxygen, pH, and salinity, as well as interspecific interactions. Because rates of climate change appear to exceed the capacity of many marine fish species to adapt, species will shift their ranges along physiological thresholds and may ultimately be forced to extend past the boundaries of their known native ranges (Walther et al., 2002; Roessig et al., 2004; Perry et al., 2005; Munday et al., 2008) or be constricted into smaller ranges, with the potential for local extinctions (Cheung et al., 2009).

The combination of exposure and sensitivity is what determines the potential impacts of climate change; however, existing pressures on marine capture fisheries can heighten both exposure and sensitivity to climate variables and potentially affect the magnitude of impacts in the face of climate change. The next section considers this interaction and reviews the potential impacts of projected climate change on marine fisheries, giving examples of studies that have already documented changes or provide insight into how fisheries might respond, before discussing the adaptive capacity of fisheries to these changes.

Synergies between Climate Change and Major Stressors

Climate change will be an additional pressure on marine fish stocks already subject to overexploitation, destructive fishing, pollution, habitat loss, and invasive species (Harley et al., 2006; UNEP, 2008). Fishery populations that are overexploited exhibit greater sensitivity to additional disturbance, including climate change, than healthy populations (Hughes et al., 2003; Brander, 2007). Overfishing can reduce age, size, and diversity, as well as lifetime reproductive success and larval quality, making fished species more susceptible to both short- and long-term perturbations (Jackson et al., 2001; Dayton et al., 2002; Pauly et al., 2003; Sobel and Dahlgren, 2004; Law and Stokes, 2005; Steneck and Sala, 2005; Brander, 2007; O'Connor et al., 2007).

Commercial exploitation of even a single keystone species, such as a top consumer, can destabilize ecosystems by decreasing redundancy and increasing susceptibility to additional disturbances due to changing climate conditions (Hughes et al., 2003; Heithaus et al., 2008). Many examples of such ecosystem destabilizations through overfishing exist, including the formerly cod-dominated system of the western North Atlantic (Steneck et al., 2004; Frank et al., 2005) and the fish grazing community on Caribbean coral reefs (Steneck, 1997; Mumby et al., 2006). Direct changes to the distribution, demography, and stock structure of target species as a result of fishing, coupled with changes in fish communities and marine ecosystems due to climate change, will have consequences for the ability of marine fisheries to operate in their current form and to adapt to future change (Brander, 2007).

Destructive fishing practices that deplete target stocks, reduce biodiversity through by-catch mortality (Condrey and Fuller, 1992; Watling and Norse, 1998; Sobel and Dahlgren, 2004; Hiddink et al., 2006), and cause damage to seafloor structures thereby reducing habitat complexity (Engel and Kvitek, 1998; Dayton et al., 2002; Thrush and Dayton, 2002; Hixon and Tissot, 2007), will compromise fisheries resilience to climate change. For example, over 95% of habitat destruction on seamounts is the result of unregulated and unreported bottom fishing using dredges, trawls, and traps (UNEP, 2008). Due to their high endemism (Morato et al., 2006) and life history traits (Koslow and Thresher, 1996), deepwater fisheries are much slower to recover (decades to centuries) than shallow water communities, and under increasing disturbance regimes that are projected due to climate change, may never fully recover (UNEP, 2008).

Increasing sediment and nutrient loads into coastal marine ecosystems will also compromise the resilience of inshore habitats, particularly shallow coral reefs, seagrass meadows, and kelp meadows. Interactions between climate and localized stressors are expected to create particularly damaging synergies, adding to concerns about climate change. For example, corals exposed to nutrients, turbidity, sedimentation, or pathogens have been shown to be more susceptible to bleaching, or less able to survive a bleaching episode (Hoegh-Guldberg et al., 2007a). Furthermore, chronic local stressors—such as poor water quality—can affect the recovery potential of reef communities (Hoegh-Guldberg et al., 2007b). This is because fertilization and larval recruitment in corals are particularly sensitive to environmental conditions, and because macroalgal growth rates increase in nutrient-rich waters (McCook, 1999).

Over 80% of marine pollution originates from land-based sources, such as untreated sewage and sediment and nutrients from erosion (UNEP, 2008). In southeast Asia alone, 600,000 tons of nitrogen are discharged from major rivers into the ocean each year (UNEP, 2006a) and it is projected that nitrogen inputs into the oceans will increase by at least 14% by 2030 under future climate scenarios (UNEP, 2006a).

These coastal areas contain habitats that are important for target fisheries species, such as tropical coral reefs, kelp meadows, coastal and associated tidal wetlands, seagrass meadows, and estuaries, and are also vulnerable to the impacts of climate change (Hobday et al., 2006; Johnson and Marshall, 2007; Poloczanska et al., 2007). Tropical coral reefs provide food and livelihoods to millions of people, producing 10–12% of the fish caught in tropical nations and 20–25% of the fish caught by developing nations in the western Pacific, Indian Ocean, Persian Gulf, Middle East, and the Caribbean (Garcia and Grainger, 2005). Loss of coral reefs due to increasing sea temperatures (causing coral bleaching and mortality; Hoegh-Guldberg et al., 2007b), increased physical disturbance from stronger storms, and reduced coral calcification rates due to ocean acidification has serious consequences for communities of reef fish. Loss of fish diversity, declines in species abundances, and shifts in community composition have been observed after loss of coral habitat in the past (Wilkinson, 2002; Munday et al., 2008; Pratchett et al., 2008).

Declines in coral reef structure and habitat has a direct effect on organisms that depend on corals for shelter or food, as well as higher trophic species. Although less that 10% of fishes and other mobile reef organisms are truly coral dependent (Munday et al., 2007; Pratchett et al., 2008), over 50% of reef species can suffer population declines following severe reductions in coral cover (Jones et al., 2004; Wilson et al., 2006). The loss of coral cover can affect many fish species, and may trigger a cascade effect that first impacts on a relatively small group of obligate coral-dwellers and corallivores (Munday, 2004; Wilson et al., 2006; Pratchett et al., 2006), followed by species that rely on live coral at settlement, to a broader range of species that use the reef structure for shelter (Syms and Jones, 2000), and finally to pelagic fish species that visit reefs to target prey (Ohman et al., 1998; Booth and Beretta, 2002; Munday et al., 2008).

Furthermore, loss of coastal habitats can reduce coastal protection from storms and tides, alter coastal hydrodynamics, result in diminished larval supply of important fisheries species, and reduce biofiltration of land-based pollutants (Kennedy et al., 2002; Johnson and Marshall, 2007). These ecosystem goods and services are of economic importance, with the total economic value of reefs estimated at between US$100,000 and US$600,000 per square kilometer per year, while mangroves have been estimated to have an ecosystem value between US$200,000–$900,000 per square km per year (UNEP, 2006b). Despite their value, these habitats are in decline, with wetland and mangrove areas reduced by 40–90% in most regions in the last 40 years (UNEP, 2008), and over 65% of global seagrass meadows have disappeared due to land reclamation, eutrophication, disease, and destructive fishing practices (Lotze et al., 2006). Continued declines in coastal habitats exacerbated by climate change are likely to impact on coastal fishing communities, essential fisheries infrastructure, and ultimately national economies.

Globally, the number and severity of invasive species infestations is increasing, with significant effects on marine ecosystems, habitats, and fisheries resources (Ruiz et al., 1997; Lotze et al., 2006). To date, the most devastating marine infestations have occurred in areas of diminished resilience; along the major global shipping routes, in the most intensively fished and polluted areas of the continental shelf (Daskalov et al., 2007; UNEP, 2008). Changes to ocean temperatures, currents, and pH are likely to further reduce resilience of these fishing grounds and accelerate invasions, which may ultimately displace important fisheries species (Brander, 2007).

Significantly, as human population increases, it is projected that up to 91% of inhabited coasts will be impacted by coastal development by 2050, particularly in east and southeast Asia, and extreme climate events (UNEP, 2008), further increasing pressure on coastal resources. The cumulative effect of these stressors will concentrate in the 10–15% of the world's oceans that also have the most productive and important fishing grounds (UNEP, 2008), with significant ecological, social, and economic consequences.

Potential Impacts: Implications for Marine Fisheries

Previous sections have reviewed how changes to the global oceans, as a result of climate change, will have a range of direct and indirect influences on target fisheries species. Future changes to ocean temperature, ocean circulation, nutrient cycling, ocean chemistry, and extreme climate events are likely to affect fish stocks through changes to reproduction, distribution, and population dynamics, and ultimately global marine fisheries production (Brander, 2007; Worldfish Centre, 2007). The range of potential impacts and consequences for fisheries are well summarized by Allison et al. (2009); however, the magnitude of impact will depend on the degree of exposure of the fishery to changes, the current state of the stock and existing pressures, and their sensitivity or resilience to climate disturbances.

There are already indications that climate change has affected marine fisheries. The following sections summarize some of the observed changes to fish populations, abundance, distribution, diversity, and fisheries productivity that can in many cases be attributed to changes in ocean climate, or used as a proxy to predict future climate effects on marine capture fisheries.

Population Changes

Many long-term changes observed in commercial fish populations have been associated with known natural climatic oscillations, such as the El Niño-Southern Oscillation (ENSO) in the Pacific and the North Atlantic Oscillation (NAO) in the North Atlantic. For example, variations in sea surface temperature driven by NAO fluctuations have been linked to fluctuations in cod recruitment off Labrador and Newfoundland and in the Barents Sea (Ellingsen et al., 2008). Populations of herring, sardine, salmon, and tuna have also shown changes linked to fluctuations in the NAO index (SAHFOS, 2006; Lehodey et al., 2006). Although it is uncertain how climate change will affect both ENSO and NAO, it is expected that they will continue to be a source of high inter-annual climate variability that may change in frequency and intensity under future climate scenario (IPCC, 2007).

A study in an intensively fished area off the North Carolina coast showed that fish species composition had changed, correlating with a winter ocean warming trend of 1–6°C, with two new families and 29 new species of tropical fishes recorded (Parker and Dixon, 2002). No new temperate fish species were observed and there was a decrease in the relative abundance and size of previously common temperate species. These changes were reflected in fisheries landings, with more tropical reef fish represented in catches, and smaller catches and average weights of temperate commercial target species, such as black sea bass and snappers.

Biogeographic Changes

Biogeographic changes to fisheries species have been observed in the northeast Atlantic (Brunel and Boucher, 2007; Schrank, 2007), Tasman Sea, China Sea, and Bering Sea (Schrank, 2007), the western Pacific (Lehodey et al., 1997), and predicted for other regions, such as the cod and salmon fisheries in the Baltic Sea (MacKenzie et al., 2007).

Comparisons of fisheries and oceanographic data, known thermal limits of Pacific salmon, and temperature projections from the Canadian climate model were used to determine the future distribution of sockeye salmon (*Onchorynchus nerka;* Welch et al., 1998). The predictions showed that by 2090 temperature conditions of the Pacific Ocean will be outside the thermal limits of sockeye salmon, and their distribution may be restricted to marginal seas, such as the Bering Sea and the Sea of Okhotsk. Similarly, Cheung et al. (2009) used a dynamic bioclimate envelop model for 1,066 species of exploited marine fish and invertebrates and projected numerous local extinctions in the sub-polar regions, the tropics, and semi-enclosed seas by 2050.

Abalone abundance surveys by Rogers-Bennett (2007) following on from previous surveys in the 1970s show a range contraction in northern abalone (*Haliotis kamtschatkan*) and flat abalone (*Haliotis walallensis*) along the Pacific coast of the USA under an increasing sea temperature trend. This contraction continues despite closures of the major commercial abalone fisheries on the western USA and Canadian coasts in the early to mid 1990s (Hobday and Tegner, 2002; Gaydos, 2007).

Similarly, on the Pacific coast of Australia, an expansion of the long-spined sea urchin (*Centrostephanous rodgersii*) into the east coast of Tasmania (Edgar, 1997) has been associated with increasing sea temperatures and effects on abalone fisheries (Ling et al., 2009; Hobday et al., 2008). Subsequent declines in urchin barrens on the NSW coast have been observed—adversely affecting the local abalone fishery—while its spread to the east coast of Tasmania appears to be disrupting the balance between macroalgae, abalone, rock lobsters, and the native urchin. It is predicted that *C. rodgersii* barrens will eventually cover 50% of the rocky reef habitat on Tasmania's east coast and have serious implications for the density and ultimately the sustainability of valuable rock lobster and abalone fisheries (Hobday et al., 2008).

Biogeographic shifts poleward have also been observed in Tasmanian marine fishes, with 45 species, representing 27 families (about 30% of the inshore families in the region), exhibiting major distributional shifts that are thought to be climate related (Last et al., in review). The majority of the species exhibiting poleward shifts are reef fish, mainly western warm temperate or eastern warm temperate species.

A study of both exploited and non-exploited North Sea fishes showed a marked response to recent increases in sea temperature, with nearly two-thirds of species shifting in latitudinal range or depth, or both, in the past 25 years (Perry et al., 2005). In addition, half of the species displayed boundary shifts with ocean warming, with all but one species shifting northward. Species that shifted distribution also had faster life cycles and smaller body sizes than non-shifting species (Perry et al., 2005).

Relative abundance of skipjack tuna, as determined by fisheries catches, is strongly determined by the El Niño Southern Oscillation (ENSO) in the western Pacific Ocean (Lehodey et al., 1997). Catches of tuna correlate with the shifting 29°C isotherm that occurs during El Niño and La Niña years, and is supported by movements of tagged individuals. The ENSO represents one of the southern hemisphere's most significant climate systems and the impacts on this system due to climate change, although uncertain, is likely to result in further shifts (spatial and temporal) in fishing grounds due to shifts in the Pacific Ocean temperature gradients.

Habitat Effect

Many marine fisheries species depend on habitats such as coral reefs, mangroves, and seagrass for critical life history stages. Changes to coastal habitats and connectivity between habitats are of most concern since most of the world's significant fishing grounds are found on continental shelves within 200 nautical miles of the coast (UNEP, 2008). In addition, more than half of marine landings are caught within 100 km of the coast in less than 200 m of water (UNEP, 2008). Tropical coral reefs are particularly productive, with a total fisheries yield estimated to be worth US$5 billion annually (Cesar et al., 2003; Sadovy, 2005). Climate change projections of increasing sea surface temperatures, storm intensity, sea level rise, and changes to rainfall patterns and nutrient cycling will impact on these habitats and threaten major fishing grounds concentrated in coastal areas (Cochrane et al., 2009). A loss of these habitats and the processes that support coastal productivity will affect fisheries species with life stages that depend on these habitats (Brierley and Kingsford, 2009) and have significant impacts on the communities that depend on these fish for protein and livelihoods.

In 1998, the largest global coral bleaching event killed an estimated 16% of the world's corals (Wilkinson, 2002). The consequences of thermally-induced coral loss for fisheries were observed in many reefs worldwide, including the western Pacific, Indian Ocean, Persian Gulf, Middle East, and the Caribbean (Wilkinson, 2002, 2004). In southern Kenyan reefs, hard coral cover declined by 44–74% within one year of the 1998 coral bleaching event, and three years after the event there was an 8% decline in total demersal catch and a 21% decline in per person catch, despite a 17% increase in fishing effort (McClanahan et al., 2002). In Caribbean reefs, loss of coral habitat due to coral bleaching mortality after the 1998 and 2005 coral bleaching events was exacerbated by other stresses, such as over-fishing, tropical storms, and disease, with a resultant reduction in coral cover in the Caribbean by 80% (Gardner et al., 2003) and corresponding declines in fish biomass (Wilkinson and Souter, 2008). Thermally-induced coral bleaching events are predicted to increase under a future regime of climate change, with resultant loss of coral reef habitat (Hoegh-Guldberg et al., 2007b). Physical damage to corals and loss of reef habitat due to increasing intensity of storms and ocean acidification will also affect reef-dependent fish species.

Studies of northern Australia prawn nursery grounds found that changes in the frequency, magnitude, or distribution of tropical storms had the potential to considerably modify these habitats and, therefore, prawn populations (Rothlisberg et al., 1988). For example, Cyclone Sandy destroyed approximately 20% or 183 km^2 of seagrass beds in the Gulf of Carpentaria, which took nearly 10 years to recover (Hobday et al., 2008). Following the loss of these nursery grounds, there was an observed reduction in the offshore fishery's catch (Poiner et al., 1993). Losses of these important habitats will increase with projections that the wind speed of tropical cyclones will increase by 5 to 12% under global warming (IPCC, 2007).

Fisheries Productivity Changes

Expected increases in Australian ocean temperatures are projected to cause a 35% reduction in the overall economic value of Australian fisheries by 2070 (Lyne et al., 2003), with temperate fisheries being more vulnerable than tropical ones. The most sensitive fisheries sectors are in Tasmania, Victoria, and Western Australia with a projected 64, 40, and 38% economic decline by 2070, respectively, assuming the fisheries remained well managed (Lyne et al., 2003).

One of the few fisheries to collapse in Australia was the gemfish fishery, which was considered overexploited when it suffered a complete collapse in 1989 after the southeast Australian zonal winds declined to their lowest point in 10 years (Hobday et al., 2006). These winds influence larval transport and coastal productivity and, therefore, have a role in recruitment success. Despite the fact that the fishery has been closed since 1989, little or no signs of recovery of the stock has been observed, which has been attributed to a continued decline in zonal winds as predicted under a regime of climate change (Larcombe and McLaughlin, 2006).

Klyashtorin and Lyubushin (2005) reviewed the twelve main commercial fish stocks harvested in the Atlantic and Pacific Oceans, which represent about 50% of the total Atlantic and Pacific marine fish harvest. This study used the fact that these fish stocks undergo long-term simultaneous oscillations linked to changes in an atmospheric circulation index to assess the effect of long-term climate change on productivity of these fisheries. Changes in commercial stock dynamics were found to mirror long-term changes of sea-air temperature, atmospheric circulation, and earth rotation. The inference is that future fisheries productivity and fisheries catches will be determined partly by how climate change affects these variables.

Hannesson (2007b) studied the geographic distribution of fish catches in the northeast Atlantic since 1945 and found correlations between sea temperature and the location and productivity of fish stocks. Catches of cod in the North Sea were inversely correlated with temperature and recruitment and catches of cod in the Norwegian and Barents Sea were positively correlated.

Some fisheries are predicted to benefit from climate change, particularly with increasing sea temperature near the poles. Arnason (2007) estimated that the economic impact of altered fish stocks as a result of warming on the Icelandic and Greenland economies is more likely to be positive than negative but unlikely to be of significant magnitude when compared to historical economic growth rates and fluctuations. The northeast Atlantic cod fishery is also projected to increase in range and productivity due to a 1–2°C increase in sea temperature by 2070 (Schrank, 2007).

MARINE FISHERIES INTO THE FUTURE

Fisheries around the world already operate under a regime of climate-related variability, from extreme weather events, floods and droughts, changes in ecosystem structure and function, and changing patterns and abundance of fish stocks. The most pressing and direct implications of future climate change for fisheries include increasing sea surface temperature, changing ocean circulation, rainfall patterns and nutrient cycling, and extreme weather events. Indirect effects through habitat degradation will have significant implications for many marine capture fisheries. All these impacts will serve to exacerbate existing variability, both in frequency and magnitude, and increase uncertainty, thus, requiring a higher level of flexible management to sustain fisheries.

Adaptive Capacity of Marine Fisheries

The adaptive capacity of marine fisheries refers to the potential for species or systems (both natural and social) to adapt to changes in variability and extremes of climate, so as to maximize fitness, moderate potential damages, take advantage of opportunities and/or cope with consequences. Ecological indicators of fisheries adaptive capacity include stock status, reproductive potential, and influence of existing pressures, such as overfishing and pollution. Socioeconomic indicators of fisheries adaptive capacity include national life expectancy, education, governance, size of economy (Allison et al., 2009), and resource dependence.

Therefore, factors that will limit the ability of fisheries to adapt to climate change include the projected rate of climate change, the compromised resilience of fisheries already under pressure, weak social and economic indices, and a high dependence on fisheries by national economies and/or subsistence fishers (Brander, 2007). Therefore, marine fisheries with low adaptive capacity include those where productivity is already suboptimal, national economies are weak and depend on fisheries, and regional communities rely on subsistence fishing for dietary protein (FAO, 2007; Allison et al., 2009).

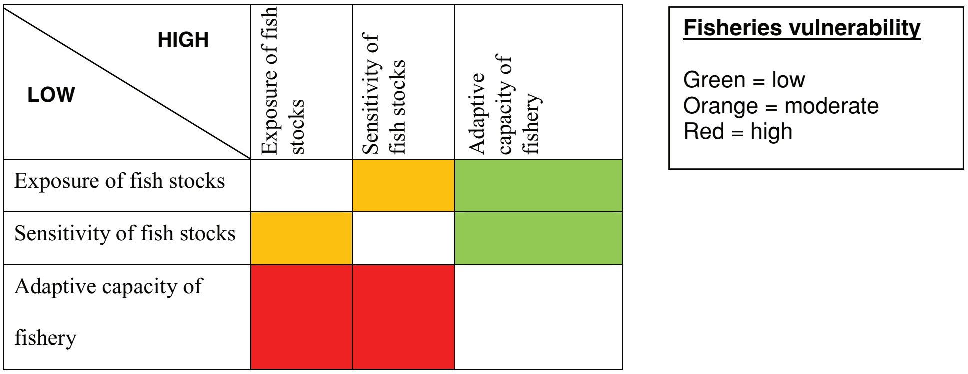
Overharvested fisheries have a limited ability to cope with further change or disturbance due to the slow recovery of fish stocks compromising their resilience. Hutchings (2001) showed that little or no recovery of over 90 different heavily harvested stocks was observed 15 years after a 45–99% reduction in biomass. This is compounded by the fact that most catch reductions are introduced too late (Shertzer and Prager, 2007) and will continue to confound adaptation of fisheries stocks to changing ocean conditions. Some climate changes will compromise reproductive capacity in fish stocks, making them more susceptible to previously sustainable fishing levels and at risk of regional or local extinctions (Brander and Mohn, 2004). Heavily fished stocks are particularly at risk, and local extinctions have been observed in some commercial species at the edge of their ranges, for example, salmon (Friedland et al., 2003) and sturgeon (Reynolds et al., 2005). Declines in reproductive capacity or productivity will have consequential effects on the adaptive capacity of fish populations and the fisheries that depend on them (Brander, 2007).

As net fishing exports in developing nations increase—growing from US$4.6 billion in 1984 to US$20.4 billion in 2004—so too does national economic dependence on fisheries (UNEP, 2008). The ability of fishing sectors and nations to adapt will depend on their economic strength, social development and production potential, and availability of alternative income and protein sources (FAO, 2008b; Allison et al., 2009). Therefore, nations in western and central Africa, Asia (Yemen, Pakistan, Bangladesh, and Cambodia), and the Pacific Islands, are exposed and sensitive to climate change, as well as having low adaptive capacity, making them highly vulnerable to climate change (FAO, 2007; Allison et al., 2009). Other regions that have the same drivers for high exposure and sensitivity but have stronger economies and higher human development potential, such as Columbia, Peru, Russia, and the Ukraine, will have a greater ability to adapt to future change, which will temper their vulnerability (FAO, 2007; Allison et al., 2009).

Vulnerability to Climate Change

Based on the vulnerability framework, marine fisheries most at risk from climate change are those whose fish stocks will experience the greatest ecological impacts due to their high exposure and sensitivity to changing ocean climate, have compromised resilience due to other pressures (such as overexploitation), and limited ability to adapt due to resource dependence and weak economies. Fisheries with stocks that have low exposure and sensitivity to changing climate conditions, coupled with high adaptive capacity, will have low vulnerability to climate change (Figure 2).

Using this approach, the countries that have been determined to be most vulnerable to climate change are in western and central Africa, despite the fact that over 80% of the world's fisheries



HIGH LOW	Exposure of fish stocks	Sensitivity of fish stocks	Adaptive capacity of fishery
Exposure of fish stocks		🟧	🟩
Sensitivity of fish stocks	🟧		🟩
Adaptive capacity of fishery	🟥	🟥	

Fisheries vulnerability

Green = low
Orange = moderate
Red = high

Figure 2 Factors that combine to determine the level of vulnerability of fisheries to climate change.

are in south and southeast Asia, and fish catches are greatest in Asia and Latin America (Allison et al., 2005). African nations are particularly vulnerable because of their high sensitivity, due to nutritional dependence on fish, their semi-arid climate increasing their exposure to future temperature increases, rainfall declines, coastal flooding and storm surge, and their low capacity to adapt to change due to weak economic and social development indices (FAO, 2007). African nations rely on fisheries to provide employment for up to 10 million people and as a vital source of protein to 200 million people (FAO, 2007). Some Asian nations (Yemen, Pakistan, Bangladesh, and Cambodia) also have high vulnerability to climate change, a function of their high sensitivity due to a heavy reliance on fish as their main source of protein, and weak economic and social indices limiting their adaptive capacity (Allison et al., 2009). For example, in Bangladesh, marine fisheries provide around 80% of the national animal protein intake (Worldfish, 2007), and there is a lack of alternative protein sources or livelihood options.

Pacific Island nations are also highly vulnerable to climate change, due to their high sensitivity (dependence on fish as a primary protein source) and their exposure to other climate change pressures, such as sea level rise, storm surge, increasing temperatures, and rainfall changes reducing water resources and increasing coastal erosion (IPCC, 2007). Fish consumption in Pacific Island nations provides 50–90% of total protein intake in rural areas and 40–80% in urban centers (Bell et al., 2009). Rural communities are particularly reliant on subsistence fishing, with a per capita consumption of over 50 kg per year (Bell et al., 2009). Reduced adaptation options, due to reliance on a limited number of fisheries, primarily coastal coral reef fisheries and pelagic tuna fisheries, also increases their vulnerability to climate change. The Secretariat of the Pacific Community Public Health Programme has advised that reliance on fish will increase in the future, required to contribute about 50% of the recommended daily protein intake, that is, about 35 kg per capita per year (Bell et al., 2009). In addition, Pacific Island nations often have weak economic and social development indices, reducing the availability of adaptation options.

The UNEP report *In Dead Water* (2008) projects that the combined pressures of climate change and increasing coastal population could result in a decline in fish availability for per capita consumption by 15% by 2015. Coastal fishing communities face a double exposure from reduced marine fisheries resources and increased risks from sea level rise, storm surge, and coastal flooding. Studies of social-ecological resilience predict that as many as 50 million people could be at risk from climate change and increasing coastal population by 2080 (Adger et al., 2005). Clearly, climate change poses an additional burden to other poverty drivers, such as food security, lack of alternative livelihoods, and health risks for the poor (Allison et al., 2009).

For fisheries with high vulnerability to be sustainable in the face of future climate change, managers need to adopt and adhere to best practices, reduce overfishing, and rebuild depleted stocks. This will be particularly difficult for developing nations with limited economic and institutional capacity and fisheries data, and may require the assistance of developed nations to strengthen governance capacity, fill critical knowledge gaps, and raise awareness (SPC, 2009). In particular, many marine fisheries will be data poor and in the absence of scientific certainty—on stock status, fish population responses, and future climate—inevitable change and the associated uncertainty must be anticipated and incorporated into local, regional, and national fisheries management strategies.

Assessment of Vulnerability

Despite there being nation- and region-specific constraints to the comprehensive assessment of fisheries vulnerability to climate change (for example, data limitations; Allison et al., 2009), this should not justify delays in preparing for the potential consequences. There is a need for regionally-focused plans of action (Brierley and Kingsford, 2009) for fisheries, ideally beginning with the assessment of vulnerability.

Allison et al. (2009) provided an approach for assessing the vulnerability of national economies due to climate change impacts on fisheries. Their approach derived indices for each of the components of exposure, sensitivity, and adaptive capacity, based on a range of variables. Vulnerability indices were then calculated as the unweighted mean of the standardized values of each of the vulnerability components. We propose the adaptation of this approach for adoption across economic, social, and biological attributes of fisheries. Through regional and expert-based initiatives, exposure, sensitivity, and adaptive capacity can be assessed against climate change variable predictions (e.g., increasing sea temperature) for different fisheries and/or fisheries regions. We have identified common variables that make up each of the vulnerability components specific to marine fisheries (Table 1), building on those provided by Allison et al. (2009), which can be drawn on to select regionally or nationally relevant variables for targeted vulnerability assessments.

The derivation of indices for each of the vulnerability components by Allison et al. (2009) comprised the use of unweighted averages of scores from the different elements, normalized and scaled to a range of 0 to 1. In their study, the quantitative approach used prevented the assessment, due largely to data limitations of many countries that were very likely to have high vulnerability indices. Therefore, although this approach is useful, we suggest that regionally-focused and expert-based programs allow for a more simple semi-quantitative assessment. This is more likely to promote the assessment of vulnerability and development of actions by nations that are data limited and requiring urgent preparation for climate change.

The proposed semi-quantitative approach uses representative, expert-based, and locally relevant information to assess vulnerability to address the issue of there being no objective measures for each of the components of exposure, sensitivity, and adaptive capacity (Allison et al., 2009) and, therefore, progress regional planning. The benefits of this approach are that it does not rely on extensive datasets and can incorporate expert judgments and locally-relevant knowledge to assess

Table 1 Summary of the common variables that make up the exposure, sensitivity, and adaptive capacity components of the vulnerability assessment framework (Schroter and the ATEAM Consortium, 2004). The variables selected for a targeted vulnerability assessment should be regionally and/or nationally relevant (adapted from Allison et al., 2009)

Component	Variables	References
Exposure	Sea temperature increase	IPCC, 2007
	Oceanic pH decrease	
	Sea level rise	
	Storm severity increase	
	Ocean current changes	
	Rainfall changes	
	River flow changes	
	Nutrient cycling	
Sensitivity	Changes in plankton productivity—extent, timing, and location	McKinnon et al., 2007; Hays et al., 2005
	Increases and decreases in larval survival	Edwards and Richardson, 2004; Poloczanska et al., 2007
	Increases and decreases in larval growth and development	Green and Fisher, 2004; O'Connor et al., 2007
	Changes in species ranges	Brander, 2007; Cheung et al., 2009
	Altered physiology	Soto, 2002; Munday et al., 2008
	Altered habitats	Hoegh-Guldberg et al., 2007b
	Changes in species tolerance ranges	Munday et al., 2008
	Disrupted larval transport	Cowen et al., 2006; Burgess et al., 2007
	Compromised reproductive performance	Brander and Mohn, 2004
Adaptive capacity	Stock status	Brander, 2007
	Reproductive potential	
	Extent of overfishing	Hutchings, 2001
	Species mobility	
	Species range	
	Pollution	
	National life expectancy	
	Education level	UNEP, 2008; Allison et al., 2009
	Governance	
	Size of economy	
	Resource dependence	
	Alternative livelihoods	

vulnerability and identify fisheries and regions of highest vulnerability and, therefore, priorities for action (Figure 3). Furthermore, by understanding the factors that influence vulnerability, these assessments can assist in identifying management options appropriate for the adaptive capacity of the particular fishery, and inform mitigation and adaption responses (Figure 3). The approach also allows for the identification of research needs by highlighting elements that are information poor.

A simple semi-quantitative assessment of vulnerability can be performed based on criteria for likelihood developed by the IPCC (2007). Using the IPCC likelihood scale we assigned a ranking of 1–7 based on the different levels of assumed probability for each of the different variables of exposure and sensitivity (1 being low and 7 being high). Adaptive capacity was also ranked using a seven-point scale (1 being high and 7 being low; Table 2) and our professional judgement of capacity. The scores

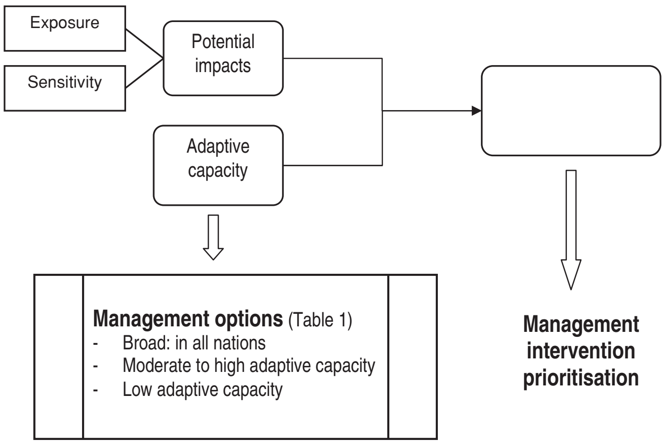


Figure 3 Schematic showing the links between the vulnerability assessment components and how they inform fisheries management to facilitate fishery resilience to climate change and its impacts.

Table 2 Suggested approach for scoring levels of likelihood for all variables identified as important to describe the exposure, sensitivity, and adaptive capacity components of vulnerability (adapted from IPCC, 2007)

Score	Terminology	Likelihood of the occurrence/outcome
1	Exceptionally unlikely	<1% probability
2	Very unlikely	<10% probability
3	Unlikely	<33% probability
4	About as likely as not	33 to 66% probability
5	Likely	>66% probability
6	Very likely	>90% probability
7	Virtually certain	>99% probability

for each of the vulnerability components were derived from the unweighted mean of the scores assigned to each variable making up each component. The level of vulnerability was then derived as the mean score across all of the key components; the higher the score, the more vulnerable the fishery is to climate change. Assigning scores to the exposure variables should be based on the best available knowledge using IPCC scenarios and on regionally relevant predictions of change as model downscaling improves. We also recommend the use of guidance material developed by the IPCC in following this approach for reporting levels of uncertainty in scoring component variables (IPCC, 2007).

We apply this approach to some example fisheries, however, stress that these fisheries have been used to demonstrate the approach and not as definitive assessments. Such assessments would require stakeholder and expert involvement and would consider regional aspects of each fishery. For this example, we have chosen the commercial sector of three fisheries from the Great Barrier Reef in Australia: the Coral Reef Finfish Fishery (CRFF), the Mud Crab Fishery (MCF), and the East Coast Trawl Fishery (ECTF) (Table 3). The CRFF is a multi-species coral reef line fishery that primarily targets live coral trout (*Plectropomus* spp.) for southeast Asian export markets as well as other finfish species mostly as fillet product. The MCF is an estuarine pot fishery that targets mud crab (*Scylla serratta*) mainly for domestic markets, and the ECTF is an inter-reef trawl fishery that primarily targets several species of prawns with smaller quantities of other crustacean and mollusc species. For the purpose of the examples, we have considered all species collectively for the multi-species fisheries, and provided a range of possible variables for each fishery that are intended to be regionally relevant.

In our worked example, the ECTF was assessed as the most vulnerable of the three fisheries (Table 3) and, therefore, identified as a priority for future management action in the face of climate change. The ECTF vulnerability was driven by a lower adaptive capacity relative to the other fisheries and examination of the scores assigned to each of the variables provides an insight into what factors should be addressed through mitigation and adaptation strategies, for example, governance issues.

Table 3 An example of the use of semi-quantitative vulnerability assessments for three commercial fisheries in the Great Barrier Reef, Australia. NB: Exposure values are based on the A2 IPCC storyline for 2050 given in parentheses (Nakicenovic and Swart, 2000), and the scores represent the likely exposure to these predictions. Regional and intra-annual variation within the fishery areas is predicted to occur but not taken into account in this example (*Sources:* Johnson and Marshall, 2007; Hutchings et al., 2007; Munday et al., 2007; Anon, 2007)

		Fishery		
Component	Variable	CRFF	MCF	ECTF
Exposure	Sea surface temperature increase (+ 1.2°C)	6	6	6
	Oceanic pH decrease (- 0.25)	6	6	6
	Sea level rise (+ 68 cm)	6	6	4
	Storm severity changes (increase)	6	6	5
	Ocean current changes (uncertain but likely)	5	4	3
	Rainfall changes (more extremes)	4	6	6
	River flow (more extremes)	3	6	6
	Nutrient cycling (more extremes)	4	6	6
	Exposure score	***5.0***	***5.8***	***5.3***
Sensitivity	Changes in plankton productivity—extent, timing, and location	5	6	6
	Changes in larval survival	5	6	6
	Decreases in larval growth and development	5	6	6
	Changes in species ranges	3	3	3
	Altered physiology	4	7	7
	Altered habitats	3	6	7
	Changes in species tolerance ranges	3	5	5
	Disrupted larval transport	4	5	5
	Compromised reproductive performance	3	5	5
	Sensitivity score	***3.9***	***5.4***	***5.6***
Adaptive capacity	Stock status	2	4	4
	Reproductive potential	2	2	3
	Species range	2	2	3
	Species mobility	3	5	5
	Pollution	2	6	5
	Governance	2	2	2
	Resource dependence	6	1	3
	Alternative livelihoods/species	2	2	5
	Adaptive capacity score	***2.6***	***3.0***	***3.8***
	Vulnerability index	**3.8**	**4.7**	**4.9**

In contrast, the MCF was assessed as less vulnerable but had a higher exposure score, thus providing guidance on research directions of interest, such as examination of the exposure variables that were ranked as 'very likely' to determine a more exact probability.

This approach can be used to assess the relative vulnerability of fisheries anywhere and provides a mechanism for identifying fisheries with high vulnerability to climate change and drivers of this vulnerability that is transparent to stakeholders. Highly vulnerable marine fisheries are likely to be primarily those of developing or small nations that have weak social and economic indices and be data limited, further challenging sustainable fisheries management. Vulnerability will be exacerbated in poor and marginalized groups as climate change will heighten already weak social and economic circumstances, such as unequal access to natural resources and low incomes (Cochrane et al., 2009). Generally, selection of appropriate management options will be influenced by the capacity of the fishery or nation to adapt to climate change. The assessment approach provides information on adaptive capacity and which variables are compromising this capacity, and can inform the selection of key targets for action. The future management options described below are therefore broadly categorized based on the adaptive capacity of the fishery.

MARINE FISHERIES MANAGEMENT

Future Options and Barriers

To date, the largely 'invisible' and relatively slow response of oceans to climate change has resulted in fairly generic policy and management recommendations. In addition, the inherent uncertainties about future climate scenarios and how systems will respond make translating the science into specific regional or sectoral predictions particularly difficult. Faced with these challenges, management has focused on awareness raising, habitat protection, and a call for better information. By assessing the vulnerability of marine fisheries to climate change, and identifying the key areas of this vulnerability, management can use a risk-based approach to target more immediate, specific, and practical management options for fisheries.

While fisheries managers cannot directly mitigate climate change, and climate change cannot be fully averted, there is an urgent need to reduce existing pressures on fisheries that undermine the resilience of fisheries to future change, and to facilitate adaption to inevitable change. The main drivers of vulnerability are, in many cases, the main barriers to fisheries adaptation. That is (i) overexploitation, (ii) weak social and economic indices, and (iii) reliance on fisheries for national economies and/or a primary source of dietary protein by rapidly growing populations. This vulnerability is heightened if the fishery relies on fish stocks that are highly exposed and sensitive to climate change. Therefore, subsistence and artisanal fisheries and fisheries that are already overexploited have the greatest vulnerability and will require significant focus to ensure their future sustainability in the face of climate change.

A portfolio of strategies for marine fisheries that address key factors that limit adaptive capacity and increase vulnerability are needed to cope with uncertainty in projected climate scenarios and allow for iterative responses to future change. That is, strategies to reduce exposure of fisheries to climate risks, reduce dependence on climate-sensitive resources, enhance socioeconomic resilience, and improve sustainability of fisheries, particularly those already overexploited. Many of these options are extensions or enhancements of existing activities or existing 'best management' approaches, and can be based to some degree on the way fisheries and communities have coped with the consequences of past climate variations (Hannesson, 2007a).

However, different fisheries will have different barriers to adaptation, and fisheries management can be targeted toward actions that are (i) broadly applicable to fisheries in all nations, (ii) applicable to fisheries with moderate to high adaptive capacity, and (iii) applicable to fisheries with low adaptive capacity (Table 4). Although fisheries of developing nations are most likely to have low adaptive capacity, any fishery that has limited opportunities for change, or where there are political and institutional barriers to change, will face the same consequences as a result of climate change. Importantly, implementing effective management strategies for fisheries with low adaptive capacity will require assistance from nations with the resources and expertise to facilitate change. In the examples provided in Table 3, the fishery assessed to have the highest vulnerability (ECTF) would be classified as a fishery with moderate to high adaptive capacity, based on global standards. This directs managers to implement management strategies under options A and B (Table 4), with consideration of local, regional, and national imperatives that focuses management effort at key targets for action that suit the adaptive capacity of their particular fishery.

Key Targets for Action

Broad Strategies: In All Nations

Effective fisheries management in the face of climate change should *preserve age and geographic structure* of populations (to sustain resilience) rather than simply managing biomass. Current management of many global fisheries exposes populations to a high risk of collapse, given the trend in climate and uncertainty over impacts (Brander, 2007). With overexploited fisheries having a reduced ability to adapt to future change, sustainable fishing levels need to be reviewed and adjusted to incorporate climate change effects on age and geographic structure, as well as productivity. By incorporating climate projections of direction, and if available, magnitude of change into stock assessments and regulations, fisheries are given a chance to recover from depletion and adapt to further perturbations. Uncertainties about climate projections and system response will pose challenges to this strategy. However, adopting a

Table 4 Summary of suggested management options for coping with climate induced changes to fisheries. Options are based on the adaptive capacity of the fishery: A. *Broad* management strategies that fisheries in all nations can adopt; B. Strategies for fisheries with *moderate to high adaptive capacity*; and C. Strategies for fisheries with *low adaptive capacity*. It is acknowledged that low adaptive capacity fisheries may require assistance with implementing management changes depending on their resource and expertise base

Fishery types	Management approaches
A. Broad: In all nations	• Preservation of age structures across geographic ranges - Promote population resilience • Facilitation of flexible (adaptive) management - To respond to fishery behavioral changes and to allow changes in fishery behavior to occur - Requires regulatory and administrative changes - Requires greater co-operation within and between nations • Integration of social, economic and ecological values - Utilization of decision frameworks to assess ‘trade-offs’ - Identify adaptation options and opportunities • Long term outlook by regulators (paradigm shift required) • Reduce overcapacity
B. Moderate to high adaptive capacity	• Adoption of precautionary catch and/or effort quotas - Requires a paradigm shift for fisheries • Differential management for different ecological roles
C. Low adaptive capacity	• Build social and economic resilience • Diversification to multi-species utilization • Facilitation of greater access to markets • Promotion of flexible livelihood strategies, e.g., Combine fishing and agriculture based on seasonality, etc. • Facilitation and implementation of institutional change - Cultural and paradigm shifts - Long-term outlook - Cooperative approaches - International assistance • Implementation assistance required from nations with resources and expertise

risk-based approach that focuses on the range of plausible impacts that could occur is one mechanism for dealing with this uncertainty.

Due to this inherent uncertainty, *more flexible management* that enhances current fisheries approaches to cope with adverse conditions allows for nonlinear or unpredictable change, and uses fisheries data to be iterative and adjust to ongoing change is essential. By allowing fisheries to respond (rapidly) to the threats and benefits of future climate variability, their vulnerability is reduced and managers can learn which adaptations work well, which do not, and why. As the spatial and temporal conditions of marine fisheries resources change, so too will fishing operations that have to respond by changing their activities to match future changes in abundance, distribution, and access. For example, full-time fishers from the Java Sea track variations in fish stock distribution through inter-island and longshore migrations and adapt their operation (Allison and Ellis, 2001), thereby reducing their exposure and sensitivity to resource changes.

This type of strategy requires policy and regulatory changes that allow for responsiveness in the fishery (Miller, 2007), and sufficient data that can be analyzed to understand what management actions are effective and to learn from different responses. Collecting sufficient monitoring data to inform adaptive management will be a challenge for some fisheries but in Cree fishing communities in northern Canada, local knowledge and experiences have been shown to be sufficient to make management adjustments in response to change. These subsistence fisheries have implemented a flexible approach with no rigid territorial system, thus allowing greater movement in catch distribution to maximize yield, and use gear limited to small units to maintain mobility and responsiveness (Allison and Ellis, 2001). A similar adaptive approach has been adopted in Palau, Micronesia, an area that has sustained climate-sensitive fisheries for decades. Again, the territorial system is flexible, with land and sea tenure integrated and redistribution of fishing rights among neighboring municipalities according to needs and abundance. Fishing in inland lagoons is limited to when bad weather prevents fishing in the open sea, and in times of local scarcity, access to neighboring community-controlled fishing grounds in exchange for part of the catch is instigated (Allison and Ellis, 2001).

To implement such a flexible and adaptive strategy in fisheries would require not only regulatory change but a paradigm shift in management objectives. This type of cooperative approach would not only benefit climate-sensitive fisheries but also those that cross jurisdictions to allow for effective adaptation options for shared fisheries stocks. For example, *co-management* and *multi-jurisdictional* management to protect deep water environments, high seas fisheries, and biodiversity hotspots that form the basis of many fisheries worldwide would require such a flexible and cooperative approach (Hannesson, 2007a). By adopting ecologically meaningful boundaries for common fisheries, fishing interests can move within and across national boundaries to respond to changes in resource distribution and abundance, which will be particularly important for straddling stocks, migratory and high seas fisheries in a changing climate. Clearly, this requires a high level of cooperation between nations and fishing interests (Miller, 2007), and there is likely to be resistance from some areas as trade-offs in access and catch levels are inevitable. However, without a unified and multilateral approach, these fisheries will remain some of the most vulnerable to future climate change in the world.

Ultimately, adaptive fisheries management in a changing climate will require trade-offs between social, economic and ecological values, and a willingness to act in the face of uncertainty. Development of regional or fisheries specific *integrated management systems* that reflect these unavoidable 'trade-offs' and provide a series of adaptation options based on conditions or resource changes will enhance the capacity of fisheries managers to deal with uncertainty and respond in the face of an unknown future. Decision frameworks should support climate change adaptation options that have the greatest overall 'benefits' while minimizing 'costs' and being responsive to inevitable change in the ecosystem or stock. These types of decision-support frameworks have been used extensively in other arenas, such as natural disaster management, and are effective at identifying and minimizing risk and enhancing opportunities where they occur (Chellis et al., 2003; Shorten et al., 2003; Buika et al., 2005; Goosby et al., 2005).

One of the biggest issues facing many fisheries and their long term sustainability is overcapacity. Pauly et al. (2002) present strong arguments in their claim that unless strong management decisions are made in *reducing fishing effort*, then there will be more fisheries collapses globally. Once again this highlights the need for a fisheries management paradigm shift.

High Adaptive Capacity Strategies

While implementing sustainable fishing levels is essentially enhancing current 'best practices' and not necessarily climate change specific, fisheries that have the greatest ability to adapt would benefit from incorporating larger 'safety margins' into harvest and/or effort levels. This would provide insurance from greater climate and stock variability, allow for uncertainty about climate change impacts on fisheries, and allow for unpredictable or non-linear change. This strategy requires a shift from managing for economic profit to managing for ecological stability by incorporating all ecological variables, including climate change (Harley et al., 2006), into stock assessments and managing for future reductions or changes in stocks.

This is essentially allocating a *climate change catch quota* that can be implemented over time to reduce catch quotas given to fishers as stocks decline with climate change. Other environmental management arenas have implemented a similar approach, for example, the allocation of water for environmental river flows with reduced irrigator allowances to protect the ecological integrity of the river system, particularly as climate change begins to affect rainfall frequency and quantity (ANZECC, 2000).

It is possible to take this approach one step further, by considering the *changing ecosystem role* of target species when setting fisheries quotas and allowing for future higher protection of species that will have increasing ecological importance under a changing climate regime. For example, the increasing importance of predators controlling herbivorous fish that graze kelp—already stressed and in decline due to increasing sea temperatures—may warrant greater protection of predators in fisheries in or adjacent to kelp forests (Hobday et al., 2006).

Low Adaptive Capacity Strategies

Fisheries with limited scope to adapt to change are unlikely to cope with reductions in catch quotas or for that matter, diminishing fish stocks due to climate change. Therefore, fundamental strategies for these fisheries are those that facilitate *social resilience* of fishing communities by addressing other drivers of vulnerability; factors such as poverty, resource reliance, and resource depletion. There are a number of actions specific to marine fisheries that can reduce resource reliance or resource depletion, such as diversification, flexible livelihood strategies, and increased access to markets.

Fisheries management actions that decrease reliance on single fish stocks will build their resilience to change in the stock, particularly of climate-sensitive stocks. *Diversifying* to multispecies fisheries will make them more resilient to environmental change and future uncertainty than highly specialized fisheries (Worm et al., 2006; Worldfish, 2007). This may be achieved through actions that encourage landing 'discards' and by-catch in commercial fisheries to provide an alternative fish source for local communities, or substituting target species to take advantage of fish species that benefit from climate change in the short-term (high turnover species) providing opportunities to reduce fisheries vulnerability to future change. Alternatively, flexible livelihood strategies that combine a range of food production systems based on resource availability and condition, such as combining fishing, aquaculture, and agriculture (Cochrane et al., 2009) or changing the seasonal patterns of fishing activities. This has been successfully employed in artisanal fisheries in West Java, Indonesia where households switch between rice-farming, tree cropping, and fishing in response to fish stock variations (Allison and Ellis, 2001). Similarly, artisanal fishers in northeast Spain only fish seasonally when stocks are abundant to supplement their income (Allison and Ellis, 2001).

These types of flexible livelihood strategies require *institutional change* that will establish adaptive fishing rights, shared fishing rights, and maintain fish catches in vulnerable regions for food security. This requires international cooperation as well as a shift away from managing for short-term economic profit and facilitating reductions in the national economic reliance on fisheries exports. That is, reposition fisheries management objectives to increase adaptive capacity of fisheries thereby ensuring long-term ecological and economic sustainability, rather than traditional management that aims to maximize short-term yields and profit. This type of approach may require commercial fisheries restructures or financial incentives to retain by-catch and share fish stocks between and among nations. For example, in the Peruvian sardine and anchoveta fishery, the government has implemented regulations that ban commercial fishing during periods of resource scarcity, allowing recovery of fish stocks (Broad et al., 2002). Countries with national economies that depend heavily on their commercial fisheries will be constrained in their ability to implement such a strategy. However, to protect the long-term sustainability of important fish stocks under a regime of change and uncertainty, facilitating recovery and enhancing their resilience will be a key management responsibility.

Building social and economic resilience is the most challenging of all strategies and one that is not specific to climate change. However, if successful, it is likely to be the most effective mechanism for reducing vulnerability to future change and uncertainty, and providing for sustainable marine capture fisheries into the future.

CONCLUSIONS

Marine capture fisheries worldwide are at risk from the effects of climate change. This is due to the high exposure and sensitivity of many fisheries stocks to changes in climate drivers and compromised adaptive capacity. Climate impacts will further exacerbate existing pressures on the world's marine fisheries, such as overexploitation and marine pollution, and, therefore, immediate action is required. Simple processes and approaches for assessing vulnerability in a data-limited environment are needed that are transparent and locally relevant (Miller, 2007) so that appropriate fisheries management can be implemented in a timely manner. Fisheries of small, poorly resourced developing nations will be most vulnerable to climate change, ironically those nations that are least able to take affirmative action. It is, therefore, imperative that developed nations step in to assist these nations in assessing vulnerability and implementing regionally-focused plans of action.

Climate change provides an unprecedented opportunity to challenge the conventional thinking and evaluate fisheries management with a fresh perspective and a longer-term view. The ability of management to adapt to climate change will be critical to the future of marine capture fisheries, and for the social and economic values these fisheries provide, particularly in developing nations. While science is providing important insights about the impacts of climate change on marine resources, effective management strategies in a changing climate need to be well-resourced, responsive, bold, and multilateral. As climate change places additional pressure on already strained fisheries productivity, a new management paradigm needs to consider social resilience, be effective under data limited circumstances, manage for long-term ecological and economic stability, and set aside traditional boundaries. Although some degree of change in marine fisheries is inevitable, the extent of that change will depend not only on mitigation but on how rapidly fisheries management can respond and how flexible it can be.

ACKNOWLEDGMENTS

We thank Bruce Mapstone, Johann Bell, and Colin Simpfendorfer for their insightful and thoughtful comments on the draft manuscript. We would also like to thank the Fishing and Fisheries Research Centre, the Queensland Department of Primary Industries and Fisheries, and C_2O–coasts climate oceans, for their support in undertaking this assessment. We also acknowledge and greatly appreciate the insightful comments of the two reviewers, which greatly improved the manuscript.

REFERENCES

Adger, W. N., T. P. Hughes, C. Folke, S. R. Carpenter, and J. Rockstrom. Social-ecological resilience to coastal disasters. *Science*, **309:** 1036–1039 (2005).

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

Allison, E. H., W. N. Adger, and M. C. Badjeck. *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*. DFID Fisheries Management Science Programme Summary Report, Norwich, UK (2005).

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

Anon. *Queensland Fisheries annual status reports 2006*. Department of Primary Industries and Fisheries Report, Brisbane, Australia, p. 331 (2007).

Armsworth, P. R. Modeling the swimming response of late stage larval reef fish to different stimuli. *Marine Ecol. Prog. Ser.*, **195:** 231–247 (2000).

Arnason, R. Climate change and fisheries: Assessing the economic impact in Iceland and Greenland. *Nat. Res. Model.*, **20:** 163–197 (2007).

Australia and New Zealand Environment and Conservation Council (ANZECC). *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*. Canberra, Australian Government (2000).

Bell, J. D., M. Kronen, A. Vunisea, et al. Planning the use of fish for food security in the Pacific. *Marine Pol.*, **33:** 64–76 (2009).

Booth, D. J., and G. A. Beretta. Changes in a fish assemblage after a coral bleaching event. *Marine Ecol. Prog. Ser.*, **245:** 205–212 (2002).

Boyce, D. G., D. P. Tittensor, and B. Worm. Effect of temperature on global patterns of tuna and billfish richness. *Marine Ecol. Prog. Ser.*, **355:** 267–276 (2008).

Brander, K. M., and R. K. Mohn. Effect of the North Atlantic Oscillation of recruitment of Atlantic cod (*Gadus morhua*). *Canad. J. Fisher. & Aquat. Sci.*, **61:** 1558–1564 (2004).

Brander, K. M. Global fish production and climate change. *Proc. Natl. Acad. Sci. USA*, **104:** 19709–19714 (2007).

Brierley A. S., and M. J. Kingsford. Impacts of climate change on marine organisms and ecosystems. *Curr. Biol.*, **19:** R602–R614 (2009).

Broad, K., A. S. P. Pfaff, and M. H. Glantz. Effective and equitable dissemination of seasonal-to-interannual climate forecasts: Policy implications from the Peruvian fishery during El Niño 1997–98. *Climat. Change*, **54:** 415–438 (2002).

Brunel, T., and J. Boucher, J. Long-term trends in fish recruitment in the northeast Atlantic related to climate change. *Fisher. Oceanogr.*, **16:** 336–349 (2007).

Buika, J., S. Goosby, S. Mielbrecht, et al. A United States-Japan-Philippines collaborative planning process to implement a multi-hazard, urban risk reduction strategy for Marikina City, Philippines. *Proceedings, First International Conference on Urban Disaster Reduction*, Kobe, Japan, 18–20 January (2005).

Burgess, S. C., M. J. Kingsford, and M. P. Black. Influence of tidal eddies and wind on the distribution of pre-settlement fishes around One Tree Island, Great Barrier Reef. *Marine Ecol. Prog. Ser.*, **341:** 233–242 (2007).

Caldeira, K., A. K. Jain, and M. I. Hoffert. Climate sensitivity uncertainty and the need for energy without CO_2 emissions. *Science*, **299:** 2052–2054 (2003).

Cesar, H., L. Burke, and L. Pet-Soede. *The Economics of Worldwide Coral Reef Degradation*. The Netherlands, Cesar Environmental Economics Consulting (2003).

Chellis, C., C. Chiesa, and R. Shirkhodai. *Integrated decision support system architecture study*. Report prepared for the U.S. Southern Command Humanitarian Assistance Program, Pacific Disaster Center, Honolulu, Hawaii (2003).

Cheung, W. W. L., V. W. Y. Lam, J. L. Sarmiento, K. Kearney, R. Watson, and D. Pauly. Projecting global marine biodiversity impacts under climate change scenarios. *Fish & Fisher.* (2009). DOI: 10.1111/j.1467-2979.2008.00315

Church, J. A., and N. J. White. A 20th century acceleration in global sea level rise. *Geophys. Res. Lett.*, **33:** L01602 (2006).

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

Condrey, R., and D. Fuller. The US Gulf shrimp fishery. **In:** *Climate Variability, Climate Change and Fisheries* (Glantz, M. H., Ed.). New York, USA: Cambridge University Press, pp. 89–96 (1992).

Cowen, R. K., C. B. Paris, and A. Srinivasan. Scaling of connectivity in marine populations. *Science*, **311:** 522–527 (2006).

Daskalov, G. M., A. N. Grishin, S. Rodionov, and V. Mihneva. Trophic cascades triggered by overfishing reveal possible mechanisms of ecosystem regime shifts. *Proc. Natl. Acad. Sci. USA*, **104:** 10518–10523 (2007).

Dayton, P. K., S. Thrush, and F. C. Coleman. *Ecological effects of fishing in marine ecosystems of the United States*. PEW Oceans Commission Report, Arlington, VA, USA (2002).

Edgar, G. J. *Australian Marine Life: The Plants and Animals of Temperate Waters*. Sydney: Reed New Holland, NSW (1997).

Edwards, M., and A. J. Richardson. Impact of climate change on marine pelagic phenology and trophic mismatch. *Nature*, **430:** 881–884 (2004).

Ellingsen, I. H., P. Dalpadado, D. Slagstad, and H. Loeng. Impact of climatic change on the biological production in the Barents Sea. *Climatic Change*, **87:** 155–175 (2008).

Engel, J., and R. Kvitek. Effects of otter trawling on a benthic community in Monterey Bay National Marine Sanctuary. *Conserv. Biol.*, **12:** 1204–1214 (1998).

Frank, K. T., B. Petrie, J. S. Choi, and W. C. Leggett. Trophic cascades in a formerly cod-dominted ecosystem. *Science*, **308:** 1621–1623 (2005).

Friedland, K. D., D. G. Reddin, J. R. McMenemy, and K. F. Drinkwater. Multidecadal trends in North American salmon (*Salmo salar*) stock and climate trends relevant to juvenile survival. *Canad. J. Fisher. & Aquat. Sci.*, **60:** 563–583 (2003).

Food and Agriculture Organization of the United Nations (FAO). *The state of world fisheries and aquaculture (SOFIA) 2006*. Rome: United Nations Report (2006).

Food and Agriculture Organization of the United Nations (FAO). *Adaptation to climate change in agriculture, forestry and fisheries: perspective, framework and priorities*. Interdepartmental Working Group on Climate Change, Rome: United Nations Report. Available from ftp://ftp.fao.org/docrep/fao/009/j9271e/j9271e.pdf (2007). Retrieved July 28, 2009.

Food and Agriculture Organization of the United Nations (FAO). *The state of world fisheries and aquaculture (SOFIA) 2008*. Rome: United Nations Report. Available from http://www.fao.org/docrep/011/i0250e/i0250e00.htm (2008a). Retrieved July 28, 2009.

Food and Agriculture Organization of the United Nations (FAO). *Building adaptive capacity to climate change: Policies to sustain livelihoods and fisheries*. New directions in fisheries: A series of policy briefs on developmental issues. No 8. Rome: United Nations Report. Available from www.sflp.org/briefs/eng/policybriefs.html (2008b). Retrieved July 28, 2009.

Garcia, S. M., and R. J. R. Grainger. Gloom and doom? The future of marine capture fisheries. *Philos. Trans. Royal Soc.*, **360:** 21–46 (2005).

Gardner, T. A., I. M. Côté, J. A. Gill, A. Grant, and A. R. Watkinson. Long-term region-wide declines in Caribbean corals. *Science*, **301:** 958–960 (2003).

Gaydos, J. *Northern Abalone Scientific Session and Recovery Workshop*. Vancouver: The Seadoc Society (2007).

Goosby, S., C. Chiesa, S. Mielbrecht, and T. Bosse. Assessing and reducing the impacts of disasters in the Asia Pacific Region. *Proceedings, First International Conference on Urban Disaster Reduction*, Kobe, Japan, 18–20 January (2005).

Green, B. S., and R. Fisher. Temperature influences swimming speed, growth and larval duration in coral reef fish larvae. *J. Experi. Marine Biol. & Ecol.*, **299:** 115–132 (2004).

Hannesson, R. Introduction: Climate change and fisheries [Special issue]. *Marine Pol.*, **31:** 1–4 (2007a).

Hannesson, R. Geographical distribution of fish catches and temperature variations in the northeast Atlantic since 1945. *Marine Pol.*, **31:** 32–39 (2007b).

Hansen, J. Huge sea level rises are coming—Unless we act now. *New Scientist*, **2614:** 30–33 (2007).

Harley, C. D. G., R. A. Hughes, K. M. Hultgren, B. G. Miner, C. J. B. Sorte, C. S. Thornber, L. F. Rodriguez, L. Tomanek, and S. L. Williams. The impacts of climate change in coastal marine systems. *Ecol. Lett.*, **9:** 228–241 (2006).

Hays, G. C., A. J. Richardson, and C. Robinson. Climate change and marine plankton. *Trends Ecol. & Evol.*, **20:** 337–344 (2005).

Heithaus, M. R., A. Frid, A. J. Wirsing, and B. Worm. Predicting ecological consequences of marine top predator declines. *Trends Ecol. & Evol.*, **23:** 202–210 (2008).

Hiddink, J. G., S. Jennings, M. J. Kaiser, A. M. Queiros, D. E. Duplisea, and G. J. Piet. Cumulative impacts of seabed trawl disturbance on benthic biomass, production, and species richness in different habitats. *Canad. J. Fisher. & Aquat. Sci.*, **63:** 721–736 (2006).

Hixon, M. A., and B. N. Tissot. Comparison of trawled versus untrawled mud seafloor assemblages of fishes and macroinvertebrates at Coquille Bank, Oregon. *J. Experi. Marine Biol. & Ecol.*, **344:** 23–34 (2007).

Hobday, A. J., and M. J. Tegner. The warm and the cold: Influence of temperature and fishing on local population dynamics of red abalone. *CalCOFI Rep.*, **43:** 74–96 (2002).

Hobday, A. J., T. A. Okey, E. S. Poloczanska, T. J. Kunz, and A. J. Richardson. *Impacts of climate change on Australian marine life*. Report prepared by CSIRO Marine and Atmospheric Research for the Australian Greenhouse Office, Canberra, Australian Government (2006).

Hobday, A. J., E. S. Poloczanska, and R. J. Matear (Eds.). *Implications of climate change for Australian fisheries and aquaculture: A preliminary assessment*. Report to the Department of Climate Change, Canberra (2008).

Hoegh-Guldberg, O., K. Anthony, R. Berkelmans, et al. The vulnerability of reef building corals on the Great Barrier Reef to climate change. In: *Climate Change and the Great Barrier Reef: A Vulnerability Assessment,* 1st Edition (Johnson, J. E., and P. A. Marshall, Eds.), Townsville, Australia: Great Barrier Reef Marine Park Authority (2007a).

Hoegh-Guldberg, O., P. J. Mumby, A. J. Hooten, et al. Coral reefs under rapid climate change and ocean acidification. *Science*, **318:** 1737–1742 (2007b).

Hughes, T. P., A. H. Baird, D. R. Bellwood, et al. Climate change, human impacts, and the resilience of coral reefs. *Science*, **301:** 929–933 (2003).

Hutchings, J. A. Influence of population decline, fishing, and spawner variability on the recovery of marine fishes. *J. Fish Biol.*, **59:** 306–322 (2001).

Hutchings, P., S. Ahyong, M. Byrne, R. Przeslawski, and G. Wörheide. Vulnerability of benthic invertebrates of the Great Barrier Reef to climate change. **In:** *Climate Change and the Great Barrier Reef: A Vulnerability Assessment,* 1st Edition (Johnson, J. E., and P. A. Marshall, Eds.). Townsville, Australia: Great Barrier Reef Marine Park Authority and Australian Greenhouse Office (2007).

Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2007: The Physical Science Basis*. Geneva: IPCC Secretariat (2007).

Jackson, J. B. C., M. X. Kirby, W. H. Berger, et al. Historical overfishing and the recent collapse of coastal ecosystems. *Science*, **293:** 629–637 (2001).

James, M. K., P. R. Armsworth, L. B. Mason, and L. Bode. The structure of reef fish metapopulations: Modeling larval dispersal and retention patterns. *Proc. Royal Soc. London*, **269:** 2079–2086 (2002).

Johnson, J. E., and P. A. Marshall (Eds.). *Climate Change and the Great Barrier Reef: A Vulnerability Assessment,* 1st edition. Townsville, Australia: Great Barrier Reef Marine Park Authority and Australian Greenhouse Office (2007).

Jones, G. P., M. I. McCormick, M. Srinivasan, and J. V. Eagle. Coral decline threatens fish biodiversity in marine reserves. *Proc. Natl. Acad. Sci.*, **101:** 8251–8253 (2004).

Kennedy, V. S., R. R. Twilley, J. A. Kleypas, J. H. Cowan, and S. R. Hare. *Coastal and marine ecosystems and global climate change: Potential effects on US resources*. Report prepared for the Pew Center on Global Climate Change (2002).

Kingsford, M. J., and D. J. Welch. The vulnerability of pelagic ecosystems in the Great Barrier Reef to climate change. **In:** *Climate Change and the Great Barrier Reef: A Vulnerability Assessment,* 1st Edition (Johnson, J. E., and P. A. Marshall, Eds.). Townsville, Australia: Great Barrier Reef Marine Park Authority (2007).

Kleypas, J. A., R. A. Feely, V. J. Fabry, C. Langdon, C. L. Sabine, and L. L. Robbins. Impacts of ocean acidification on coral reefs and other marine calcifiers: A guide for future research. Report of the Ocean Acidification Workshop—The 11th International Coral Reef Symposium in Ft. Lauderdale, FL on 9 July 2008, sponsored by NSF, NOAA, and the U.S. Geological Survey (2006).

Klyashtorin, L. B., and A. A. Lyubushin. *Cyclic climate changes and fish productivity*. Moscow, Russia: VNIRO Publishing. ISBN 5-85382-212-8 (2005).

Koslow, T., and R. Thresher. *Climate and fisheries on the southeast Australian continental shelf and slope*. CSIRO Marine Research Report. (1996).

Kurihara, H., S. Shimode, and Y. Shirayama. Sub-lethal effects of elevated concentration of CO_2 on planktonic copepods and sea urchins. *J. Oceanogr.*, **60:** 743–750 (2004).

Larcombe, J., and K. McLaughlin (Eds.). *Fishery status reports 2006: Status of fish stocks managed by the Australian Government*. Australian Government Department of Agriculture, Fisheries and Forestry, Bureau of Rural Sciences, Canberra (2006).

Last, P. R., W. T. White, D. C. Gledhill, A. J. Hobday, R. Brown, G. J. Edgar, and G. T. Pecl. Long-term shifts in abundance and distribution of a temperate fish fauna: A response to climate change and fishing practices. *Global Ecol. & Biogeogr.* (In review; submitted August 2009).

Law, R., and K. Stokes. Evolutionary impacts of fishing on target populations. **In:** *Marine Conservation Biology: The Science of Maintaining the Sea's Biodiversity* (Norse, E. A., and L. B. Crowder, Eds.). Washington, DC: Island Press, pp. 232–246 (2005).

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

Lehodey, P., J. Alheit, M. Barange, T. Baumgartner G. Beaugrand, K. Drinkwater, J.-M. Fromentin, S. R. Hare, G. Ottersen, R. I. Perry, C. Roy, C. D. van der Lingen, and F. Werner. Climate variability, fish and fisheries. *J. Climate*, **19:** 5009–5030 (2006).

Ling, S. D., C. R. Johnson, K. Ridgway, A. J. Hobday, and M. Haddon. Climate driven range extension of a sea urchin: Inferring future trends by analysis of recent population dynamics. *Global Change Biol.*, **15:** 719–731 (2009).

Lotze, H. K., H. S. Lenihan, B. J. Bourque, et al. Depletion, degradation, and recovery potential of estuaries and coastal seas. *Science*, **312:** 1806–1809 (2006).

Lough, J. Climate and climate change on the Great Barrier Reef. **In:** *Climate Change and the Great Barrier Reef: A Vulnerability Assessment,* 1st Edition (Johnson, J. E., and P. A. Marshall, Eds.). Townsville, Australia: Great Barrier Reef Marine Park Authority (2007).

Luthi, D., M. L. Floch, B. Bereiter, T. Blunier, J.-M. Barnola, U. Siegenthaler, D. Raynaud, J. Jouzel, H. Fischer, K. Kawamura, and T. F. Stocker. High-resolution carbon dioxide concentration record 650,000–800,000 years before present. *Nature*, **435** (2008). DOI:10.1038/nature06949

Lyne, V., N. Klaer, P. Last, and G. Yearsley. *Economic analysis of identified impacts of climate change: Marine impacts*. CSIRO Marine Research Report prepared for the Australian Greenhouse Office, Canberra (2003).

MacKenzie, B. R., H. Gislason, C. Mollmann, and F. W. Koster. Impact of 21st century climate change on the Baltic Sea fish community and fisheries. *Global Change Biol.*, **13:** 1348–1367 (2007).

McClanahan, T., J. Maina, and L. Pet-Soede. Effects of the 1998 coral mortality event on Kenyan coral reefs and fisheries. *Ambio* **31**: 543–550 (2002).

McCook, L. J. Macroalgae, nutrients and phase shifts on coral reefs: Scientific issues and management consequences for the Great Barrier Reef. *Coral Reefs*, **18:** 357–367 (1999).

McKinnon, A. D., A. J. Richardson, M. A. Burford, and M. J. Furnas. Vulnerability of plankton on the Great Barrier Reef to climate change. **In:** *Climate Change and the Great Barrier Reef: A Vulnerability Assessment,* 1st Edition (Johnson, J. E., and P. A. Marshall). Townsville, Australia: Great Barrier Reef Marine Park Authority (2007).

McNeil, B. I., and R. J. Matear. Climate change feedbacks on future oceanic acidification. *Tellus Ser. B Chem. & Phys. Meteor.*, **59:** 191–198 (2007).

Meekan, M. G., J. H. Carleton, A. D. McKinnon, K. Flynn, and M. Furnas. What determines the growth of tropical reef fish larvae in the plankton: Food or temperature? *Marine Ecol. Prog. Ser.*, **256:** 193–204 (2003).

Miller, K. A. Climate variability and tropical tuna: Management challenges for highly migratory fish stocks. *Marine Pol.*, **31:** 56–70 (2007).

Morato, T., W. W. L. Cheung, and T. J. Pitcher. Vulnerability of seamount fish to fishing: Fuzzy analysis of life-history attributes. *J. Fish Biol.*, **68:** 209–221 (2006).

Mumby, P. J., C. P. Dahlgren, A. R. Harborne, et al. Fishing, trophic cascades and the process of grazing on coral reefs. *Science*, **311:** 98–101 (2006).

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

Munday, P. L., G. P. Jones, M. Sheaves, A. J. Williams, and G. Goby. Vulnerability of fishes on the Great Barrier Reef to climate change. **In:** *Climate Change and the Great Barrier Reef: A Vulnerability Assessment,* 1st Edition (Johnson, J. E., and P. A. Marshall). Townsville, Australia: Great Barrier Reef Marine Park Authority (2007).

Munday, P. L., G. P. Jones, M. S. Pratchett, and A. J. Williams. Climate change and the future of coral reef fishes. *Fish & Fisher.*, **9**: 1–25 (2008).

Munday, P. L., D. L. Dixson, J. M. Donelson, G. P. Jones, M. S. Pratchett, G. V. Devitsina, and K. B. Doving. Ocean acidification impairs olfactory discrimination and homing ability of a marine fish. *Proc. Natl. Acad. Sci.* **106**: 1848–1852 (2009).

Nakicenovic, N., and R. Swart (Eds.). *IPCC special report on emission scenarios*. Cambridge: Cambridge University Press (2000).

O'Connor, M. I., J. F. Bruno, S. D. Gaines, et al. Temperature control of larval dispersal and the implications for marine ecology, evolution, and conservation. *Proc. Natl. Acad. Sci. USA*, **104:** 1266–1271 (2007).

Ohman, M. C., P. L. Munday, G. P. Jones, and M. J. Caley. Settlement strategies and distribution patterns of coral-reef fishes. *J. Experi. Marine Biol. & Ecol.*, **225:** 219–238 (1998).

Parker, R. O., and R. L. Dixon. Reef faunal response to warming middle US continental shelf waters. *Amer. Fisher. Soc. Symp.*, **32:** 141–154 (2002).

Pauly, D., V. Christensen, S. Guénette, T. J. Pitcher, U. R. Sumaila, C. J. Walters, R. Watson, and D. Zeller. Towards sustainability in world fisheries. *Nature*, **418:** 689–695 (2002).

Pauly, D., J. Alder, E. Bennett, V. Christensen, P. Tyedmers, and R. Watson. The future for fisheries. *Science*, **302:** 1359–1361 (2003).

Perry, A. L., P. J. Low, J. R. Ellis, and J. D. Reynolds. Climate change and distribution shifts in marine fishes. *Science*, **308:** 1912–1915 (2005).

Poiner, I., C. Conacher, N. Loneragan, R. Kenyon, and I. F. Somers. *Effects of cyclones on seagrass communities and penaeid prawn stocks of the Gulf of Carpentaria*. Final Report, FRDC Projects 87/16 and 91/45. CSIRO Marine Laboratories. Cleveland, OH: CSIRO Division of Fisheries (1993).

Poloczanska, E. S., R. C. Babcock, A. Butler, et al. Climate change and Australian marine life. *Oceanogr. & Marine Biol. Ann. Rev.*, **45:** 409–480 (2007).

Poloczanska, E. S., A. J. Hobday, and A. J. Richardson. In hot water: Preparing for climate change in Australia's coastal and marine systems. Proceedings of *In Hot Water*, Brisbane, Australia, November 12–14, 2007. Available from http://www.cmar.csiro.au/climateimpacts/index.htm (2008). Retrieved August 12, 2009.

Pratchett, M. S., S. K. Wilson, and A. H. Baird. Declines in the abundance of Chaetodon butterfly fishes (Chaetodontidae) following extensive coral depletion. *J. Fish Biol.*, **69:** 1269–1280 (2006).

Pratchett, M. S., S. K. Wilson, and N. A. J. Graham. Coral bleaching and consequences for mobile reef organisms: Past, present and uncertain future. **In:** *Coral Bleaching: Patterns, Processes, Causes and Consequences* (Van Oppen, M., and J. Lough, Eds.). *Ecological Studies* **205.** Heidelberg: Springer (2008).

Rahmstorf, S. A semi-empirical approach to projecting future sea-level rise. *Science*, **315:** 368–370 (2007).

Ray, G. C., B. P. Hayden, A. J. J. Bulger, and M. G. McCormick-Ray. Effects of global warming on the biodiversity of coastal-marine zones. **In:** *Global Warming and Biological Diversity* (Lovejoy, T. E., and R. L. Peter, Eds.). New Haven, CT: Yale University, pp. 91–104 (1992).

Reynolds, J., N. Dulvey, N. Goodwin, and J. Hutchings. Biology of extinction risk in marine fishes. *Proc. Royal Soc. London Ser.*, **272:** 2337–2344 (2005).

Richardson, A. J., and D. S. Schoeman. Climate impact on plankton ecosystems in the Northeast Atlantic. *Science*, **305:** 1609–1612 (2004).

Roessig, J. M., C. M. Woodley, J. J. Cech, and L. J. Hansen. Effects of global climate change on marine and estuarine fishes and fisheries. *Rev. Fish Biol. & Fisher.*, **14:** 251–275 (2004).

Rogers-Bennett, L. Is climate change contributing to range reductions and localized extinctions in northern (Haliotis kamtschatkana) and flat (Haliotis walallensis) abalones? *Bull. Marine Sci.*, **81:** 283–296 (2007).

Rothlisberg, P., D. Staples, I. Poiner, and E. Wolanski. The possible impact of the greenhouse effect on commercial prawn populations in the Gulf of Carpentaria. **In:** *Greenhouse: Planning for Climate Change*. Melbourne, Australia: CSIRO Publications (1988).

Royal Society. *Ocean acidification due to increasing atmospheric carbon dioxide*. The Royal Society, Policy document 12/05 (2005).

Ruiz, G. M., J. T. Carlton, E. D. Grosholz, and A. H. Hines. Global invasions of marine and estuarine habitats by non-indigenous species: Mechanisms, extent and consequences. *Amer. Zool.*, **37:** 621–632 (1997).

Sabates, A., P. Martin, J. Lloret, and V. Raya. Sea warming and fish distribution: The case of the small pelagic fish, Sardinella aurita, in the western Mediterranean. *Global Change Biol.*, **12:** 2209–2219 (2006).

Sadovy, Y. Trouble on the reef: The imperative for managing vulnerable and valuable fisheries. *Fish & Fisher.*, **6:** 167–185 (2005).

Scavia, D., J. C. Field, D. F. Boesch, et al. Climate change impacts on US coastal and marine ecosystems. *Estuaries*, **25:** 149–164 (2002).

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

Schneider, S. H. The worst-case scenario. *Nature*, **458:** 1104–1105 (2009).

Schrank, W. E. The ACIA, climate change and fisheries. *Marine Pol.*, **31:** 5–18 (2007).

Schroter, D. and ATEAM Consortium. *Global change vulnerability—Assessing the European human-environment system*. Potsdam, Germany: Potsdam Institute for Climate Impact Research (2004).

Secretariat of the Pacific Community (SPC). Fisheries and aquaculture in our changing climate. *Policy Brief.* Available fromwww.spc.int/sppu/images/stories/multiagency%20policy%20brief.pdf (2009). Retrieved June 24, 2009.

Sir Alister Hardy Foundation for Ocean Science (SAHFOS). *Marine Climate Change Impacts Encyclopedia. Continuous Plankton Record in the North Atlantic and North Sea*. SAHFOS, Plymouth, UK (2006).

Shertzer, K. W., and M. H. Prager. Delays in fishery management: Diminished yield, longer rebuilding, and increased probability of stock collapse. *ICES J. Marine Sci.*, **64:** 149–159 (2007).

Shorten, G. G., S. Goosby, K. Granger, et al. *Developing risk-management options for disaster in the Pacific region*. SOPAC Joint Contribution Report 147, SOPAC Catastrophe Insurance Pilot Project, prepared for World Bank Office, Sydney and AusAID, Canberra (2003).

Sobel, J., and C. Dahlgren. *Marine Reserves: A Guide to Science, Design and Use*. Washington, DC: Island Press (2004).

Soto, C. G. The potential impacts of global climate change in marine protected areas. *Rev. Fish Biol. & Fisher.*, **11:** 181–195 (2002).

Steneck, R. S. Crustose corallines, other algal functional groups, herbivores and sediments: Complex interactions among reef productivity gradients. **In:** *Proceedings of the Eighth International Coral Reef Symposium*, Panama, June 24–29, 1997 (Lessios, H. A., and I. G. Macintyre, Eds.). Balboa: Smithsonian Tropical Research Institute, pp. 695–700 (1997).

Steneck, R. S., J. Vavrinec, and A. V. Leland. Accelerating trophic-level dysfunction in kelp forest ecosystems of the Western North Atlantic. *Ecosystems*, **7:** 323–332 (2004).

Steneck, R. S., and E. Sala. Large marine carnivores: Trophic cascades and top-down controls in coastal ecosystems past and present. **In:** *Large Carnivores and the Conservation of Biodiversity* (Ray, J., K. Redford, R. Steneck, and J. Berger, Eds.). Maine Sea Grant Program, Island Press, Washington, DC, pp. 110–137 (2005).

Stenevik, E. K., and S. Sundby. Impacts of climate change on commercial fish stocks in Norwegian waters. *Marine Pol.*, **31:** 19–31 (2007).

Syms, C., and G. P. Jones. Disturbance, habitat structure, and the dynamics of a coral-reef fish community. *Ecology*, **81:** 2714–2729 (2000).

Thrush, S. F., and P. K. Dayton. Disturbance to marine benthic habitats by trawling and dredging: Implications for marine biodiversity. *Ann. Rev. Ecol. & Syst.*, **33:** 449–473 (2002).

United Nations Environment Programme (UNEP). *The state of the marine environment—Trends and processes*. United Nations Environment Programme and the Global Programme of Action for the Protection of the Marine Environment from Land-based Activities, The Hague (2006a).

United Nations Environment Programme (UNEP). *In the front line: Shoreline protection and other ecosystem services from mangroves and coral reefs*. United Nations Report, The Hague (2006b).

United Nations Environment Programme (UNEP). *Global outlook for snow and ice.* United Nations Report, The Hague (2007).

United Nations Environment Programme (UNEP). *In dead water: Merging of climate change with pollution, over-harvest and infestations in the world's fishing grounds*. United Nations Report, The Hague (2008).

Walther, G. R., P. E. Convey, A. Menzel, et al. Ecological responses to recent climate change. *Nature*, **416:** 389–395 (2002).

Watling, L., and E. A. Norse. Disturbance of the seabed by mobile fishing gear: A comparison to forest clearcutting. *Conserv. Biol.*, **12:** 1180–1187 (1998).

Welch, D. W., Y. Ishida, and K. Naoa-Awa. Thermal limits and ocean migrations of sockeye salmon (Onchorynchus *nerka):* Long-term consequences of global warming. *Canad. J. Fisher. & Aquat. Sci.*, **55:** 937–948 (1998).

Wilkinson, C. R. *Status of Coral Reefs of the World*. United States Coral Reef Taskforce and Australian Institute of Marine Science. Townsville, Australia: Australian Institute of Marine Science. (2002).

Wilkinson, C. R. *Status of Coral Reefs of the World*. United States Coral Reef Taskforce and Australian Institute of Marine Science. Townsville, Australia: Australian Institute of Marine Science. (2004).

Wilkinson, C. R., and D. Souter. *Status of Caribbean coral reefs after bleaching and hurricanes in 2005*. Townsville, Australia: Global Coral Reef Monitoring Network and Reef and Rainforest Research Centre, 152 pp. (2008).

Wilson, D. T., and M. G. Meekan. Growth-related advantages for survival to the point of replenishment in the coral reef fish *Stegastes partitus* (Pomacentridae). *Marine Ecol. Prog. Ser.*, **23:** 247–260 (2002).

Wilson, S. K., N. A. J. Graham, M. S. Pratchett, G. P. Jones, and N. V. C. Polunin. Multiple disturbances and the global degradation of coral reefs: Are reef fishes at risk or resilient? *Global Change Biol.*, **12:** 2220–2234 (2006).

Worldfish Centre. The threat to fisheries and aquaculture from climate change. *Policy Brief.* Penang, Malaysia: The Worldfish Centre (2007).

Worm, B., E. B. Barbier, N. Beaumont, et al. Impacts of biodiversity loss on ocean ecosystem services. *Science*, **314:** 787–790 (2006).