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Climate change impacts on the biophysics and economics of world fisheries

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Global marine fisheries are underperforming economically because of overfishing, pollution and habitat degradation. Added to these threats is the looming challenge of climate change. Observations, experiments and simulation models show that climate change would result in changes in primary productivity, shifts in distribution and changes in the potential yield of exploited marine species, resulting in impacts on the economics of fisheries worldwide. Despite the gaps in understanding climate change effects on fisheries, there is sufficient scientific information that highlights the need to implement climate change mitigation and adaptation policies to minimize impacts on fisheries.

Gross revenues from marine capture fisheries worldwide are estimated at between US$80 billion and 85 billion annually[1–3]. As a primary industry[4], fisheries support the well-being of nations through direct employment in fishing, processing and ancillary services amounting to between US$220 billion and 235 billion annually in 2003 (ref. 5). Globally, fish provide nearly three billion people with 15% of their animal protein needs[1], and not only to people who reside in the 144 maritime countries of the world, as international fish trade has made fisheries truly global[6]. When post-harvest activities and workers' dependants are considered, the number of people directly or indirectly supported by marine fisheries is about 520 million, or nearly 8% of the world's population[1]. In most low- and middle-income maritime countries, fisheries employment is crucial as it provides some of the world's poorest with a cash income and nutrition, especially during times of economic hardship[7].

Global marine fisheries are underperforming, mainly because of overfishing, but also because of pollution and other anthropogenic causes[8–10]. Climate change will complicate the challenges currently facing global fisheries, as it has begun to alter ocean conditions, particularly water temperature and biogeochemistry. These changes are expected to affect the productivity of marine fisheries[11,12]. Preliminary results from recent studies estimate that climate change will lead to losses in revenues, earnings to fishing companies and household incomes in many regions, although some countries and/or regions may realize increases in fisheries benefits[13–17].

The close links between the biophysical components of marine ecosystems and the socio-economics of fisheries mean that integrated assessments across disciplines are needed to understand climate change impacts on human welfare through marine fisheries. Effects of global ocean–atmosphere changes act at multiple levels of organization of marine ecosystems and human society, including individual organisms, populations of organisms, communities and ecosystems, the economics of fisheries and larger global issues, such as global food security, energy supply and food prices (Fig. 1).

Here, we review existing knowledge on the responses of marine ecosystems to ocean and climate changes, and how these changes are expected to affect the economics of global marine fisheries, and describe approaches that can be used to adapt to these changes. We focus on climate change (long-term changes in mean conditions), as well as on long-term changes in the level of climate variability (cyclical changes, for example, annual, decadal). We also look at studies that investigate the responses of marine ecosystems and fisheries to climate variability to reveal the potential implications of climate change for fisheries. Furthermore, we discuss other environmental changes resulting from human-induced greenhouse-gas emissions that affect marine ecosystems directly, for example, ocean acidification.

Biophysical impacts on fisheries

Anthropogenic climate change is already causing long-term changes in atmospheric and oceanographic conditions that affect marine ecosystems[18]. There is compelling evidence that during the twentieth century the ocean became warmer (Fig. 2a), with less sea ice[18], as well as more stratified and more acidic. These trends are expected to continue into the next century under the climate change scenarios considered by the Intergovernmental Panel on Climate Change[18]. Evidence indicates that climate change may result in the expansion of oxygen minimum zones[19], changes in primary productivity[20,21] and ocean circulation patterns[22], sea-level rises and an increase in extreme weather events[18]. However, projecting the magnitude and regional patterns of such changes are more uncertain.

Changes in the productivity of fish stocks. Marine fisheries catches consist almost solely of fishes and invertebrates — animals that are strongly dependent on oceanographic conditions[8,23]. Theory and recent experimental evidence suggest that changes in temperature and ocean chemistry directly affect the physiology, growth and reproduction of these organisms[23,24]. For example, fishes in warmer waters are expected to have a smaller maximum body size and smaller size at first maturity[25–28]. Fishes with smaller bodies that live in warmer environments are likely to suffer higher natural mortality rates[25,29]. These are important factors that determine population dynamics and productivity. There is also evidence that ocean acidification and expansion of oxygen minimum zones may have negative impacts on marine organisms and fisheries, although their generality is uncertain[30–32]. Studies suggest that species' responses to more acidic waters may vary between species — invertebrates are likely to suffer the most, but the effect on finfish is more uncertain[33,34]. The expansion of oxygen minimum zones is

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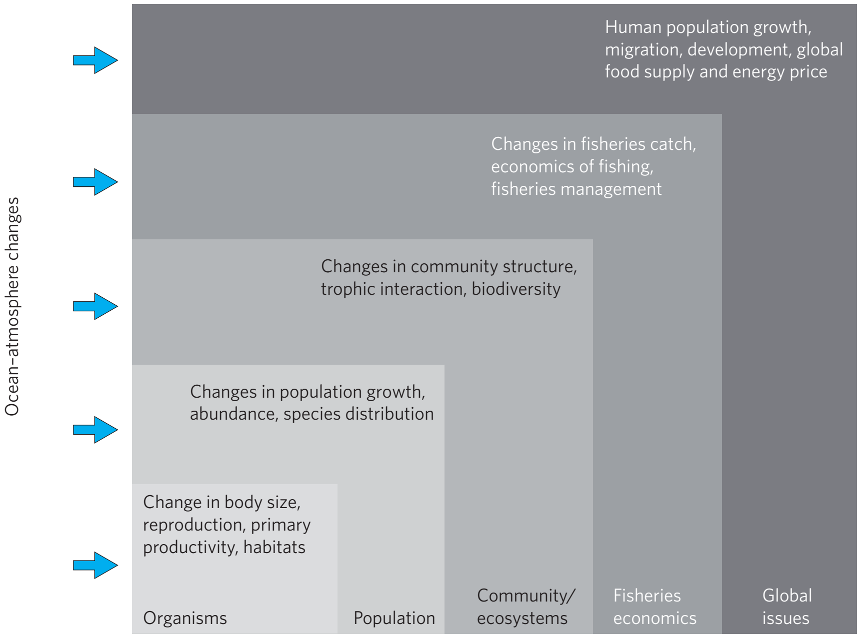

Figure 1 | Schematic diagram indicating the biophysical and socio-economic impacts of climate change at different levels of organizations, from individual organisms to the society.

likely to affect the physiological performance and distribution of pelagic marine organisms[35], which would have direct implications for fisheries through changes in the quantity, quality and predictability of catches[36].

Shifts in fish-stock distribution. Changes in environmental conditions also strongly affect the spatial distributions of marine fishes and invertebrates[23,35]. This is among the most commonly reported ecological responses of marine species. Fishes and invertebrates have different environmental preferences and limits (upper and lower) where animals cannot survive (for example, temperature, salinity)[25,37]. Moreover, ocean currents and temperature affect the dispersal of larvae, thus determining the connectivity of marine populations[38,39]. Recruitment of many exploited fishes and invertebrates are correlated with environmental conditions[40]. For example, comparison of temperature–stock-recruitment relationships between different populations of Atlantic cod shows a unimodal relationship with an optimal temperature for recruitment[41]. Together, these factors are expected to affect, directly and/or indirectly, the distribution of marine species, including those that are targeted by fisheries.

Studies show that many marine species have moved towards the poles and into deeper waters under ocean warming, such as in the Northeast Atlantic[42,43], US East Coast[44], the Bering Sea[45] and Australia[46] (Fig. 2c). For instance, in response to warming, the centre of distribution of 15 (out of 36) species of demersal fishes in the North Sea shifted latitudinally[44], and some species shifted into deeper waters at a rate of around 3 m per decade[31]. The magnitude of observed distribution shifts corroborate the model projections, and distribution shifts are expected to continue in the future under most emission scenarios[47,48]. Shifts in distributions will result in species gains and losses, and changes in community structure (Fig. 2c). In the northern Gulf of Mexico, local extinctions (losses) and invasions (gains) of species have been reported between the 1970s and 2007, and are thought to be related to climate change[49].

A shift in species' geographic range will thus affect the distribution and composition of fisheries resources. This may affect fishing operations, the allocation of catch shares and the effectiveness of fisheries management measures, although it may also create new fishing opportunities. For example, ocean warming may be linked to the increase in abundance of legal-sized lobsters in deep relative to shallow waters in Western Australia, and thus a shift in catch to deeper waters[50]. In the North Sea, the increased abundance of warmer-water species such as sea bass (*Dicentrarchus labrax*) and red mullet (*Mullus surmuletus*) created new fishing opportunities[51]. In some cases, changes in the location of straddling stocks will lead to increasing conflicts between countries. For example, the northward shift of Atlantic mackerel (*Scomber scombrus*) into Icelandic and Faeroese waters is causing disputes over the right to take a share of the >0.5-million-tonne annual catch[52].

Changes in ecosystem productivity. Climate change affects primary productivity, which most marine animals are dependent on as a source of energy[21,53]. One — much contested — analysis suggests that global ocean phytoplankton biomass may have declined substantially over the past 50 years[21]. Moreover, the timing of biological events (phenology) and size structure of planktonic communities is likely to change[28,54], leading to mismatches in the timing of ecological interactions, potentially affecting the survival of recruits to fish populations[55]. Changes in primary productivity and planktonic community structure affect the amount of energy transferred to higher trophic levels and, eventually, the productivity of trophic groups that contribute to fisheries catches[56,57]. However, our understanding of the magnitude and direction of climate change effects on primary productivity is uncertain. For example, projections of primary production based on an empirical relationship estimate increases of 0.7–8.1% by 2050 relative to 2000 (ref. 39), whereas outputs from four Earth-system models suggest a possible decrease of 2–20% by 2100 relative to pre-industrial conditions[12]. The opposite trends and the large regional differences of the estimates highlight the uncertainty in the projection of large-scale changes in primary productivity. Also, these global-scale estimates focus strongly on the open ocean, whereas most continental shelves, where the majority of fisheries catches are caught (Fig. 2b), are poorly represented. Given the strong links between primary productivity and fisheries resources, there is a strong need for improved understanding of the effects of climate change on primary productivity at the scale that is relevant to fisheries[36].

Insights on the combined effects of climate change-induced biophysical changes on trophic interactions and ecosystem dynamics is gained from studying regions where large-scale climate variability and oceanographic changes has led to structural shifts in ecosystems. In the central Baltic Sea, for instance, climate-induced changes in hydrography intensified the effects of fishing on cod (*Gadus morhua*), leading to an increased abundance of sprat (*Sprattus sprattus*), its main prey, which caused a large decline in the abundance of zooplankton and an increase in phytoplankton and eutrophication[58]. This contributed to the large changes in the catches of cod and sprat from the Baltic. Changes in climate, sea-ice extent and hydrographic conditions in the past decade has led to changes in the biological communities of the Bering Sea, including distributional shifts in marine mammal populations, reductions in benthic prey populations and increases in pelagic fish abundance[59]. In the Arctic, although sea-ice retraction may increase access to fisheries resources, it also greatly alters the ecosystem, which is strongly dependent on sea ice, making it more vulnerable to the potential impact of human activities, for example, shipping, and oil and gas exploration. The increased frequency of extreme water temperatures in the tropics is expected to increase the frequency of coral bleaching. In the Seychelles, for example, the biomass of exploited species did not change significantly for ten years following a bleaching event in the mid-1990s; however, fish community structure did change, with declines in smaller fish and increases in larger fish. Such 'lagged' changes are related to a reduction in the structural complexity of reefs following bleaching — a phenomenon that is expected to become more frequent with global warming[60].

Projecting fisheries impacts into the future. Model simulations suggest that many of the observed and projected oceanographic changes are expected to impact fisheries production. One global modelling study linked climate-induced changes in the physical conditions of the ocean, primary productivity, population dynamics of >1,000 species of exploited marine fishes and invertebrates, and the changing distribution of these species with impacts on potential fisheries catches[12] (Fig. 3a). Notwithstanding the various uncertainties associated with such a global model[36], the results suggest that under the two emission scenarios considered by the Intergovernmental Panel on Climate Change, climate change can be expected to lead to an increased catch potential in the Arctic and sub-Arctic regions, but a decreased potential in the tropics (Fig. 3b). Moreover, the model projected a general increase in the relative abundance of warmer-water species in most communities. A follow-up study using a more detailed version of the above model further suggested that projected fisheries catch potential can be reduced substantially by acidification and reduced dissolved oxygen in the ocean[35]. Other climate change modelling studies that focus on resource assessment at regional scales also project similar shifts in resource abundance by the end of this century[36,52]. However, there are still key gaps in our understanding of the effects of climate and oceanographic changes on marine ecosystems and fisheries, rendering projections of such effects less certain.

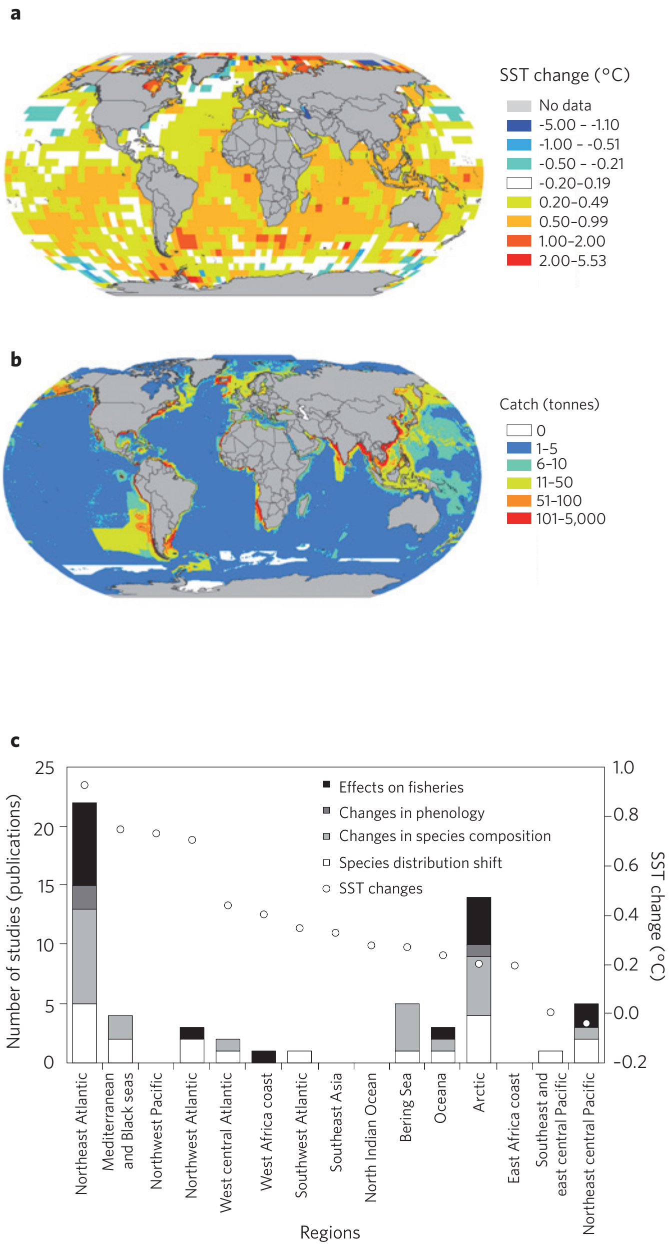

Figure 2 | Sea surface temperature changes, global fish catch and the number of publications on the relationship between climate change and fisheries. a, Sea surface temperature (SST) changes between the 1960s (average 1950–1969) and 2000s (average 1988–2007). Data taken from ref. 98. **b**, Estimated global catches (average 2000–2007). Data taken from Sea Around Us Project. **c**, Number of publications reporting observed biological and ecological changes that are considered to be related to climate change, and may have direct implications for fisheries (bars) and the change in sea surface temperature (circles), between 1982 and 2006 by geographic regions. Changes that are not directly related to fisheries (for example, changes in zooplankton distribution) are not included.

Economic impacts on fisheries

Climate change will affect the economics of fishing because both the quantity and quality of marine fish catch and its distribution within and between nations' exclusive economic zones will be impacted by it[15,58]. The economic consequences of climate change on fisheries might manifest themselves through changes in the price and value of catches, fishing costs, fishers' incomes, earnings to fishing companies, discount rates and economic rent (that is, the surplus after all costs, including 'normal' profits, have been covered), as well as throughout the global economy.

Insights into the possible economic effects of climate change on fisheries can partly (not fully) be drawn from the effects of El Niño/Southern Oscillation (ENSO)-induced climate variability on fisheries, because ENSO events are short-term in nature compared with climate change. During the 1997–1998 El Niño event, Chilean and Peruvian pelagic marine landings declined by about 50%, resulting in a drop in fishmeal export values by about US$8.2 billion. This huge drop generated negative economic effects and caused severe hardship (lost jobs, incomes and earnings) in both countries[61]. Similarly, landings of the Southeast Asian mackerel

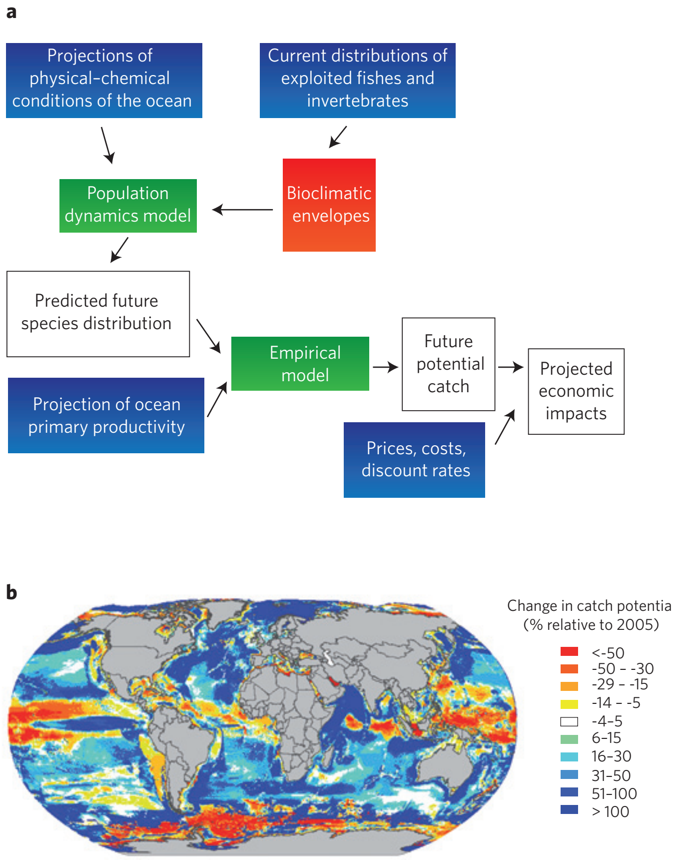

Figure 3 | Summary of the approach and key results of a modelling study that assesses the impacts of climate change on potential catches from global fisheries. a, First, by applying a spatial dynamic model (dynamic bioclimate envelope model) to 1,066 species of exploited fishes and invertebrates, future distributions of species under climate change are projected. Second, by combining these projections with projected primary productivity through an empirical model[58] and fisheries economic data, changes in future maximum potential catch and their economic implications are projected. **b**, Projected changes in maximum potential catch under the Intergovernmental Panel on Climate Change's A1B scenario. Reproduced with permission from ref. 12, © 2010 Wiley.

purse-seine fishery suffered severe declines of about 48% during the same event owing to changes in sea surface temperature, which resulted in an estimated decline in revenues of about US$6.2 million in 1998 (ref. 62).

Impact on prices and ex-vessel revenues. Everything being equal, when climate change reduces fish supply, fish price should increase, which could be large enough to balance out the loss in gross revenues due to reduced catches. However, consumers may seek substitutes as prices increase, thereby dampening the demand for fish and reducing the potential for price increases. It is worth noting that price increases would come at a cost to consumers through loss in consumer surplus, that is, the welfare that consumers gain from the consumption of goods and services. How much consumer surplus is lost under various scenarios and what are the real deadweight losses as a result of climate change impacts on fisheries? To our knowledge, these economic questions have not yet been addressed in the literature, and therefore deserve attention.

Ex-vessel revenues can be affected by climate change through effects first on the quantity, quality and distribution of catches, and then, on ex-vessel prices of fish. Climate change research predicts that catches in high-latitude countries may increase, thus it is expected that fisheries in countries in these regions (for example, Iceland) would benefit economically from climate change, at least in the short term[17]. However, revenues from fisheries are not only dependent on the quantity of catches, but also on catch composition. For example, in spite of the increased catches in the Celtic Sea, the total landed value decreased because a larger proportion of the catch consisted of smaller, lower-priced species[63]. In the Southern Hemisphere, the reduction in landings of pelagic fisheries in Peru as a result of changes in sea surface temperature during the 1997–1998 El Niño event caused more than US$26 million of revenue loss[64].

Impact on fishing costs. Capital costs, that is, the cost of vessels, fishing gear, processing plants and so on, would be affected by climate change if additional capital for fishing and processing operations is required to adapt to climate change impacts on the quantity, composition and distribution of fisheries resources[65]. Changes in migratory routes and fish distribution would affect travel time, which can lead to increases or decreases in fuel and ice cost depending on catch levels and patterns, and the management regime in place. It is estimated that under a scenario of a 1.2 °C sea surface temperature increase — which corresponds to the ENSO event of 1983 — the number of active boats landing sablefish in Monterey Bay, California could decrease by 60% (ref. 66). Decadal oceanographic changes affected the distribution of tuna in the central western Pacific, which in turn impacted how the tuna purse-seine fleet operated, and thus increased fishing costs[67]. Most of the world's large, fuel-consuming fishing vessels[1] are from developed countries, implying that these vessels would face the much higher cost of rising fuel and climate change mitigation than small fishing vessels. Developed countries may be forced to engage in the expensive business of scrapping their large vessels as climate change impacts intensify.

Impact on resource rent and other indicators. With the expected changes in landed values and costs under climate change, earnings to fishing companies and the resource rent generated through fishing will be altered, with the direction and magnitude of change varying across regional fishing zones. For example, earnings to the European sardine fishery are estimated to decrease by up to 1.4% on average per year with rising temperatures[68]. Owing to increased sea temperatures, the reduction in coral cover and its associated fisheries production is expected to lead to a potential net revenue loss of between US$95 million and 140 million (current net revenue is US$310 million) per year in the Caribbean basin by 2015 (ref. 69). A World Bank report estimated the annual economic impact of climate change on the coast of Viti Levu, Fiji to be US$0.1 million to 2 million for subsistence fisheries, and US$0.05 million to 0.8 million for commercial coastal fisheries by 2050 (ref. 70). For a small country such as Fiji, these numbers are significant.

In contrast, resource rent from fishing Pacific sardine (*Sardinops sagax*) could increase — sardine is known to be more productive during warm-water regimes in the California Current ecosystem[71]. The fisheries impacts of global warming on both Iceland's and Greenland's gross domestic product are likely to be positive, with the economy of Greenland projected to benefit substantially[17]. Paradoxically, this situation could worsen if governments use climate change as a cover for increasing harmful subsidies to the fisheries sector[72]. However, to be certain about the impact of climate change on economic rent globally, we need more information about seafood demand elasticity and the degree of substitution between seafood and other protein sources.

Another important consideration is how climate change may affect the stream of benefits that fisheries resources are expected to generate over time, and how beneficiaries are likely to discount future

Table 1 | Summary of potential impacts of climate change on the economics of fisheries based on information from the published literature.

Impacts	Region	Catch	Prices	Cost	Earnings to companies	Resource rent
Shift in distribution of species	Arctic	Catch potential: increase[12] Invasion of warmer water species[47]	Decrease[*]	Fishing: decrease Adaptation: increase	Not yet known[†]	Increase[69,‡]
	Temperate	Catch potential: no change[12] Changes in species composition resulting from both species gains and losses[47]	Not yet known	Fishing: not yet known Adaptation: increase	Not yet known[†]	Increase[13,‡]
	Tropics	Catch potential: decrease[12] Species losses[47]	Not yet known	Fishing: increase Adaptation: increase	Not yet known[†]	No change
Ocean acidification	Global	Catch potential: decrease[32]	Increase[§]	Fishing: increase Adaptation: increase	Not yet known[†]	Increase[13]
Expansion of oxygen minimum zones	Global	Catch potential: decrease[32]	Increase	Fishing: increase Adaptation: increase	Not yet known[†]	Increase
Reduction in body size	Global	No change	Increase[72]	Fishing: no change Adaptation: increase	Not yet known[†]	Not yet known/ increase
Increased variability	Global	No change	Variable	Fishing: increase Adaptation: increase	Not yet known[†]	Not yet known/ increase
Increased extreme weather	Global	Actual catch: decrease	Increase[*]	Fishing: increase Adaptation: increase	Not yet known[†]	Not yet known/ increase

Details of each topic, and the supporting references, are summarized in this review. [*] Everything being equal, an increase in catch means a decrease in price, but recall discussion in main text. [†] Depends on the interplay between changes in price and the cost of fishing and adaptation. [‡] In general, whether rent will increase or decrease depends on the state of the resources before climate change, and the institutional and management regimes in place. [§] Everything being equal, if catch decreases then price increases, but recall discussion in main text.

benefits. Discounting accounts for the compensation individuals require for sacrificing benefits now for potentially greater benefits in the future. The relative difference between the required future benefit and the current benefit represents the discount rate, and reflects the weight placed on receiving benefits at present in contrast to the uncertainty of receiving greater benefits in the future. The more distant and uncertain the future benefit, the greater the compensation required and correspondingly the higher the discount rate. As a result, those preferring to sacrifice future for immediate benefits will have a higher discount rate than those placing a higher value on benefits to be realized in the future. Therefore, the uncertainty associated with climate change may result in a relatively high discount rate for privately owned commercial fishing firms, driving them to pursue fishing strategies that favour current catches over those in the future. On the other hand, the greater society's interest in maintaining both market and non-market values of ocean goods and services for the benefit of all generations, the more society would favour a more conservative fishing strategy that defers current use to maintain higher stock levels for the future. In general, society has a longer time horizon, so the social discount rate would be comparatively lower than the private discount rate. In view of the range of benefits fisheries resources are capable of providing, the choice of discount rates becomes an extremely critical issue in formulating and evaluating conservation and management policy to address climate change[73,74].

In the absence of published research on the macroeconomic impacts of climate change on fisheries, we can only conjecture that climate change will probably have impacts on national labour markets, industry re-organization and re-orientation to changes in export earnings (some negative) owing to the predicted declines of fisheries in many maritime countries[75]. Further research on the potential macroeconomic effects of climate change on fisheries is needed.

It is predicted that developing countries would experience relatively more reductions in fish catch with climate change because they are concentrated in tropical and sub-tropical regions of the world. Whether these predicted decreases in catch would result in real negative economic impacts remains to be seen. This is partly because most of these countries have relatively weak fisheries governance and management institutions[76], implying that their fisheries are already at or near open-access equilibrium, where resource rent from fisheries is zero[77]. In such cases, climate change can hardly make resource rent worse. In fact, because climate change could increase the cost of fishing, it is likely to lead to reductions in fishing effort and overcapacity, resulting in potential increases in resource rent. On the other hand, because these countries tend to rely on fish and fisheries as a source of livelihood and protein, climate change would intensify their socio-economic and food-security problems[66,78]. Table 1 summarizes the predicted biophysical and economic impacts of climate change on fisheries, and highlights impacts that are unknown at present.

Adapting fisheries for the future

Fish stocks will be more robust to climate change if the combined stresses from overfishing, habitat degradation, pollution runoff, land-use transformation, competing aquatic resource uses and other anthropogenic factors are minimized. This could be largely achieved not through more biophysical research, but by developing and applying institutions and mechanisms for achieving effective adaptive management[79]. In this context, fisheries that have been successfully managed to achieve resource sustainability will probably have a higher capacity and be better positioned to respond to the vagaries of climate change than those whose governance has been much more *laissez-faire* in nature. Fisheries in the latter case would have been fishing above sustainable limits (for example, maximum sustainable yield) with respect to the current climatic, oceanographic and biological conditions. Such fisheries may thus be more sensitive to shifts in these conditions and would need to respond much more proactively to disruptive changes resulting from climate change. For example, fishers would be forced to retire from fishing prematurely if their fishery is negatively affected by climate change. This may not be completely negative as labour and capital displaced from fishing might be used more productively in other sectors of the economy.

The global fishing sector has had to adapt to declining fish stocks and catches over time because of overfishing (for example, by fishing deeper and into the high seas[80]) or because of seasonal, interannual and multidecadal variability (for example, the warm period in the North Atlantic from 1925 to 1960; ref. 41) or combinations of both. When climate change affects the composition and productivity of exploited species in a region, some fishers can adapt by switching target species or gear type[81] or by moving to marginally productive areas. For example, new fisheries have already developed for several southern species in the UK (for example, red mullet) as these species have started to migrate to the North Sea because of an increase in sea temperature[82].

The ability of fishers and fishing enterprises to adapt depends on a number of factors, including the mobility of the fishing fleet. At present, the dominant hypothesis is that more technologically advanced fleets, usually located in rich northern countries, are more likely to be better prepared to adapt to climate change by moving to other fishing grounds and by shifting gears[83]. Fleets of distant-water fishing nations, which have access arrangements with several island states in the Pacific, for example, may be able to adapt to the change[67]. In contrast, domestic fleets and their associated canneries of the Pacific islands have less ability to adjust to the change because they are usually confined to their own exclusive economic zone[71].

Based on experience from historical responses of countries to fisheries changes, possible adaptation strategies include vessel buybacks[84], restricting the use of some gear types[80] and livelihood diversification measures[85]. Also, large countries or political entities, such as members of the European Union[86], Japan[87], China[86] and the United States[88] have resorted to buying fishing access rights, mainly from developing countries, to keep their excess fishing capacity active, and meet their populations' growing demand for seafood[88].

To adapt successfully, perverse incentives, such as subsidizing unprofitable fishing fleets, need to be replaced, where feasible, with initiatives such as catch shares management and other incentive mechanisms to reduce overcapacity in overexploited fisheries. Climate change impacts on fish stocks could bring about changes in current trade patterns in fish and fish products between regions and countries, as has been shown to be the case with agricultural commodities[89]. Shifts in the distribution of exploited species may lead to increasing disputes between countries that share fish stocks. For example, the salmon treaty between Canada and the United States would need to be re-negotiated as salmon distribution changes in response to climate change[90]. The heavy dependence of modern fisheries on fossil fuels[91] would require that the fisheries sector, like other sectors of the economy, mitigates its carbon footprint — a change that would be beneficial to society at large, but costly to fishing enterprises in the short term[92].

There are a number of efforts underway to estimate the economic costs of adapting fisheries to climate change and the means of absorbing these costs[14,16,93]. One approach that has been proposed is the 'adaptation endowment fund', which is defined as the capital that a country, region or the world as a whole would need to replace the projected loss in annual gross revenues as a result of climate change[15]. The authors argue that both the private and public sectors of an economy will have to find ways to replace the annual revenues that would have been generated by fisheries in the absence of climate change.

More work is needed to make the endowment-fund idea useful in practice. First, the real world is composed of a mix of fisheries that, in varying degrees, are more like open access, regulated open access, regulated restricted access or some version of optimal management. Hence, to really determine how much of the economic benefits (or resource rent) would be lost owing to climate change, the current proposal has to be extended to include an institutional layer that captures and incorporates how management institutions in a country would help protect fisheries benefits from being eroded by climate change. Second, as per economic theory, using gross revenue loss as a basis for the endowment fund overestimates the compensation needed to mitigate the impact of climate change on fisheries. The appropriate economic indicator to use is resource rent, or more broadly, welfare loss.

How societies deal with climate change will depend largely on their capacity to adapt, which will be strongly influenced by social, economic, political and cultural conditions. A wide range of adaptations and mitigation measures are possible, either carried out in anticipation of future effects or in response to impacts once they have occurred. Some can be implemented through public institutions, others by private individuals. In general, responses to the direct impacts of extreme events on fisheries infrastructure and communities are likely to be more effective if they are anticipatory, as part of a long-term participatory, broad-based approach to fisheries management. Such an integrated approach has the potential to increase ecosystem and community resilience, and provide a valuable framework for dealing with climate change. In any case, preparation should be commensurate with risk, as excessive protective measures could themselves have negative social and economic impacts[94].

Conclusion

Climate change is expected to affect fish stocks, marine ecosystems and fisheries. However, there are still key knowledge gaps that prevent a comprehensive understanding of the full range of impacts that climate change could have on the economics of fisheries. Both disciplinary and interdisciplinary studies that investigate fisheries responses to global change are needed. At present, the available studies on climate change effects on fisheries are patchy globally and concentrated in a few well-studied regions where fisheries may be less negatively affected by climate change. We need an improved understanding of how the biophysical impacts of climate change on the global ocean would influence factors that affect catches and fish protein supply, revenues, fishing costs, jobs and incomes, resource rent and other economic activities generated by the world's fisheries. Studies on the macroeconomic impacts of climate change on fisheries and the effect of climate change on the consumer surplus derived from the world's fisheries are needed.

Given that climate change is already affecting fisheries, it is important for both public and private actors to take actions to adapt fisheries to climate change. Biologically, maintaining more abundant populations is a way to increase their capacity to adapt to environmental change. Hence, solving the overfishing problem is fundamental[91]. The economic impacts of climate change on fisheries will largely depend on our actions now. Governments have generally been reactive rather than anticipatory in their response to declining fishing opportunities, with huge economic consequences, for example, the collapse of the Canadian cod stock[95]. Given the scale of the anticipated effects of climate change on fisheries, reactive measures are likely to be costly.

Reducing greenhouse-gas emissions would substantially diminish the ecological impacts of climate change on fish stocks and thus minimize its economic effects. Also, the cost of adapting to climate change would be lower with reduced emissions. Thus, it is important for all with interests in the marine fishing sector to make the case for lower emissions. This is especially important, because with the intensification of climate change impacts throughout the global economy, it is likely that in the future, other strategically more important sectors of the economy (for example, energy and agriculture) would attract the bulk of society's scarce resources to the detriment of fisheries.

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Additional information

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