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DEVELOPMENT AND CLIMATE CHANGE

Cost of Adapting **Fisheries** to Climate Change

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KEY FINDINGS

- Climate change will have significant impacts on the world's fisheries through losses in catch and gross revenues.
- The world stands to lose up to 50 percent of current gross revenues of about $80 billion per year from the world's fisheries in the face of severe climate change and continued overfishing in global fisheries.
- The loss in gross revenues could result in billions of dollars in lost income by fishing households worldwide, with serious economic and social consequences.
- Replacing the predicted loss in gross revenues due to climate change globally will require an endowment in the hundreds of billions of dollars.
- The direct cost of adapting global fisheries to climate could run into tens of billions of dollars.
- The world's developing and most vulnerable countries, who contribute very little to climate change, are predicted to suffer most of the estimated losses.
- The losses in gross revenues from high seas' fisheries are predicted to be high—much higher than we expected at the beginning of the study.

This study has revealed a number of important insights. First, adapting fisheries to climate change will not be cheap, especially for developing countries, many of whom lack adaptive capacity. Second, overfishing plus climate change means severe depletion of the world's fishery resources, with about half of current gross revenues predicted to be lost under severe climate change scenarios. Third, the combination of climate change and the lack of effective management of the high seas mean heavy losses. To stem this tide, well-functioning management systems need to be quickly put in place for the high seas.

1. BACKGROUND AND CONTEXT

This study has two objectives. The first is to help decision makers, especially in developing countries, to better understand and assess the risks posed by climate change, and to better design strategies to adapt their fishing sectors to climate change. The second objective is to develop global estimates of adaptation costs in the fisheries sector of countries to inform the international community's efforts, including UNFCCC and the Bali Action Plan, to provide access to adequate, predictable, and sustainable support, and to provide new and additional resources to help the most vulnerable developing countries meet adaptation costs. Adaptation is here understood to mean any action taken to reduce the risk posed by the impact of climate change in a given sector of the economy, for example, fisheries. Adaptation cost is then the cost of taking such action.

To help meet these two objectives, this study is global in its scope. First, we will provide country/regional adaptation costs to contribute to the discussion on climate change leading up to the Copenhagen conference in late 2009. Second, this work will begin to develop the procedures that will be needed to generate aggregate adaptation cost numbers once country case studies are completed.

We use four variables to help us capture the cost of adapting fisheries to climate change in a broad sense: (1) the estimated cost of adjusting fisheries to catch declines as a result of climate change; (2) the potential loss in gross revenues or landed values due to climate change; (3) the capital that will be required as an endowment to replace the predicted loss in gross revenues through time; and (4) the potential loss in household incomes from fisheries as a result of climate change. It should be noted that we have not been able to include more direct welfare related measures (e.g., calorie consumption) because of lack of readily available relevant data.

This report focuses on marine capture fisheries, not inland or aquaculture, for a number of reasons. In the first place, the study of the impact of climate change on fisheries is more advanced in the case of capture fisheries, so we have the necessary basic scientific information on which to base our analysis. Second, marine capture fisheries are still over 50 percent of the total value of global fisheries (capture, inland, and aquaculture) and support a large number of economically vulnerable people in coastal communities of the world, especially in developing countries. Third, there are indications that both inland fisheries and aquaculture are likely to suffer similar challenges identified for marine capture fisheries. Hence, the results from this study can provide insights about the potential cost of adapting inland fisheries and aquaculture to climate change.

1.1 POTENTIAL IMPACTS OF CLIMATE CHANGE ON CAPTURE FISHERIES

Marine fisheries productivity is likely to be affected by the alteration of ocean conditions—including water temperature, ocean currents, upwelling, and biogeochemistry—as a result of climate change (IPCC 2007; Diaz and Rosenberg 2008). Empirical observations and climate models both indicate that global climate and ocean conditions have been changing over the last 100 years and will likely change more rapidly in the future (IPCC 2007). The major changes include ocean warming, acidification, and expansion of oxygen minimum zones (Brewer & Peltzer 2009). Biological responses to these ocean changes have been observed in the marine biomes (Perry et al. 2005; Dulvy et al. 2008; Hiddink and Hofstede 2008; Richardson 2008; Cheung et al. 2009). For instance, nearly two-thirds of exploited marine fishes in the North Sea shifted in mean latitude or depth or both over 25 years as sea temperature increased (Perry et al. 2005; Dulvy et al. 2008). Also, annual growth rates for the juveniles of eight long-lived fish species in the southwest Pacific increased in shallow waters where ocean warming occurred, and decreased in deep waters where ocean cooling occurred (Thresher et al. 2007). These responses are suggested to be due to changes in physiology, distribution ranges, and population dynamics as ocean conditions change (Hiddink and Hofstede 2008; Richardson 2008; Cheung et al. 2009). Such changes affect primary productivity, species distribution, and community and foodweb structure, which have direct and indirect impacts on distribution and productivity of marine organisms.

Specifically, climate change is likely to affect marine living resources in a number of ways:

- Many fish and shellfish are likely to shift their distribution as a result of changes in ocean conditions and habitats.
- Changes in ocean conditions will result in changes in primary productivity, population dynamics and marine food chain, thereby reducing ocean fish productivity.
- Change in phenology (timing) of marine organisms (such as planktons) may lead to a mismatch between food availability and predator requirement. This may have impacts on the foodchain.
- The warming of the global ocean may result in the symbiotic algae on corals dying; that is, it may lead to what is described in the literature as coral bleaching. This is predicted to have devastating effects on fish species associated with coral reefs.
- With climate change, it is highly likely that the volume of water in the sea may increase to such an extent that many of the world's corals will drown, again with potentially serious consequences for species associated with coral reefs.
- Climate change is modifying the chemistry of the ocean, which can result in undesirable consequences—for example, a rapid increase in the number of areas in the global ocean without oxygen—and hence cannot support living creatures.
- There are currently 407 dead zones in the global ocean. There has been a doubling of dead zones each decade since 1960. This means that there are now 16 times more dead zones than there were in 1960. Dead zones are areas without oxygen where no fish or invertebrates can survive. Climate change is one of the likely factors that increase the number and intensity of dead zones.
- Oxygen minimum zones in the open ocean may expand under climate change.
- Climate change is acidifying the ocean, which increases dissolved CO_2 and decreases ocean pH, carbonate ion concentration, and calcium carbonate mineral saturation in the ocean (Cooley and Doney 2009).

We divide marine climate change impacts on fisheries into two main types. First, we focus on impacts on fishing sectors through shifts in the distribution of fish biomass and changes in productivity. Second, we examine climate change impacts through other mechanisms such as acidification of the ocean from higher CO_2 levels and through climate change-included loss of critical habitats. The latter includes degradation of coral reefs through coral bleaching. These two impact types are interrelated. For example, ocean acidification may lead to changes in fish habitats and therefore cause shifts in biomass. Hence, such division is mainly for operational purposes in this analysis.

1.2 WHO (ACROSS COUNTRIES) IS LIKELY TO BE MOST AFFECTED?

1.2.1 Geographically

We see from our data, models, and analysis that:

- Fish will generally redistribute away from tropical countries toward cooler temperate countries; thus tropical countries may generally suffer larger impacts.
- Countries that are heavily dependent on coral reef resources are likely to suffer big impacts.
- Countries and regions with large areas of dead zones—for example, the Gulf of Mexico—are likely to see declines in their catches.

1.2.2 By income or vulnerability class

Given that most of the world's developing and poor countries are situated in the tropics, and the fact that most coral reef resources are also found in developing regions such as the Coral Triangle in the Western Central Pacific, it is clear from both earlier work (Allison et al. 2009) and the current analysis that low-income, developing, and mostly already economically vulnerable countries are the ones that will suffer the most from the vagaries of climate change.

1.3 WHAT EXPERIENCE IS THERE WITH ADAPTATION IN THE SECTOR?

1.3.1 Private sector adaptation

The private sector has been undertaking continuous adaptation because of declining fish stocks over time. Fishers have had to go further into the deep and high seas to catch fish at much higher cost. They have had to acquire bigger vessels and sophisticated gear that will allow them to stay out fishing for days. Some fisheries have suffered declines in the number of fishers as the opportunities for fishing have diminished. Particularly, private sectors in developed countries have high adaptive capacity. For example, some fisheries—such as Norwegian herring fisheries—have experienced change in species distribution and species composition; many of these fishing sectors were able to adjust and adapt to the changes, especially with active assistance from government. Moreover, as fish stocks decline, some fishers in both developed and developing countries have attempted to diversify their income by engaging in other non-fishing livelihood activities, such as aquaculture and shipping.

Environmental nongovernmental organizations have and continue to play important roles in helping to adapt fisheries to changing opportunities.

1.3.2 Public sector investment

Over time, the public sector has invested resources in the fishing sector of various countries to deal with diminishing catches and fishing opportunities. Some of the adaptation measures that have been employed by governments include (a) fisheries buybacks, (b) individual transferable quotas, and (c) livelihood diversification measures.

In addition to the above, some countries—such as members of the European Union and the United States—have been compelled to buy fishing access rights from mainly developing countries as an adaptation measure to keep their bloated fishing capacity busy and supply fish to meet the growing demand at home.

Countries also have sought to adapt to declining marine fishing opportunities by investing in the development of the fish farming sector, with mixed results.

In general, some countries have tried to use "soft" adaptation by using policies and regulations to adapt their fisheries to changing times. Unfortunately, however, most of these efforts have been reactive rather than anticipatory in nature, with huge economic consequences. A case in point is the cod fishery off Newfoundland. The Canadian government spent over $3 billion in reaction to the cod stock collapse in 1992, yet a much smaller amount could have been spent earlier to avert the destruction of the fish stocks and the communities that depend on them.

1.4 WHAT IS THE NATURE AND EXTENT OF ADAPTATION/DEVELOPMENT DEFICIT IN THIS SECTOR?

Our analysis and the literature show that the nature and extent of adaptation to climate change and the development deficit varies greatly depending on the country and region of the world. The nature and extend of adaptation and the development deficit depends on a number of factors, including (a) how climate change will affect the distribution of fish to or away from a country's EEZ; (b) how other impacts of climate change such as ocean acidification and hypoxic (low-oxygen) zones will affect the abundance and productivity of the fish species in a country's waters; and (c) how rich, diverse, advanced and adaptable an economy is.

1.5 HOW WILL EMERGING CHANGES IN DEVELOPMENT AND DEMOGRAPHICS INFLUENCE ADAPTATION?

Changes in development and demographics will have a great deal of impact on the ability of developing countries, in particular, to cope and adapt to climate change. A combination of factors—increasing population, low gross domestic product, low scores on the UN Human Development Index (HDI), and low economic development—together with decreasing opportunities from ocean fisheries due to climate change, is likely to ensure that developing countries face increasing challenges with time.

1.6 UNCERTAINTIES

Certain aspects of potential impacts of climate change on fishing sectors are considered likely, but the overall impacts and the capacity and cost for adaptation are considered uncertain. Specifically, it is very likely that climate change will result in a shift in the distribution of fish stocks. In fact, a climate-induced shift in distributions of major commercial fish stocks have been observed in the last few decades. However, projections of changes in the potential catch, and their effects on the fishing sectors, are considered uncertain (Cheung et al. in press). Also, the effects of climate change on exploited fish stocks—through ocean acidification, hypoxic zones, coral bleaching, etc.—have not been quantified by previous studies. Moreover, the synergistic effects of fishing and other human impacts on the ocean—such as pollution and habitat destruction—with climate change are not well-understood. In socioeconomic terms, the potential response of seafood markets to climate change or changes in seafood demand and supply are unclear. These add uncertainty to our understanding of the potential impacts of climate change on the fishing sector.

2. LITERATURE REVIEW

2.1 PREVIOUS STUDIES

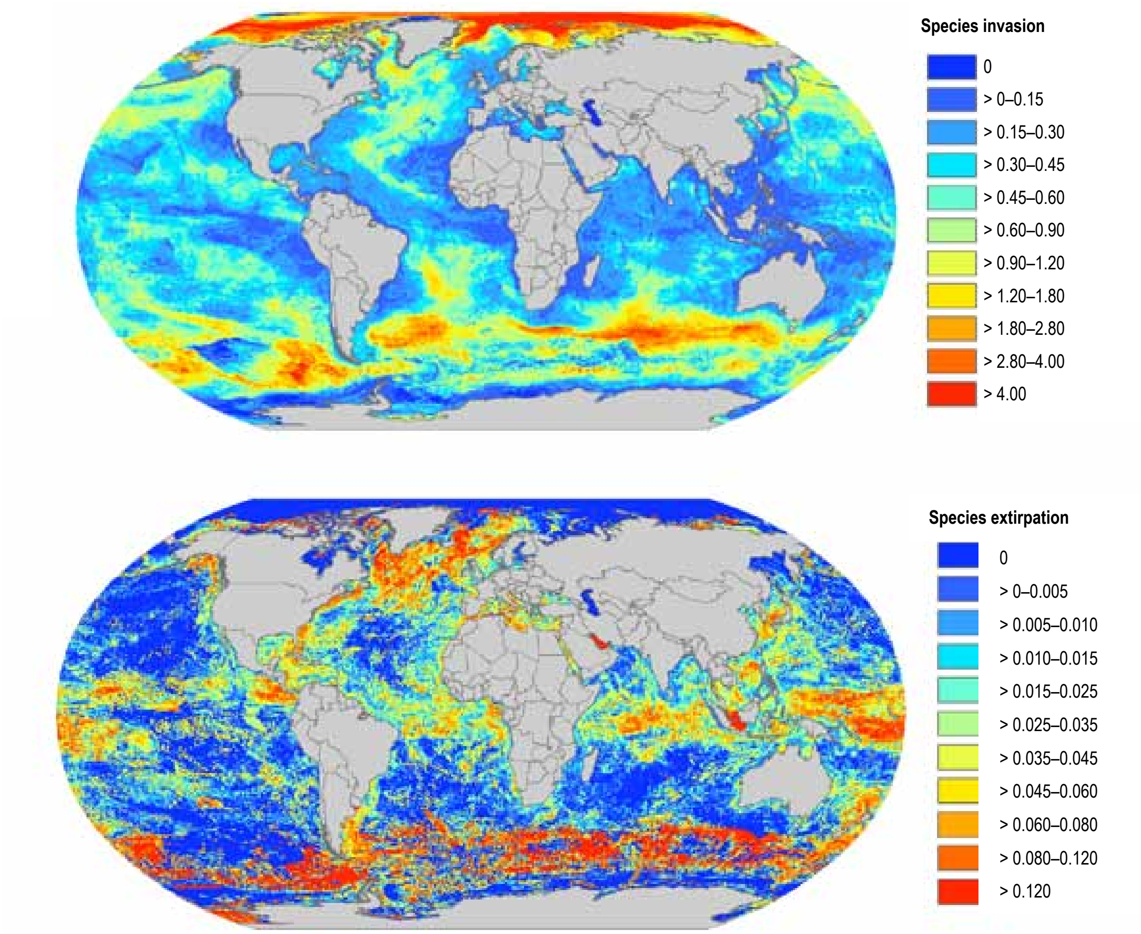
2.1.1 Nature and extent of damages

Climate change affects the distribution of biomass of marine species that are exploited by fisheries. In the ocean, distribution of marine species, notably for fish and invertebrates, is strongly related to environmental factors. Specifically, observations and theory suggest that marine species respond to ocean warming by shifting their latitudinal range (Perry et al. 2005; Parmesan 2006; Hiddink and Hofstede 2008; Mueter and Litzow 2008) and depth range (Dulvy et al. 2008). For example, in the North Sea, nearly two-thirds of exploited marine fishes shifted in mean latitude or depth or both over 25 years as sea temperature increased (Perry et al. 2005; Dulvy et al. 2008). Recently, a study using a dynamic bioclimate envelope model (Cheung et al. 2008a; Cheung et al. 2009) examined the potential global shift in the distribution ranges of 1,066 exploited marine fish and shellfishes by 2050. The study found that distribution of most species may continue to shift toward the pole at an average rate of around 40 km per decade. The projected distribution shift may result in high rates of species invasion in the high latitude regions and local extinctions along the tropics and semi-enclosed seas (Figure 1). A distribution shift of exploited species will result in changes in abundance and composition of species in each region. Fisheries may be affected by the potential shift in fishing grounds of targeted species and the associated changes in the cost of fishing.

Climate change may lead to changes in ocean productivity, affecting the potential catch of exploited stocks. Using an empirical model to predict ocean primary production with outputs from global circulation models, Sarmiento et al. (2004) estimated that global primary production may increase by 0.7–8.1 percent by 2050, with very large regional differences—such as decreases in productivity in the North Pacific, the Southern Ocean, and around the Antarctic continent, and increases in the North Atlantic region. Such changes in primary productivity will affect marine species along the food chain. Recently, Cheung et al. (in press) examined the potential global change in future fisheries catch potential by the mid-21st century resulting from changes in primary productivity and species distribution ranges. They suggest that climate change may cause large-scale redistribution of catch potential, with a considerable reduction in catch potential in the tropics and increase in high latitude regions (Figure 2). Such a shift in catch potential will directly affect the fishing sectors. For example, it is estimated that climate change may cause a 35 percent reduction in the overall economic value of Australian fisheries by 2070 (Winn 2008). Another study found that climate change may have been reducing the maximum production of cod at a rate of 32,000 metric tons per decade since 1980 (Pinnegar et al. 2007).

Other marine climate change effects may have additional negative impacts on fish stocks. Changes in ocean temperature, ocean acidification, changes in ocean chemistry (e.g., expanded area with low oxygen) and sea level are likely to damage marine habitats such as coral reefs that are ecologically important to many exploited species. Ocean acidification may have additional impacts on other calcifying organisms. Many of the potentially affected species are commercially valuable or are

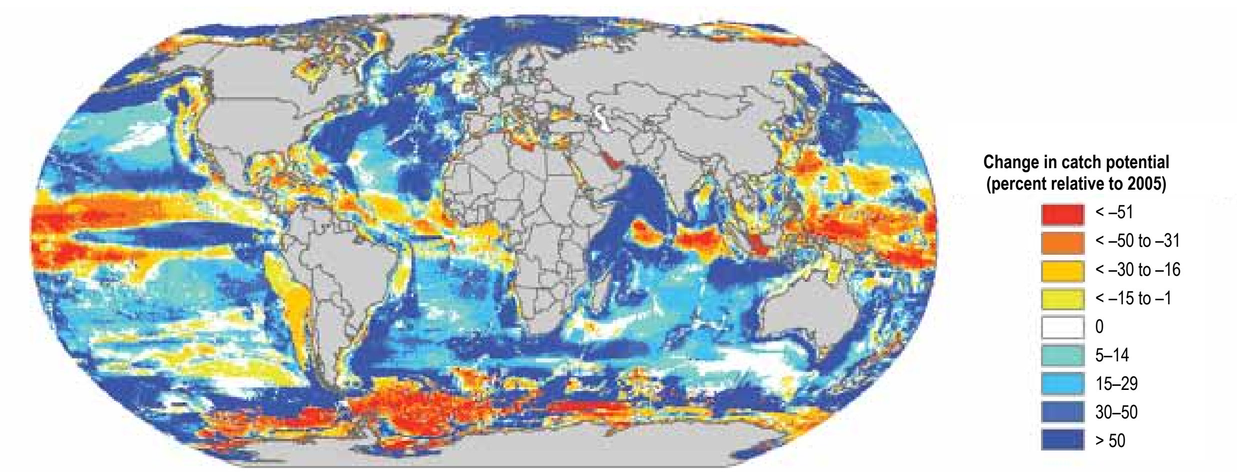
FIGURE 1. PROJECTED RATE OF (A) SPECIES INVASION AND (B) EXTIRPATION BY 2050 RELATIVE TO THE 2000S UNDER THE SRES A1B SCENARIO (CO_2 CONCENTRATION OF 720 PPM BY 2100) (CHEUNG *ET AL*. 2009A)



ecologically important to targeted species. Increased severe weather conditions may affect fishing operations. On the other hand, retraction of sea ice, particularly in the Arctic, may allow fishing operations in previously inaccessible fishing grounds.

In summary, climate change will affect the distribution of fish in the ocean and the fish population that the world's fisheries depend on. These will obviously have serious impacts on the gross revenues to be derived from fisheries and the cost of fishing. In addition, it will have impacts on fishing infrastructure such as fishing ports. There will also be many social, cultural, and institutional implications. For example, if fish move from one part of a country to another part, will it be possible for people who will lose fish to «follow» their fish? Even within countries, this is not a trivial question, and when it comes to transboundry and straddling stock, this question becomes even more challenging. The current report focuses more on the economic impacts and therefore covers impacts related to the loss/gain in gross revenues and the cost of fishing that is likely to occur with climate change.

FIGURE 2. PROJECTIONS OF CHANGE IN GLOBAL CATCH POTENTIAL BY 2055 UNDER THE SRES A1B SCENARIO (CHEUNG *ET AL*. 2009B).



2.1.2 Nature of Adaptation and its Cost, Private and Public

The private and public sectors will need to adapt to the following realities under climate change:

- Some of the species of fish they currently catch will disappear, meaning that those who currently catch these fishes will have to find something else to do.
- Some of the fishes caught by a given fishing fleet may move to other parts of the country or even out of the country's EEZ. This will be costly in a number of ways because fishers may have to "follow" the fish, which in many instances will mean a higher cost of fishing.
- Predictions of future productivity and revenue from fish stocks may be more uncertain, making it more difficult for the private sector to set their investment goals or for fisheries management agencies to decide management strategies and tactics.
- In many countries, climate change will result in a significant reduction in revenues from fishing. This will mean that the public sector will need to find ways that not only help fishers replace their lost incomes, but also compensate for the lost tax revenues that this will entail.
- Countries, especially, developing ones with large subsistence fishing communities, will have to find alternative sources for meeting the animal protein needs of their people.

2.2 HOW OUR STUDY COMPLEMENTS EXISTING WORK

This work is groundbreaking in a number of ways. First, as far as we know, this is the first time anyone has looked at the cost of adapting fisheries to climate change at the global level in a quantitative fashion. We know that climate change is likely to affect the goods and services provided by ecosystems. In particular, it will impact on the ability of marine ecosystems to continue to serve as a reliable source of seafood supply, with direct implications for the welfare of human society (Antle et al. 2001; Easterling et al. 2007; Battisti and Naylor 2009). Such impacts and their cost and benefits have been quantified in terrestrial systems. For example, food-crop production is projected to be negatively affected under the more intensive CO_2 emission scenarios, with most severe impacts projected for low-latitude regions (Fischer et al. 2005; Parry et al. 2004, 2005; Easterling et al. 2007). Similar projections for pastures and livestock production have also been made (Easterling et al. 2007). Although such projections are uncertain, they allow analysis of potential socioeconomic vulnerability, impacts on global food security and benefits and costs of climate change.

In the marine biome, except the modeling studies that are included in this chapter (Cheung et al. 2009, in press), studies of climate change impacts on fisheries focus largely on a few species, regional climate variability, and regime shifts, or qualitative inferences of potential changes (Lehodey 2001; Lehodey et al. 2003; Drinkwater 2005; Brander 2007; Roessig et al. 2004). There are currently few studies estimating the costs and benefits of climate change impacts on fisheries, let alone estimation of the actual adaptation cost to the society. Various studies investigated the vulnerability and adaptive capacity of countries or communities to climate change impacts on fisheries (Allison et al. 2009). They show that tropical developing countries are socioeconomically most vulnerable to climate change; not only will the impacts of climate change be felt most in these regions, but also these countries are the most vulnerable in terms of their ability to absorb the cost of adapting to climate change. Unfortunately, there are few, if any, national adaptation efforts in these regions. Our study is global and therefore will give a broader view of the situation than most current studies.

3. METHODOLOGY

Our methodology consists of the following main components:

- We determine the potential loss/gain in catches due to the redistribution of fish biomass and changes in primary production in the global ocean under different climate change scenarios, for all maritime countries of the world and the high seas.
- Since change in the distribution of fish populations and primary production—and therefore catches—will likely not be the only important impact, we will examine—based on spatial knowledge of the location of different fish species in the global ocean—the potential effects of climate change through changes in (a) acidification of the oceans from higher CO_2 levels; (b) loss of coral reefs from ocean warming and acidification; and (c) other changes in ocean biogeochemistry such as oxygen levels. We then modify the potential impact of climate change on fish catches, identifying climate change vulnerability hotspots insofar as fisheries are concerned.
- As many fish stocks are fully exploited, overexploited, or depleted, the global fish catch may not be sustainable (Pauly et al., 2003). Thus, the current fisheries catch (and thus revenue) level may decrease in the future. The additional effect of the decline in fish stocks on adaptation costs of the fisheries sector to climate change is considered as a separate scenario.
- Steps 1 to 3 will help us isolate the impact of climate change on fisheries from impacts coming from other sources, such as overfishing and pollution.
- Determine the potential loss/gain in **ex** - vessel landed values or gross revenues and household incomes from global fisheries under different climate-change and demand-growth scenarios.
- Determine the amount of endowment needed to replace lost gross revenues in the case of countries that lose catch revenues, and the amount of capital that will be gained in the case of countries that may make extra catch revenues.
- Finally, we will estimate the actual cost of adapting marine fisheries to climate change worldwide using historical cost data for adjusting fisheries after big declines in catches such as in the case of northern cod off Newfoundland, Canada.

3.1 DETERMINING THE POTENTIAL LOSS/GAIN IN CATCHES DUE TO THE REDISTRIBUTION OF FISH BIOMASS

The potential loss/gain in catches is based on estimates from Cheung et al. (in press). Such estimates include changes in maximum potential catch for 1,066 exploited fish and shellfish species and are segregated spatially into 0.5 degree latitude x 0.5 degree longitude. This includes a wide range of taxonomic groups, ranging from krill, shrimps, anchovy and cod to tuna and sharks. Overall, they contributed 70 percent of the total reported global fisheries landings from 2000–04 (*Sea Around Us* Project database: www.seaaroundus.org). There are three steps involved in the projection of future fisheries catch potential: (1) projecting future species distribution ranges with a simulation model (Cheung et al. 2009); (2) projecting primary production in the future with empirical models (Sarmiento et al. 2004); and (3) calculating potential change in catch with an empirical model (Cheung et al. 2008b, in press).

We simulated future changes in the distribution by using a dynamic bioclimate envelope model (Cheung et al. 2008a, 2009). First, the distribution map of each species in recent decades (i.e., 1980—2000) was derived from an algorithm described in Close et al. (2006). The model identified species' degree of preference to and association with environmental conditions that include sea water temperature (bottom and surface), salinity, distance from sea-ice, and habitat types (coral reef, estuaries, seamounts, and coastal upwelling). Second, species' environmental preferences were then linked to the expected carrying capacity in a population dynamic model in which growth, mortality, and spatial dynamics of adult movement and larval dispersal along ocean currents were explicitly modeled (Cheung et al. 2008a, 2009). Finally, given the projected changes in ocean conditions and advection fields from an ocean-atmosphere-coupled global circulation model (GCM) under climate change scenarios, the model simulated the annual changes in distribution of relative abundance of each species on the global 30' x 30' grid.

We used projections of future primary production estimated from the methods documented in Sarmiento et al. (2004). To predict ocean primary production, we employed three different published algorithms described in Carr (2002), Marra et al. (2003), and Behrenfeld and Falkowski (1997) that calculate phytoplankton primary productivity as a function of the modeled surface cholorophyll content and its distribution, light supply and vertical attenuation, and sea surface temperature (Sarmiento et al. 2004). All the physical parameters were outputs of the NOAA/GFDL's coupled model. Spatial resolution of the estimated annual average primary productivity is scaled onto a 30' lat. x 30' long. grid. Thus we predicted annual primary production from the world ocean from 2001 to 2060 for the two climate change scenarios from each of the above algorithms.

Using a published empirical model described in Cheung et al. (2008b), we calculated the annual maximum catch potential for each of the 30' x 30' grid cells. The empirical model estimates a species maximum catch potential (*MSY*) based on the total primary production within its exploitable range (*P*), the area of its geographic range (A), its trophic level (λ), and includes terms correcting the biases from the observed catch potential (*CT*: number of years of exploitation, and *HTC*: catch reported as higher taxonomic level aggregations):

$$\mathrm{Log}_{10}\, MSY_t = -2.991 + 0.826 \cdot \log_{10} Pt - 0.505 \cdot \log_{10}(A_t) - 0.152 \cdot \lambda + 1.887 \cdot \log_{10} CT + 0.112 \cdot \log_{10} HTC + \varepsilon$$

where t is year and ε is the error term. The spatial distribution of the calculated maximum catch potential was assumed to be proportional to the predicted relative abundance of each species in each 30' x 30' cell.

We computed the projected future maximum catch potential for all the 1,066 species included in this study by 2050 under the "severe' and "mild" climate change scenarios (Cheung et al. in press). The projected changes in catch potential are by exclusive economic zones and exploited species. Assuming that **ex**-vessel prices remain constant from now to 2050, we calculated the projected landed value by 2050. It equals to the product of the landed value in 2000 and the projected changes in landed value.

3.2 ADJUSTING CATCH POTENTIAL TO ACCOUNT FOR OTHER CLIMATE CHANGE AND FISHING IMPACTS

We modify the potential loss/gain determined under section 3.2 above to take into account the other effects of marine climate change—such as ocean acidification, coral bleaching, and other changes in ocean biogeochemistry—and the additional impact of overfishing. Specifically, we considered two scenarios of the effect of climate-induced coral reef degradation, ocean acidification, and other impacts on future catch potential and landed values. In addition, we include a scenario where unsustainable fishing resulted in an overall reduction in global fish catch.

3.2.1 Climate-induced coral reef degradation

In the severe climate change impact scenario, catch potential of coral-reef-associated species are assumed to decrease by a maximum of 50 percent by 2050. Since different species have different levels of dependency on coral reefs, their levels of impact will also be different. First, we divide exploited species into five broad categories according to their degree of association to coral reef: no, low, medium, high, very high. Their degree of association is based on a published index of association to coral reef (see www.seaaroundus.org for details). This index scales from 0 to 1, with 1 having the strongest association to coral reefs. Thus, the categories are assigned the index values of: 0, >0 & <=0.4, >0.4 & <=0.6, >0.6 & <=0.8, >0.8 for no, low, medium, high, and very high categories, respectively. Next, the related impacts of coral reef degradation on the species' catch potential increases with their association to coral reefs: no (0 percent), low (30 percent), medium (50 percent), high (70 percent), and very high (100 percent). Species with very high association to coral reefs will thus receive full impact (that is, 100 percent x 50 percent reduction in catch potential), while those with low coral reef association will only suffer from partial impact (30 percent x 50 percent reduction in catch potential).

3.2.2 Other climate-induced impacts

We assume that other potential climate change impacts such as ocean acidification or increased hypoxic zones will reduce the overall maximum catch potential. In the severe climate change impact scenario, these other impacts are assumed to reduce overall catch potential by 30 percent. Under the mild climate change impact scenario, coral-reef-associated species will receive a maximum of 10 percent reduction in catch potential, while the impacts from other ocean climate change impacts will reduce the overall catch potential by 5 percent.

3.2.3 Impacts of declining fish catch from unsustainable fishing

We consider two scenarios: The first scenario considers an optimistic scenario where most fish stocks are properly managed from now on, and global fish catch is maintained at the year 2000 levels for the next 50 years. The second scenario is a "worst-case scenario," which is presented in Pauly et al. (2003). Reported statistics suggest that the global marine fish catch has been decreasing since the late 1980s. Extrapolating from this trend results in a nearly 40 percent reduction in global fish catch by 2050 (Pauly et al. 2003). We assume this decline in the worst-case scenario.

3.3 DETERMINING THE POTENTIAL ECONOMIC LOSS/GAIN IN LANDED VALUES AND HOUSEHOLD INCOMES

Using our estimates of potential catches of fish globally under our baseline, mild and severe scenarios as determined in 3.1 and 3.2 above, we (a) calculated the difference in catch between the mild and the baseline scenarios, and between the severe and baseline scenarios; (b) applied ex vessel prices to the catch changes to obtain the loss/gain in landed values or gross revenues to the fishing sector under our mild and severe climate change scenarios; and (c) used an input-output table approach (Dyck and Sumaila 2009) to determine the losses/gains in household incomes under the two climate change scenarios based on the losses/gains in gross revenues.

3.4 CALCULATING THE AMOUNT OF ENDOWMENT NEEDED TO REPLACE LOST GROSS REVENUES FROM THE WORLD'S FISHERIES

The premise for calculating the amount of endowment needed to replace lost fisheries' gross revenues under climate change is that the ultimate goal of adaptation in economic terms should be to replace the loss in gross revenues from the fisheries sector under climate change. This approach is further justified because data on actual adaptation cost is very scanty for this sector, with the implication that any estimate of actual adaptation costs will be limited. The endowment approach asks the following question: What is the capital that a country, region, or the world will need to have in other to replace the loss in gross revenues that is likely to be incurred as a result of climate change?

3.5 ESTIMATING ACTUAL ADAPTATION COST FOR THE COUNTRIES THAT WILL SUFFER LOSSES UNDER CLIMATE CHANGE

To deal with diminishing catches and fishing opportunities, countries around the world have invested resources in the fishing sector of their countries over time. The adaptation measures that have been used by governments are fisheries buybacks (Clark et al. 2005), individual transferable quotas (Clark et al., in press) and livelihoods diversification measures (Teh et al. 2008). Countries such as members of the European Union and the United States have been compelled to buy fishing access rights from mainly developing countries as an adaptation measure to keep their bloated fishing capacity busy and supply fish to meet the growing demand at home. Furthermore, countries have sought to adapt to declining marine fishing opportunities by investing in the development of a fish farming sector, with mixed results.

To provide a first estimate of the actual cost of adapting fisheries to climate change, we first collected data for instances where these measures have been applied to deal with declines in fish catches in the past. The data collected include the amount of money spent relative to either the quantity of fish catch the spending was meant to take care of, or the number of boats or fishers it was meant to ease the declining fishery.

We split the world's maritime countries into two groups, made up of developing and developed countries, based on the World Bank's classification. We then searched the literature and the World Bank's database for the data needed for our analysis. In all, we obtained data for seven developing and five developed countries. We then calculated the average cost per metric ton of fish that a given reported amount supported in terms of, for example, buying fishers out of a fishery suffering catch declines for these two groups. The calculated averages are then applied in the case of countries we could not find data for. Clearly, this is a first approximation only. Data for more countries are needed to improve the current estimate.

3.6 HOW WE REPRESENT THE FUTURE—2010 TO 2050

3.6.1 The baseline

3.6.2 Without climate change

We assume that without climate change, global fisheries may either be able to maintain the current level (year 2000) of catch or continue with the declining trend seen since the 1980s, depending on other things such as fisheries management interventions, etc. The total gross fisheries revenues for the baseline (without climate change) scenario was thus calculated from the net present value from 2010 to 2050 with (1) annual landed value and catch maintained at the 2000 level, and (2) annual landed value and catch decreases by 20 percent by 2050 to take into account the potential for continued overfishing of the world's fish stocks.

With economic and demographic projections
The United Nations Population Division, in a recent projection (United Nations, Department of Economic and Social Affairs 2007) predicts a global population of 8.04 billion for the year 2025 and 9.37 billion for 2050. According to this estimate, therefore, there will be about 50 percent more people to feed by 2050. Also, incomes in many emerging economies, some of them large developing countries (China, India, and Brazil, for example), are projected to increase dramatically in the coming decade. In addition it is expected that the march of economic integration and globalization that was witnessed in the last several decades will continue into the future, resulting in further cointegration of the markets for fish and fish products. The first two trends are likely to increase demand and put pressure on the price of fish even without considering the impact of climate change. On the other hand, market integration is likely to put downward pressure on the price of fish as fish moves quickly from areas of low demand to those of high demand. This latter point may be the reason for the apparent lack of noticeable increases in the real price of fish in general recently (Sumaila et al. 2007). For the purposes of the current analysis therefore, we assume fish prices will increase enough over time to make up for inflation, leaving real prices constant.

3.6.3 Climate change scenarios

- *Global severe climate change impact*. Ocean conditions change as projected under the "business as usual" scenario (Special Report on Emission Scenario A1B) in which CO_2 concentration will stabilize at 720 ppm by 2100, and ocean acidification, coral bleaching, and other ocean changes have a large impact on fisheries productivity.
- *Global mild climate change impact*. Ocean conditions change as projected under the scenario in which greenhouse gas concentrations are maintained at the 2000 level (380 ppm), an ocean acidification, coral bleaching, and other ocean changes have a low impact on fisheries productivity.

3.7 HOW COSTS OF ADAPTATION ARE DEFINED

Adaptation is here understood to mean any action taken to reduce the risk posed by the impact of climate change on the gross revenues obtained from fisheries worldwide. The cost of adapting fisheries to climate change is then the cost of taking such action to reduce the risk of losing revenues from fishing as a result of climate change. To capture this cost, we used two approaches. First, we pose the question: What is the capital that a country will need in terms of an endowment to replace the loss that is likely to be incurred as a result of climate change? Second, we use historical cost data for adjusting fisheries in crisis worldwide because of declines in catches as a basis for calculating what the cost of adapting fisheries to climate change is likely to be.

3.8 HOW COSTS OF ADAPTATION ARE CALCULATED

First, we determine the potential loss/gain in ex vessel landed values or gross revenues. We do this because of the lack of cost data that would have allowed us to calculate economic rent. Second, we calculate estimated household incomes from global fisheries under different climate change scenarios. Third, we determine the amount of endowment needed to replace lost gross revenues at the global and regional levels. Finally, we estimate direct (actual) adaptation cost under climate change using historical cost data for adjusting fisheries after big drops in catches such as in the case of northern cod off Newfoundland, Canada.

These four variables together capture the cost of adapting fisheries to climate change in a broad sense.

3.9 DATA (SOURCES, ASSUMPTIONS, AND SIMPLIFICATIONS)

Ex vessel price data for each taxonomic groups and fishing countries were obtained from Sumaila et al. (2007). We calculated the ex vessel landed values by exclusive economic zones and the high seas for the world ocean in year 2000 in constant 2005 dollars. We obtained catch data from the *Sea Around Us* project to evaluate the trends of reported global fish catch. The *Sea Around Us* project developed an algorithm that disaggregated reported catch data from 1950 to 2004 into a 30' lat. x 30' lon. grid of the world ocean (see Watson et al. 2004 and www.seaaroundus.org for details). The main source of catch data is the fisheries statistics from the Food and Agriculture Organization of the United Nations (FAO), which is modified where appropriate with more reliable data.

We only included exploited stocks that were reported in the catch statistics as species-specific groups (a total of 1,066 species). We excluded groups that were aggregated under higher taxonomic units, e.g., groupers, snappers, and sharks. Species composition of these higher taxonomic groups are generally unknown and the methodology employed here to simulate future changes in fish distributions and catch potential does not account for these groups. For economic data (e.g., the direct cost of adaptation) we searched the literature, the Internet, and the World Bank's project database for relevant data.

4. RESULTS

4.1 THE POTENTIAL LOSS/GAIN IN LANDED VALUES DUE TO CLIMATE CHANGE

Globally, the fishing sector may have an annual loss in landed values or gross revenues of between $17 to $41 billion in constant 2005 dollars as a result of climate change. As can be seen in Table 4.1, this loss is distributed unevenly across different continents. Specifically, developing countries are likely to suffer a two to three times larger loss in landed value or gross revenue under the more intensive and less intensive scenarios, respectively. For example, under the more intensive severe climate change scenario, the calculated potential loss of

TABLE 4.1. ANNUAL LOSS IN LANDED VALUE UNDER DIFFERENT CLIMATE CHANGE SCENARIOS (CONSTANT 2005 $ BILLION). NUMBERS IN PARENTHESES REPRESENT PROJECTED GAIN IN LANDED VALUE.

	Mild scenario ($ billions)			*Severe scenario ($ billions)*		
	Less intensive[4]	*More intensive*[5]	*Over- exploitation*[6]	*Less intensive*	*More intensive*	*Over-exploitation*
Global	16.75	31.31	9.64	21.59	40.99	19.32
Developed country[1]	4.13	8.07	2.27	5.02	10.36	4.56
Developing country[1]	11.19	18.77	7.02	15.16	24.93	13.18
World bank region						
Sub-Saharan Africa[2]	1.37	2.22	0.87	1.68	2.80	1.45
East Asia & Pacific[2]	7.02	10.94	4.63	10.83	15.49	9.18
Europe & Central Asia[2]	0.32	1.31	(0.01)	(0.26)	1.26	(0.06)
Latin America & the Caribbean[2]	1.21	2.17	0.73	1.42	2.72	1.28
Middle East & North Africa[2]	0.61	0.84	0.43	0.67	0.98	0.57
South Asia[2]	0.44	0.96	0.21	0.55	1.26	0.51
Other developing[3] countries	0.22	0.34	0.16	0.28	0.42	0.25
High seas	1.43	4.47	0.35	1.40	5.70	1.58

[1] The numbers for developed and developing countries do not sum to the global total because of the high seas. The regional numbers do not add up because countries that are not eligible for World Bank loans are not included in the six regional classification; and also because the high seas numbers are not included.
[2] Only includes countries that are considered by the World Bank in their regional classification.
[3] All other countries (excluding high seas) that are not considered by the World Bank. We assume that all countries that are eligible to receive loans from the World Bank are developing countries.
[4] For the mild scenario, this refers to a maximum of 10 percent reduction in annual catch of coral-reef-associated species due to climate-related coral reef impacts and 5 percent reduction in overall catch resulting from other impacts. For the severe scenario, this refers to a maximum of 20 percent of reduction in coral reef catch and 10 percent of overall catch.
[5] For the mild scenario, this refers to a maximum of 30 percent reduction in annual catch of coral-reef-associated species due to climate-related coral reef impacts and 20 percent reduction in catch resulting from other impacts. For the severe scenario, this refers to a maximum of 50 percent of reduction in coral reef catch and 30 percent of overall catch.
[6] The scenario where the severe scenario (footnote 5) relative to a baseline scenario of 20 percent reduction in catch by 2050 from 2000 because of overfishing.

annual landed value in developing countries is $25 billion, while the equivalent number for developed countries is $11 billion per year. In terms of World Bank regions, East Asia and the Pacific is predicted to suffer the largest loss in landed value ($7–$16 billion).

4.2 THE POTENTIAL LOSS/GAIN IN HOUSEHOLD INCOMES DUE TO CLIMATE CHANGE

The projected loss in household income shows similar trends as the potential loss in landed values. Under the various scenarios, global loss in household income may be between $6–$14 billion per year depending on the climate change scenario. Households in developing countries may suffer a bigger loss of $3.9–$8.4 billion relative to those in developed countries ($1.6–$4.2 billion) as a result of decreased landed value from their EEZs. Under the severe climate change scenario, the East Asia and the Pacific region suffers the biggest loss of up to $6 billion per year. This is followed by Latin America and the Caribbean and Sub-Saharan Africa.

TABLE 4.2. ANNUAL LOSS IN HOUSEHOLD INCOME UNDER DIFFERENT CLIMATE CHANGE SCENARIOS (CONSTANT 2005 $ BILLION). NUMBERS IN PARENTHESES REPRESENT GAINS INSTEAD OF LOSS.

	Mild scenario ($ billions)			*Severe scenario ($ billions)*		
	Less intensive[1]	*More intensive*[2]	*Over- exploitation*	*Less intensive*	*More intensive*	*Over- exploitation*
Global[3]	5.90	10.94	3.41	7.58	14.30	6.77
Developed country	1.57	3.09	0.86	1.90	3.96	1.73
Developing country	3.89	6.48	2.45	5.25	8.59	4.56
World bank region						
Sub-Saharan Africa	0.44	0.72	0.27	0.53	0.92	0.47
East Asia & Pacific	2.66	4.11	1.76	4.02	5.75	3.41
Europe & Central Asia	0.10	0.40	0.00	(0.07)	0.39	(0.01)
Latin America & the Caribbean	0.33	0.64	0.19	0.34	0.77	0.31
Middle East & North Africa	0.15	0.21	0.11	0.17	0.24	0.14
South Asia	0.14	0.30	0.07	0.18	0.40	0.17
Others developing countries[3]	0.07	0.10	0.05	0.08	0.12	0.07
High seas	0.44	1.37	0.11	0.43	1.74	0.48

[1] The numbers for developed and developing countries do not sum to the global total because of the high seas. The regional numbers do not add up because countries that are not eligible for World Bank loans are not included in the six regional classification; and also because the high seas numbers are not included.
[2] Only includes countries that are considered by the World Bank in their regional classification.
[3] All other countries (excluding high seas) that are not considered by the World Bank. We assume that all countries that are eligible to receive loans from the World Bank are developing countries.

4.3 THE AMOUNT OF ENDOWMENT NEEDED TO REPLACE LOST CATCH REVENUES

The loss in landed value and household income may require a total of $419–$1025 billion endowment to offset by 2050 under the various scenarios of climate change and fishing impacts (Table 4.3). Developing countries may require $277–$605 billion to offset the loss from their EEZs, while developed countries may require $106–$278 billion under the various scenarios. Regionally, under all scenarios, East Asia and the Pacific are predicted to require the largest endowment ($175–$387 billion), followed by the Latin America and the Caribbean ($30–$68 billion) and Sub-Saharan Africa regions ($34–$70 billion).

TABLE 4.3. ANNUAL AMOUNT OF ENDOWMENT REQUIRED TO OFFSET THE POTENTIAL IMPACTS UNDER DIFFERENT CLIMATE CHANGE SCENARIOS (CONSTANT 2005 $ BILLION). NUMBERS IN PARENTHESES REPRESENT GAINS INSTEAD OF LOSS.

	Mild scenario ($ billions)			*Severe scenario ($ billions)*		
	Less intensive[1]	*More intensive*[2]	*Over- exploitation*	*Less intensive*	*More intensive*	*Over- exploitation*
Global[3]	418.75	782.76	240.88	539.80	1024.78	482.90
Developed country	103.31	201.69	56.66	125.59	259.09	114.05
Developing country	279.81	469.23	175.46	379.09	623.22	329.45
World bank region						
Sub-Saharan Africa	34.21	55.44	21.73	41.88	70.05	36.34
East Asia & Pacific	175.38	273.38	115.66	270.68	387.13	229.41
Europe & Central Asia	8.00	32.72	(0.19)	(6.49)	31.52	(1.39)
Latin America & the Caribbean	30.32	54.26	18.15	35.53	68.04	31.93
Middle East & North Africa	15.33	20.99	10.78	16.73	24.38	14.17
South Asia	10.97	24.03	5.35	13.75	31.52	12.84
Others countries Developing	5.61	8.41	3.99	7.02	10.57	6.15
High seas	35.63	111.84	8.76	35.11	142.47	39.40

[1] The numbers for developed and developing countries do not sum to the global total because of the high seas. The regional numbers do not add up because countries that are not eligible for World Bank loans are not included in the six regional classification; and also because the high seas numbers are not included.
[2] Only includes countries that are considered by the World Bank in their regional classification.
[3] All other countries (excluding high seas) that are not considered by the World Bank. We assume that all countries that are eligible to receive loans from the World Bank are developing countries.

4.4 ESTIMATED ACTUAL ADAPTATION COST UNDER DIFFERENT CLIMATE CHANGE

We estimated that the annual direct adaptation cost required for the fishing sectors is between \$7–\$30 billion (Table 4.4). Developing countries may require \$5–\$14 billion of adaptation cost per year, while developed countries may require \$3–\$12 billion depending on the scenario being considered. Again, because of the higher loss in potential fisheries catches, the East Asia and the Pacific region is likely to require the highest per annum direct adaptation costs for fishing.

TABLE 4.4. ESTIMATED ANNUAL ACTUAL ADAPTATION COST UNDER DIFFERENT CLIMATE CHANGE SCENARIOS (CONSTANT 2005 \$ BILLION). NUMBERS IN PARENTHESES REPRESENT GAINS INSTEAD OF LOSS.

	Mild scenario (\$ billions)			*Severe scenario (\$ billions)*		
	Less intensive[1]	*More intensive*[2]	*Over-exploitation*	*Less intensive*	*More intensive*	*Over-exploitation*
Global[3]	7.44	21.75	2.19	9.89	29.47	9.91
Developed country	3.09	8.78	0.99	3.82	11.66	3.88
Developing country	5.11	10.98	2.54	6.84	14.71	6.27
World bank region						
Sub-Saharan Africa	0.24	0.73	0.06	0.38	1.05	0.37
East Asia & Pacific	2.80	4.89	1.69	4.55	7.10	3.90
Europe & Central Asia	0.27	1.12	(0.02)	(0.50)	0.88	(0.26)
Latin America & the Caribbean	1.25	3.19	0.49	1.90	4.48	1.78
Middle East & North Africa	0.19	0.28	0.12	0.29	0.40	0.24
South Asia	0.31	0.64	0.16	0.16	0.66	0.18
Others countries developing	0.07	0.13	0.04	0.06	0.15	0.06
High seas	(0.76)	1.99	(1.34)	(0.78)	3.10	(0.24)

[1] The numbers for developed and developing countries do not sum to the global total because of the high seas. The regional numbers do not add up because countries that are not eligible for World Bank loans are not included in the six regional classification; and also because the high seas numbers are not included.
[2] Only includes countries that are considered by the World Bank in their regional classification.
[3] All other countries (excluding high seas) that are not considered by the World Bank. We assume that all countries that are eligible to receive loans from the World Bank are developing countries.

4.5 SUMMARY OF ADAPTATION COSTS RELATIVE TO THE BASELINE (WITH 5 PERCENT DISCOUNT RATE)

The potential loss or endowment/adaptation costs in the fishing sector resulted worldwide due to climate change are not evenly distributed across the next 40 years (2010–50) (Table 4.5a). Globally, the loss in gross revenues, household income, and the endowment required to offset the losses over time increases from the short term (2010–19), peak in the mid-term (2020–40), and then declines slightly by the long term (2040–49) under all climate change scenarios and with a 5 percent discount rate. A similar temporal pattern is consistent in developed/developing countries or in the major World Bank regions. It should be noted that the reduction in cost in the long term is due to the "diminishing" effects of discounting with time.

TABLE 4.5A. SUMMARY RESULTS: LOSS IN GROSS REVENUES WITH 5 PERCENT DISCOUNT RATE (CONSTANT 2005 $ BILLIONS). NUMBERS IN PARENTHESES REPRESENT GAINS INSTEAD OF LOSS.

		Time profile of cost ($ billion)			
Region	*Scenario*	*2010–19*	*2020–29*	*2030–39*	*2040–49*
Global	Mild	13.92	29.39	30.84	26.79
	Severe	56.45	119.21	125.09	108.66
	Overexploit	16.05	33.89	35.56	30.89
Developed	Mild	3.43	7.25	7.61	6.61
	Severe	14.81	31.27	32.81	28.50
	Overexploit	3.79	8.00	8.40	7.30
Developing	Mild	9.30	19.64	20.61	17.90
	Severe	31.95	67.47	70.80	61.50
	Overexploit	27.46	64.33	68.87	60.32
World bank region					
Sub-Saharan Africa	Mild	1.14	2.40	2.52	2.19
	Severe	3.64	7.68	8.06	7.00
	Overexploit	1.21	2.55	2.68	2.32
East Asia & Pacific	Mild	5.83	12.31	12.92	11.22
	Severe	18.20	38.44	40.33	35.04
	Overexploit	7.62	16.10	16.89	14.67
Europe & Central Asia	Mild	0.27	0.56	0.59	0.51
	Severe	2.82	5.95	6.24	5.42
	Overexploit	(0.05)	(0.10)	(0.10)	(0.09)
Latin America & the Caribbean	Mild	1.01	2.13	2.23	1.94
	Severe	3.76	7.93	8.32	7.23
	Overexploit	1.06	2.24	2.35	2.04
Middle East and North Africa	Mild	0.51	1.08	1.13	0.98
	Severe	1.16	2.46	2.58	2.24
	Overexploit	0.47	0.99	1.04	0.91
South Asia	Mild	0.36	0.77	0.81	0.70
	Severe	1.87	3.95	4.14	3.60
	Overexploit	0.43	0.90	0.95	0.82
Other developing countries	Mild	0.19	0.39	0.41	0.36
	Severe	0.50	1.07	1.12	0.97
	Overexploit	0.20	0.43	0.45	0.39
High seas	Mild	1.18	2.50	2.62	2.28
	Severe	9.69	20.47	21.48	18.66
	Overexploit	1.31	2.76	2.90	2.52

TABLE 4.5B. SUMMARY RESULTS: LOSS IN HOUSEHOLD INCOME (CONSTANT 2005 $ BILLIONS). NUMBERS IN PARENTHESES REPRESENT GAINS INSTEAD OF LOSS.

		Time profile of cost ($ billion)			
Region	*Scenario*	*2010–19*	*2020–29*	*2030–39*	*2040–49*
Global	Mild	4.90	10.34	10.86	9.43
	Severe	19.63	41.46	43.50	37.79
	Overexploit	5.62	11.88	12.46	10.83
Developed	Mild	1.31	2.76	2.89	2.51
	Severe	5.69	12.01	12.60	10.94
	Overexploit	1.44	3.04	3.19	2.77
Developing	Mild	3.23	6.82	7.16	6.22
	Severe	10.98	23.19	24.33	21.14
	Overexploit	9.44	22.11	23.67	20.73
World bank region					
Sub-Saharan Africa	Mild	0.36	0.77	0.81	0.70
	Severe	1.20	2.54	2.66	2.31
	Overexploit	0.39	0.82	0.86	0.75
East Asia & Pacific	Mild	2.21	4.67	4.90	4.25
	Severe	6.77	14.29	15.00	13.03
	Overexploit	2.83	5.98	6.27	5.45
Europe & Central Asia	Mild	0.08	0.18	0.18	0.16
	Severe	0.86	1.81	1.90	1.65
	Overexploit	(0.01)	(0.02)	(0.02)	(0.02)
Latin America & the Caribbean	Mild	0.28	0.58	0.61	0.53
	Severe	1.14	2.40	2.52	2.19
	Overexploit	0.26	0.55	0.58	0.50
Middle East and North Africa	Mild	0.13	0.27	0.28	0.24
	Severe	0.28	0.60	0.63	0.55
	Overexploit	0.12	0.25	0.26	0.23
South Asia	Mild	0.12	0.25	0.26	0.23
	Severe	0.59	1.24	1.30	1.13
	Overexploit	0.14	0.29	0.31	0.27
Other developing countries	Mild	0.06	0.12	0.12	0.11
	Severe	0.15	0.31	0.33	0.28
	Overexploit	0.06	0.13	0.13	0.12
High seas	Mild	0.36	0.76	0.80	0.70
	Severe	2.96	6.26	6.57	5.71
	Overexploit	0.40	0.85	0.89	0.77

TABLE 4.5C. SUMMARY RESULTS: ENDOWMENT NEEDED TO MAKE UP FOR LOSS IN GROSS REVENUES (CONSTANT 2005 $ BILLIONS). NUMBERS IN PARENTHESES REPRESENT GAINS INSTEAD OF LOSS.

		Time profile of cost ($ billion)			
Region	*Scenario*	*2010–19*	*2020–29*	*2030–39*	*2040–49*
Global	Mild	347.92	734.67	770.92	669.67
	Severe	1411.33	2980.15	3127.19	2716.46
	Overexploit	401.22	847.22	889.03	772.26
Developed	Mild	85.83	181.25	190.19	165.21
	Severe	370.17	781.65	820.22	712.49
	Overexploit	94.76	200.10	209.97	182.40
Developing	Mild	232.48	490.91	515.13	447.47
	Severe	798.85	1686.85	1770.08	1537.59
	Overexploit	686.54	1608.20	1721.80	1507.95
World bank region					
Sub-Saharan Africa	Mild	28.42	60.02	62.98	54.71
	Severe	90.94	192.04	201.51	175.05
	Overexploit	30.19	63.76	66.90	58.12
East Asia & Pacific	Mild	145.72	307.69	322.88	280.47
	Severe	455.08	960.95	1008.36	875.92
	Overexploit	190.61	402.49	422.35	366.87
Europe & Central Asia	Mild	6.65	14.03	14.72	12.79
	Severe	70.41	148.67	156.00	135.51
	Overexploit	-1.16	-2.45	-2.57	-2.23
Latin America & the Caribbean	Mild	25.19	53.19	55.82	48.49
	Severe	93.93	198.33	208.12	180.78
	Overexploit	26.53	56.03	58.79	51.07
Middle East and North Africa	Mild	12.74	26.89	28.22	24.51
	Severe	29.12	61.50	64.53	56.06
	Overexploit	11.78	24.86	26.09	22.66
South Asia	Mild	9.11	19.24	20.19	17.54
	Severe	46.75	98.72	103.59	89.99
	Overexploit	10.66	22.52	23.63	20.53
Other developing countries	Mild	4.66	9.84	10.32	8.97
	Severe	12.62	26.64	27.96	24.28
	Overexploit	5.11	10.79	11.33	9.84
High seas	Mild	29.61	62.52	65.60	56.99
	Severe	242.30	511.65	536.89	466.38
	Overexploit	32.73	69.12	72.53	63.00

TABLE 4.5D. SUMMARY RESULTS: ESTIMATED ACTUAL ADAPTATION COST (CONSTANT 2005 $ BILLIONS). NUMBERS IN PARENTHESES REPRESENT BENEFITS RATHER THAN COSTS.

		Time profile of cost ($ billion)			
Region	*Scenario*	*2010–19*	*2020–29*	*2030–39*	*2040–49*
Global	Mild	6.18	13.05	13.69	11.89
	Severe	47.20	99.66	104.58	90.84
	Overexploit	22.86	48.27	50.65	44.00
Developed	Mild	2.57	5.42	5.69	4.94
	Severe	18.75	39.60	41.55	36.09
	Over-xploit	9.04	19.09	20.04	17.41
Developing	Mild	4.24	8.96	9.40	8.17
	Severe	21.36	45.11	47.34	41.12
	Overexploit	11.52	24.33	25.53	22.18
World bank region					
Sub-Saharan Africa	Mild	0.20	0.42	0.44	0.38
	Severe	1.65	3.47	3.65	3.17
	Overexploit	0.81	1.72	1.80	1.56
East Asia & Pacific	Mild	2.32	4.91	5.15	4.47
	Severe	8.86	18.70	19.62	17.05
	Overexploit	5.63	11.89	12.48	10.84
Europe & Central Asia	Mild	0.22	0.47	0.49	0.43
	Severe	2.33	4.91	5.15	4.48
	Overexploit	0.63	1.34	1.40	1.22
Latin America & the Caribbean	Mild	1.04	2.19	2.30	2.00
	Severe	6.73	14.20	14.90	12.95
	Overexploit	3.50	7.39	7.76	6.74
Middle East and North Africa	Mild	0.15	0.32	0.34	0.30
	Severe	0.46	0.98	1.02	0.89
	Overexploit	0.32	0.67	0.70	0.61
South Asia	Mild	0.26	0.54	0.57	0.49
	Severe	1.13	2.38	2.49	2.17
	Overexploit	0.51	1.07	1.12	0.98
Other developing countries	Mild	0.06	0.12	0.12	0.11
	Severe	0.22	0.47	0.49	0.43
	Overexploit	0.12	0.25	0.26	0.22
High seas	Mild	(0.63)	(1.33)	(1.40)	(1.21)
	Severe	7.08	14.96	15.69	13.63
	Overexploit	2.30	4.85	5.09	4.42

In addition to computing the present values using a discount rate of 5 percent, we also run sensitivity analysis using discount rates of 3 percent and 7 percent. As would be expected, the lower discount rate produced much larger adaptation costs because future costs are given higher weights.

5. LIMITATIONS

5.1 TREATMENT OF EXTREME EVENTS

Our analysis focuses largely on the effects of changes in mean conditions of ocean conditions, while we did not consider the effects of extreme weather events such as changes in frequency and intensity of storms and hurricanes. These extreme events are likely to have a strong impact on the fishing sectors as these events may affect fishing operations, increase risk of fishing, or damage fishing gear or infrastructure. Consideration of these events may thus increase the amount of endowment and adaptation cost required for the fishing sectors under marine climate change.

5.2 TREATMENT OF TECHNOLOGICAL CHANGE

Technological change is partially and implicitly considered in the analysis. In our analysis, we assume that the fishing sectors would develop or modify fishing gear or technology to cope with the change in species compositions resulting from the shift in species distributions and fishing grounds. However, we do not consider the potential improvement in the efficiency of fishing from new technology, which may reduce fishing cost, or **new** technology that allows the fishing sector to target previously unexploited stocks.

5.3 TREATMENT OF INTER-TEMPORAL CHOICE

Inter-temporal choice is the study of the relative value people assign to two or more payoffs at different points in time. This relationship is usually simplified to today and some future date. Economists incorporate inter-temporal choice through the process of discounting future values (Sumaila and Walters 2005). Inter-temporal choice is fundamental to the study of environmental and natural resource use and can single-handedly determine the outcome of economic analysis in natural resource economic models (Sumaila and Walters 2005). The baseline discount rate used for this analysis is 5 percent. Sensitivity analysis using discount rates of 3 percent and 7 percent showed that the lower discount rate produced much larger adaptation costs because future costs are given higher weights.

5.4 TREATMENT OF "SOFT" ADAPTATION MEASURES

Our estimates focus largely on "soft" adaptation measures that are needed to facilitate fishing sectors' ability to adapt to climate change. Such soft adaptation measures focus largely on reducing excessive fishing capacity resulting from loss of potential fisheries catch under marine climate change. However, we did not consider "hard" adaptation measures such as development of fishing equipment and fisheries infrastructure (fishing ports or processing plants) that may be affected by climate change.

5.5 TREATMENT OF CROSS-SECTOR MEASURES

We did not explicitly address cross-sector measures. We assume that fishers displaced from the loss of fishing revenues due to climate change could be transferred to other livelihoods given that sufficient funds are provided to them either directly or indirectly.

5.6 AREAS FOR FOLLOW-UP WORK AND RESEARCH ADVANCES

There are several major areas of research that could improve the estimates of cost of adaptation to climate change in fisheries in the future. Firstly, we should improve our understanding of the effects of climate change on fisheries productivity. We have identified areas of major uncertainty in our projections of potential change in fisheries catch. These include the effects of marine climate change on primary productivity, distributions and abundance of fish stocks, the impacts of change in ocean chemistry including acidification, and increased hypoxic zones and habitat impacts (e.g., coral bleaching) on fisheries production. Second, the effects of changes in potential fisheries catch on costs of fishing should be better understood to improve the assessment of climate change effects of the economics of fishing. Third, alternative scenarios of changes in seafood demand and prices under marine climate change and its implications for the fishing sector could be developed and considered. Moreover, there is currently scarce information on the potential cost of implementing climate change adaptation strategies for fishing sectors. Future studies could provide better estimates on the potential adaptation cost to different regions and fishing sectors. In addition, the implication of extreme events for the fishing sectors could be considered when a better understanding of the effects of extreme events on the cost of fishing are gained.

CONCLUSIONS

This study provides the first estimate of the potential cost of adapting the world's fishing sector to climate change. We found that, globally, the fishing sector may suffer from $17–$41 billion of annual loss in landed value depending on how mild or severe climate change is likely to be. This may result in an annual loss in household income of $6–$14 billion. Given these potential losses, the fishing sector may require an endowment of $420–$1025 billion to offset the impacts of climate change. Moreover, the estimated annual adaptation cost is from $7 to $30 billion depending on the assumptions on the severity of climate change.

Impacts to fishing sectors in developing countries in terms of loss in landed values or gross revenues from fishing and household incomes is estimated at about 2–3 times higher than those for developed countries. These countries would also require higher adaptation costs than developed countries under all the scenarios considered in this study.

Regionally, East Asia and the Pacific suffers the most in losses and in the need for endowment and adaptation costs. This is followed by Latin American and the Caribbean and Sub-Saharan Africa. These regions consist of some of the countries that have been identified as most socioeconomically vulnerable to climate change impacts through fisheries.

This study represents the first attempt to estimate adaptation costs to climate change in the fishing sector. As a result, the numbers presented are uncertain and may be a conservative estimate of the potential costs. However, by exploring different scenarios, we provide a set of reasonable and robust estimates that will support current international work on how to adapt fisheries to climate change. In addition, this work provides a foundation for further work in this topical area of research.

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