ENVIRONMENTAL STUDIES

Benefits of the Paris Agreement to ocean life, economies, and people

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The Paris Agreement aims to mitigate the potential impacts of climate change on ecological and social systems. Using an ensemble of climate-marine ecosystem and economic models, we explore the effects of implementing the Agreement on fish, fishers, and seafood consumers worldwide. We find that implementing the Agreement could protect millions of metric tons in annual worldwide catch of top revenue-generating fish species, as well as billions of dollars annually of fishers' revenues, seafood workers' income, and household seafood expenditure. Further, our analysis predicts that 75% of maritime countries would benefit from this protection, and that ~90% of this protected catch would occur within the territorial waters of developing countries. Thus, implementing the Paris Agreement could prove to be crucial for the future of the world's ocean ecosystems and economies.

INTRODUCTION

Marine social-ecological systems are already being affected by climate change (*1*), with fish species shifting their distributions, resulting in the decline of some local fish stocks. Scientific projections suggest increasing stress on biodiversity and ecosystem services over the course of the 21st century if temperatures are not held below 2°C above preindustrial levels (*1*). Warming, ocean acidification, and deoxygenation combined with other stresses could change primary productivity, growth, and distribution of fish populations, resulting in changes in the potential yield of exploited marine species (*1*) and the economic (*2*) and social benefits that they provide (*3*). To mitigate the negative effects of climate change, the global community adopted the Paris Agreement in 2015 (the Agreement), aiming to implement strategies to keep average temperature increase at "well below 2°C" and "pursue efforts to limit warming to 1.5°C" (*4*). Achieving the Paris Agreement has been projected to benefit fisheries through reducing changes in species composition and catch losses (*5*). Also, previous research efforts have projected economic outcomes linked to shifting abundance and distribution of marine species targeted by fisheries (*6*), finding that most of the negative impacts will be borne by tropical—and often developing—countries, with potential benefits to countries in northern latitudes as a result of poleward shifts in species distributions.

Here, we build on previous findings regarding the impact of climate change on biomass, catch, and revenue to determine how implementing the Paris Agreement could mitigate these reported changes and how this mitigation may be effected through changes in ex-vessel fish prices, and through subsequent changes to fishers, and to seafood workers' income (SWI), and to seafood consumers' expenditures worldwide. The effect of changes in supply on price is a fundamental concept in economic theory, although it has been used sparingly in global fisheries analyses (*7*) and usually not disaggregated by taxon and region. The fact that seafood is a highly traded commodity that is sourced from other regions of the world is a relevant factor that can influence the outcome of such studies (*8*). While international trade can influence price flexibilities (or how domestic supply and demand change), our analysis indicates that the influence of trade on domestic markets is small. Available data on seafood trade suggest the plausibility of this conclusion because (i) a large portion of the catch in seafood-producing countries is consumed locally, and (ii) price transmissions (or pass-through) from international markets to domestic markets are generally low (0 to 5%) (Materials and Methods).

We integrate taxa and country-specific supply-demand and economic impact models with climate-marine ecosystem models to carry out our analysis and estimate the effect of achieving the Agreement compared to "business-as-usual" on the (i) fish biomass (FB); (ii) maximum catch potential (MCP; i.e., potential maximum sustainable yield); (iii) fishers' revenues (FRs); (iv) SWI; and (v) household seafood expenditure (HSE; i.e., the amount spent by households to purchase seafood) (Fig. 1).

Two scenarios were evaluated, using outputs from an ensemble of three Earth system models (ESMs) (*9*–*11*) to determine the year when warming targets are reached (Fig. 1 and Materials and Methods): an average increase in global atmospheric temperature by 3.5°C relative to preindustrial levels, which is consistent with expected warming based on the currently implemented greenhouse gas mitigation policies (*12*) (business-as-usual scenario), and a target atmospheric warming of 1.5°C as per the Agreement ("achieving the Agreement scenario"). Resulting FB and MCP given these scenarios are projected using the dynamic bioclimatic envelope model (DBEM) reported in (*5*).

We projected changes in FB and MCP for 381 distinct top revenue-generating fish species that were caught worldwide from 2001 to 2010, the latest time period for which there are systematic data available on total (including unreported bycatch and illegal and unregulated discards) catches (*13*). FRs are determined under each climate scenario by using reported fish price flexibilities [i.e., change in fish price relative to change in quantity supplied (*14*)] by taxon, categorized by developed and developing country to account for the relative purchasing power of these groups of countries (Materials and Methods). These price flexibilities are applied to the net change in MCP to determine the net change in FR under each scenario (Materials and Methods).

Income and economic impact multipliers for the fishing sector are applied to projected FRs to determine the effects of achieving the

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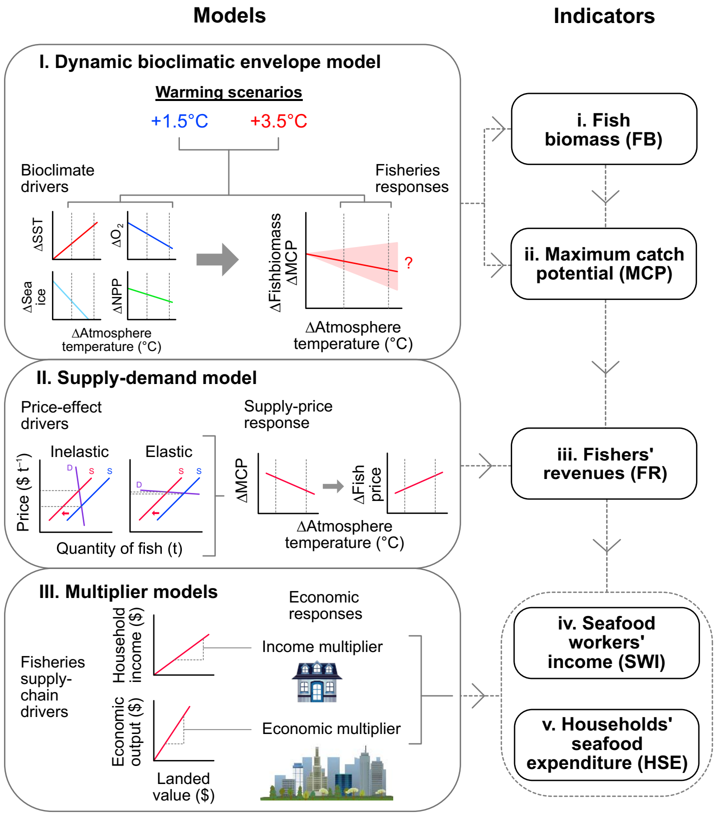

Fig. 1. Conceptual diagram of the biophysical and economic models used in this study. NPP, net primary production; SST, sea surface temperature; t, metric tons.

Agreement on SWI and the HSE for fish consumers. The economic impact multiplier is a factor representing downstream economic impacts from a given industry (*15*). For example, on average globally, each dollar of landed value is estimated to generate about three dollars of economic activity involving seafood processors and retailers as well as fishers (*16*). We thus apply multipliers to FRs to obtain their total contribution to economic output, including activities directly and indirectly dependent on fisheries catch. To capture the total SWI generated throughout the economy by output in the fisheries sector through indirect and induced effects, we apply the income multiplier (refers to the increase in final income arising from any new injection of spending (Materials and Methods).

RESULTS

Our study projects a positive global average change of 6.5% (see Table 1 for ranges) in the FB of the top revenue-generating fish species under the achievement of the Agreement scenario. For the Exclusive Economic Zones of developing and developed countries, we report average changes of 8.4 and −0.4%, respectively (Table 1). All continents, except Europe, are projected to see higher FB with (versus without) achieving the Agreement. Also, we find that 75% of all maritime countries would benefit from implementation of the Agreement. The larger gain in FB in developing country waters is due to the substantially high sensitivity of tropical habitat conditions and fish stocks to different warming scenarios. Thus, achieving the Agreement maintains habitat suitability for tropical species, mitigating large potential decreases in biomass and catch.

Larger FB and higher ocean productivity mean higher catch potential. Achieving the Agreement is projected to increase sustainable global fish catches of the top revenue-generating fish species studied by 7.3% per year or 3.3 million metric tons (Table 1 and table S1); ~90% of this increase would occur within developing country waters. The implementation of the Agreement increases FRs by \$4.6 billion annually and SWI by \$3.7 billion and reduces HSE by \$5.4 billion (table S1).

Extrapolating from the catch of the top revenue-generating fish species to be protected to the global catch of ~130 million metric tons suggests that the Agreement could protect a total of 9.5 million metric tons of catch annually. Everything being equal, this gain in catch translates into gains of \$13.1 billion in FR and \$10.6 billion in SWI, while reducing HSE by \$18.3 billion (table S2).

We find that FRs are affected by quantity and price effects in different ways throughout the world (Fig. 2). Russia, for instance, is projected to see reduced catch (quantity effect) by 25%, led by lower biomass of pollock (*Theragra chalcogramma*) and cod (*Gadus morhua*) under the 1.5°C warming target (relative to the 3.5°C). This quantity effect is projected to lower FRs by 21%, but a subsequent projected 19% increase in ex-vessel prices (price effect) resulted in a negligible overall loss (<2%) in FRs for the country. Conversely, for the United States, FRs decrease by 8% because of price effects but are more than offset by a 21% increase in catch potential, resulting in a net increase of 13% in FRs (Fig. 2).

DISCUSSION

These findings are noteworthy in several ways. First, other sources of animal protein (freshwater fisheries, aquaculture, and animal husbandry) are also being affected by climate change, which, together, means that implementing the Agreement would protect a larger

Table 1. Projected percentage differences of indicators relative to 2001–2010 period between two scenarios: +1.5°C warming Agreement target and +3.5°C warming relative to preindustrial levels. Values calculated from outputs of DBEM multimodel mean changes in abundance and catch are in bold, while values from outputs of DBEM lower and upper bounds are in parentheses below.

	FB gains (%)	MCP gains (%)	FR gains (%)	SWI gains (%)	Savings in HSE (%)
Global	**6.5** (1.4, 9.1)	**7.3** (0.1, 14.1)	**7.4** (5.3, 9.4)	**7.8** (6.3, 10.6)	**3.2** (−0.8, 5.3)
Region					
Developing	**8.4** (5.1, 12.2)	**11.4** (6.6, 16.5)	**7.8** (4.9, 9.4)	**8.4** (5.8, 10.7)	**2.0** (−2.2, 4.1)
Developed	**−0.4** (−11.9, 12.3)	**−0.3** (−11.7, 9.7)	**6.8** (5.2, 9.4)	**7.2** (4.4, 10.5)	**4.5** (0.6, 6.5)
Africa	**8.4** (6.7, 10.3)	**12.8** (10.5, 14.2)	**6.9** (4.9, 8.3)	**7.6** (5.0, 9.4)	**3.5** (0.0, 8.3)
Asia	**10.1** (7.4, 11.7)	**7.6** (4.0, 11.1)	**6.8** (3.0, 12.6)	**5.2** (2.4, 9.6)	**2.5** (−3.5, 6.2)
Europe	**−1.7** (−15.4, 13.1)	**−4.3** (−18.4, 7.8)	**6.4** (3.3, 8.0)	**6.2** (3.6, 8.6)	**3.1** (−4.8, 7.7)
North America	**9.1** (0.5, 19.5)	**9.7** (2.1, 17.0)	**9.1** (5.3, 12.5)	**9.7** (4.8, 13.8)	**3.4** (0.4, 5.4)
Oceania	**5.0** (2.9, 6.2)	**10.3** (9.3, 11.3)	**4.0** (2.4, 6.0)	**4.1** (2.2, 6.5)	**7.1** (5.1, 8.6)
South America	**5.3** (3.9, 6.3)	**14.1** (7.1, 22.0)	**10.0** (4.7, 17.5)	**10.8** (4.7, 19.0)	**3.8** (3.0, 4.9)

amount of animal protein supply (*17*). Second, the estimated effects on catch, revenues, fishers' incomes, and household seafood budgets are not trivial for developing regions with higher levels of seafood dependence (Fig. 3). For example, seafood provides more than 50% of animal protein in many small island developing states, and the relative impact of losses will be much greater for these regions than the global average if the Agreement warming target is not achieved (Table 1 and Fig. 3).

There is a well-recognized mismatch between the main sources of greenhouse gas emissions and the locations where the negative consequences of those increased emissions would be felt most, including the specific consequences for marine fisheries. People living in developing countries (Fig. 3, blue circles) generally emit much less CO_2 per capita, yet are relatively more dependent on seafood for their animal protein and more likely to be negatively affected than residents of developed countries if the Agreement is not implemented (Fig. 3). The scientific consensus predicts that the potential catch will decrease in the tropics (low per capita emissions) and increase in higher-latitude economically developed regions (high per capita emissions) (*1*, *5*). Benefits from implementing the Agreement, as reflected by our findings, also contribute directly to key related international agreements such as the United Nations Sustainable Development Goals (*18*), particularly goals 1 (no poverty), 2 (zero hunger), 8 (decent work and economic growth), and 14 (life below water), and others through downstream cobenefits (*19*).

The marine fisheries sector supports ~260 million full- and part-time jobs worldwide, many of these in large developing countries such as India, Indonesia, and Nigeria (*20*). A steady supply of fish is essential to support these jobs, food sovereignty, and human well-being. Also, seafood products remain a critical export commodity for many developing countries, offering foreign currency opportunities that may otherwise be lost and intensifying poverty with considerable social consequences such as forced internal and international migration. These negative impacts jeopardize our ability to meet other policy targets, such as the SDGs (sustainable development goals) (*18*) or Aichi Biodiversity Targets (*21*). Adapting to existing climate change effects (*17*, *22*) and implementing the Paris Agreement are crucial for the future of the world's ocean fisheries while helping to meet the growing challenges of supporting healthy and peaceful societies into the future, worldwide.

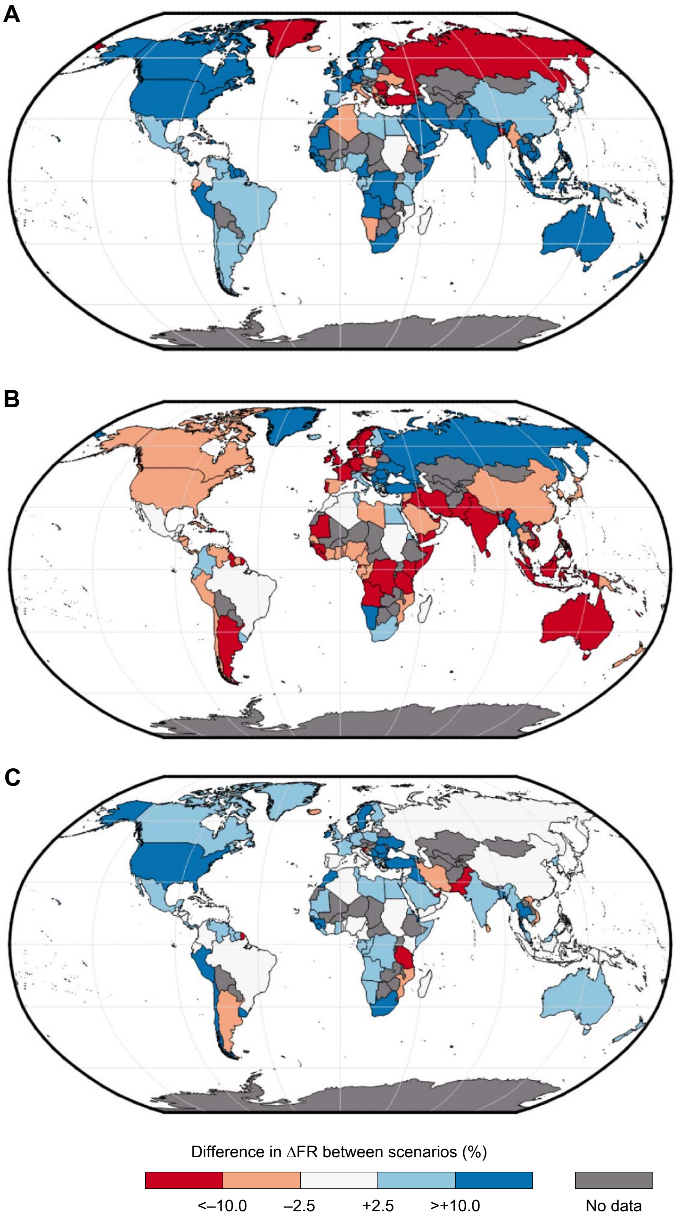

Fig. 2. Effects meeting Paris Agreement targets. Effects of meeting Paris Agreement targets (1.5°C warming) on FRs relative to 3.5°C warming due to (**A**) changes in MCP, (**B**) changes in price as a result of changes in supply, and (**C**) net change to FRs from combined quantity and price effects. Projections are relative to the 2001–2010 period. Similar figures for other economic indicators are given in fig. S1.

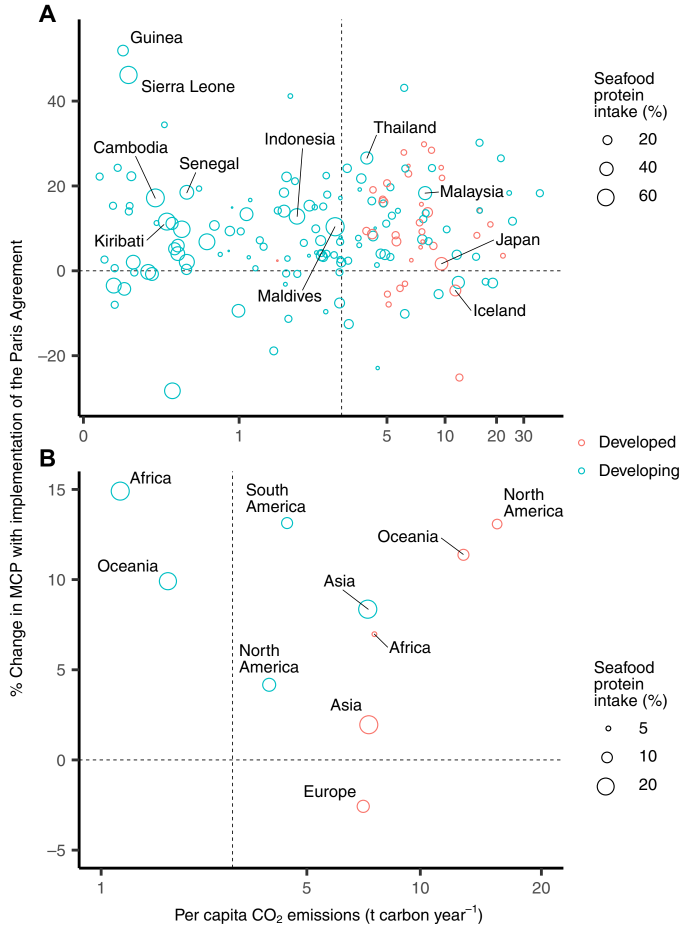

Fig. 3. Projected gains in MCP. Projected gains in MCP (relative to the 2001–2010 period) if Paris Agreement targets are met (1.5°C relative to 3.5°C warming) and the 2015 CO_2 emissions by (**A**) country and (**B**) continent (table S3). Larger point size indicates a greater proportion of protein derived from seafood, while the vertical line represents the median per capita CO_2 emission levels. Note the log scale for CO_2 emissions.

MATERIALS AND METHODS

Indicators of the effects on fish and people

To capture how well fish and people will cope with and without meeting the Paris Agreement target, we selected the following indicators: (i) FB, (ii) MCP, (iii) FRs, (iv) SWI, and (v) HSE. Typically, economists use economic rent (i.e., a payment to a factor of production, e.g., fish stocks, in excess of that needed to keep it in its present use) to determine the economic performance of a fishery. Because of the scale and the broad scope of our analysis, we decided to use a set of indicators instead, which do not include profit because of the extreme difficulty of determining future costs.

Institutional setting for study

In fisheries economic analyses, the institutional setting in which a fishery operates is important. The performance of a fishery depends on whether the fishery is managed effectively or not; is the fishery effectively regulated or not regulated at all, is illegal fishing and unreporting of catch a problem, or is fish regulated only on paper without real enforcement—in other words, is the fishery operated under open access or catch shares with strictly enforced total allowable catches? Incorporating the institutional setting is important when one is studying a specific fishery because it can affect how fishing fleets respond to changes in fish stocks and thus how seafood is supplied to the market.

Here, we are analyzing performance at the national level, and there is evidence to show that, while some countries perform better at managing their fisheries than others, the overall performance of virtually all countries is not that good (*23*, *24*). To provide an aspirational benchmark, we assumed a positive, even if not realistic, future in which all fisheries are managed and used at their MCP. In making this assumption, we are well aware that achieving MSY (maximum sustainable yield) conditions for all fisheries (or even all fisheries in one country) is certainly a big challenge. In practice, managers should be more cautious of using MSY as a target and instead operate with reference points and targets that reflect national or regional fisheries management objectives and capacities.

Developing an analysis that captures a "realistic" scenario of particular fisheries would become highly complicated, as decisions would need to be made regarding the expected deviation from MSY for each fishery or each country. While this can be done, the purpose of this paper is not to develop scenarios of cross-national fisheries management but to evaluate the expected impacts of mitigating climate change, ceteris paribus, on fish stocks. Hence, we chose MSY as the aspirational baseline reference given that it is widely recognized in the marine governance and scientific community (for example, its presence as a goal in the United Nations Convention on the Law of the Sea). We do, however, acknowledge that fisheries management is crucial to the achievement of potential benefits under any climate scenario and that, since actual fisheries management performance is typically far from ideal, actual realized gains are likely to be less than we estimate in this contribution.

Climate-marine ecosystem models

Following (*5*), we projected changes to the biomass and MCP of fish species under two contrasting climate change scenarios characterized by Representative Concentration Pathways (RCPs). The RCP 2.6 is a strong mitigation greenhouse gas emission scenario, which, by the end of the 21st century, is projected to lead to a net radiative forcing of 2.6 Wm^{-2}. The RCP 8.5 is a high business-as-usual greenhouse gas emission scenario that projects a net radiative forcing of 8.5 Wm^{-2} by the end of this century. We projected the results using a DBEM and an ensemble of ESMs consisting of a GFDL-ESM2M model from National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamics Laboratory (GFDL) (*9*), IPSL-CM5LR model from the Institut Pierre Simon Laplace (IPSL) (*10*), and MPI-ESM from the Max Planck Institute for Meteorology (MPI-M) (*11*) to estimate the uncertainties associated with the physical and biogeochemical components of climate change. These models were used as the basis for estimating the changes in MCP. Note that our underlying assumption is that the MCP is fully fished, i.e., MCP equals the supply of fish on the market. It should be noted that this assumes away fishing effort dynamics, although we are aware that different profit margins in different fisheries would induce different behavioral responses of fishers.

We chose two temperature benchmarks, i.e., 1.5° and 3.5°C warming relative to preindustrial levels, as our warming target scenarios. Under the 1.5°C warming scenario, we assumed that the Agreement is successfully implemented, limiting global warming to 1.5°C relative to the preindustrial levels. We used RCP 8.5 and 2.6 scenarios to trace the year at which the target atmospheric temperatures (i.e., 1.5° or 3.5°C) are achieved under each of these models (table S3). The models simulate how changes in temperature, oxygen content (represented by O_2 concentration), net primary production, and other variables, such as ocean current patterns, salinity, and sea ice extent, would affect growth, production, and distribution of marine fishes and invertebrates (*25*) in the year at which the target temperature is achieved. Fishing mortality is assumed to be the level required to achieve maximum sustainable yield to simulate MCP. With this information, changes in FB and potential catch, relative to the average level from 2001 to 2010, of each taxon reported in official statistics, in each maritime country, were computed. Then, the changes in FB and MCP were estimated for each model when the atmospheric surface temperature is 1.5° and 3.5°C warmer than the preindustrial level.

We assumed full adaptation to and utilization of new species in our analysis. For example, when a new species emerges in an Exclusive Economic Zone of a country, we assume that a fishery will be developed to capture possible economic benefits and jobs. However, it would only be included in the analysis if it ranked in the top 10 by landed value for each country.

Choice of economic modeling approach

To determine the impact of the Paris Agreement on SWI and HSE for fish consumers (i.e., the amount required to purchase seafood for household consumption), net changes in landed values are combined with income and economic multipliers reported in (*16*). Thus, we used the input-output (I-O) approach for our analysis in contrasts to, e.g., computable general equilibrium (CGE) models.

It is worth noting that the I-O approach is not without its shortcomings (*19*, *26*). Other methods used to analyze the economic impacts of fishing include social accounting matrices, fisheries economic assessment models, and CGE models. Each of these techniques has its merits and demerits, which have been discussed in the literature at length (*27*–*29*). Given that I-O and CGE approaches have much in common in terms of questions addressed, data requirements and range of applications (*27*, *28*), and the above strengths and weaknesses, it was clear to us that, although not perfect, an I-O–based economic model was the best choice given the objectives and scale (global, temporal, and interdisciplinary) (*30*) of our work. As with all modeling efforts, we highlighted the weaknesses and caveats of this approach.

Supply-demand models and price flexibilities

To isolate the impact of climate change on fish prices through changes in supply, we have to keep all other factors that can affect price constant: $P = P(Q, \bar{M})$, where P is the price per unit and Q is the quantity of fish demanded, which is assumed to be equivalent to the MCP under different climate scenarios. $\bar{M}$ denotes a vector that represents all other demand determinants, e.g., income, price of substitutes, and inventory changes that are held constant to help us isolate the effect of climate change on the ex-vessel price of fish. It is assumed that an increase (or decrease) in Q with $\bar{M}$ held constant would decrease (or increase) price. This is a conventional assumption that is supported by available empirical evidence, i.e., $\frac{\partial P(Q,\bar{M})}{\partial Q} < 0$.

Seafood economists often use demand models to measure the responsiveness of demand to price and income change. Most studies have focused on own price elasticity, which measures the responsiveness of demand to its price change, with everything else remaining constant (*14*). Here, we instead focused on price flexibility to help us capture both the price and quantity effects of implementing the Paris Agreement. Conceptually, elasticity is estimated from the quantity-dependent demand function (ordinary): $Q_x = f(P_x, P_y, I)$, where Q_x is the quantity demanded of product x, P_x is the product's own price, P_y is the price of related products, and I is the income.

Price flexibility is defined inversely in that it answers the question, how might price be affected by changing quantity demanded? This concept of flexibility is based on a price-dependent (inverse) demand function: $Px= f(Qx,Qy,I)$, where Px is the price of product x, Qx is the quantity demanded of product x, Qy is the quantity demanded of related products, and I is the income. Inverse demand models are widely used in cases where quantity is constrained by exogenous factors and environmental conditions (e.g., local carrying capacity or regulations such as quotas), including fisheries. In these cases, supply is independent of or less dependent on price, making demand factors the most important for determining price (*31*).

Here, we analyzed the potential changes in prices under different fish abundances linked to climate change scenarios. Given that the quantity that can be supplied is affected by different climate conditions, coupled with higher demand from a growing population and increasing incomes, prices are likely to be influenced by a demand factor relative to supply. The own-price flexibility used in the analysis can then be expressed as: $\psi = \Delta Px/\Delta Qx$, where ψ represents the own-price flexibility.

We relied on existing literature for the price flexibilities applied in this analysis, including reported flexibilities for species or species groups in developed and developing countries, respectively (table S4). For species or species groups with multiple reported price flexibilities, an average value was used. Because of limited empirical flexibility estimates, some of the own-price flexibilities used in this analysis are the reciprocal of reported own-price elasticities. Mathematically, the price elasticity and flexibility are reciprocal to each other. However, given the likelihood that the demand for fish is substitutable (among fish and/or shellfishes), each reciprocal of own-price elasticity should be viewed as a lower limit (*30*).

International fish price transmission into domestic markets

Seafood markets and trade

The discussion below is based on our analysis of trade data provided by the Food and Agricultural Organization (FAO) of the United Nations. Most fish export data reported to the FAO consist of the combined total of exports of fish caught within national borders and the re-export of fish caught abroad. There is evidence that re-exports of fish for processing and quality sorting can be high (*32*) and that this fact can result in double counting of trade, leading to the overestimation of standard trade statistics such as the estimation of trade "openness" (*33*). A subset of countries report special trade, which includes only exports of the fish caught within their border. This subset is composed of 45% of all countries reporting trade statistics to the FAO, with 24 developed and 60 developing countries, for a total of 84 countries that, together, produced approximately 33% of the world's catch from marine capture fisheries in 2011–2015.

Of these 84 countries, 46% (*30*) exported more than half their domestic production to other countries. However, their share of production in world catch was a little less than 14% (approximately 42% of the share of our subset). Many countries in our subset did not export a large portion of their domestic production, with 25 countries exporting less than 10% of their catch (table S5). This evidence suggests that, for this subset, our assumption of domestic models of supply and demand is a good approximation.

Examining the pass-through of changes in the world price of food to the domestic price of food

While changes in the global price of food can sometimes influence domestic prices, the literature finds that the transmission is small. This is because most food markets are protected by high trade barriers (agriculture and food are typically subject to large tariff and nontariff barriers). It is also likely due to the high cost needed to transport food that is fresh and subject to spoilage. This high cost of transportation further insulates these markets. For fisheries, both these factors imply that price changes in international markets transmit in small proportions to domestic fish markets (as reported from research at the World Bank (*34*–*36*). In analyzing whether changes in world prices of staple food influence domestic prices and thus poverty levels in developing countries Ivanic *et al.* (*36*), demonstrated that a 13% decrease in the international price of fish has a minimal impact on prices in 28 developing countries. The pass-through was zero for 50% of the 28 countries, between 0 and 5% for 12 countries, and above 5% for the remaining 2 countries (table S6).

The evidence we find suggests that domestic supply and demand changes are unlikely to have impacts outside the border of the country experiencing changes. It also implies that changes in international prices (largely determined by the developed economies of the world) are unlikely to pass through to the developing countries of the world.

If this is true, then a domestic supply and demand model is appropriate for our analysis. However, it is possible that trade plays a larger role in fishery markets than reported for our subset. Even in that case, the main insight gained from using our domestic demand and supply model is robust to the inclusion of trade. Our analysis makes it clear that limiting climate change will help improve fisheries catch and create large social and economic benefits to those in the fisheries industry. The magnitude of these benefits is subject to the size of trade, and if trade is sizable in the countries that we ignore, then some of the price changes will be dampened. In that case, our estimates can be seen as an upper bound of the gains from limiting climate change.

Net change in landed values

Historical landed values were obtained from combining a reconstructed marine fisheries catch database (*13*) with a complementary ex-vessel fish price database (*37*). Reconstructed catches begin with reported FAO catches but include additional details from different fishing sectors (i.e., recreational, artisanal, and subsistence) and fisheries catch composition (e.g., discards and species breakdown). The reconstruction of fisheries catch records involves compiling data from multiple sources including primary and gray literature, government and nongovernment agencies, and direct contact with partners located around the world for region-specific data. Other records of marine fisheries catch are known to be largely underestimated and exclude large quantities of biomass that have been removed from marine environments (*13*).

Ex-vessel fish prices were obtained from a reconstructed version of a global ex-vessel fish price database developed to complement the reconstructed SAU (Sea Around Us) catch database (*37*). In other words, each unique species-country-year catch record has a corresponding price, which was either a direct match from price data collection or derived from an estimation model. Ex-vessel fish prices are the prices received directly by a fisher for their catch or at the first point of sale when the fish first enters the supply chain. For catch records with no direct price match, prices were estimated using a country-product-dummy model where reported prices were matched on the basis of taxonomic classification and converted using purchasing power parities (*37*). Ex-vessel prices used are an average weighted by the landed values for the proportion of landings destined for various fisheries end products: direct human consumption, fishmeal and fish oil production, and other purposes.

Catches, prices, and landed values were averaged from 2001 to 2010 as a baseline to quantify the potential changes in the years that the two target warming temperatures (+1.5° and +3.5°C) are reached. Projected changes in future catches were estimated by combining historical catch numbers with outputs from the climate-marine ecosystem models

$$C_{\text{target}\,\Delta°\text{C}} = C_{2001-2010} * \Delta\text{MCP}_{\text{target}\,\Delta°\text{C}}$$

where $C_{\text{target}\,\Delta°\text{C}}$ is the projected catch in the year that the target temperature is reached, $C_{2001-2010}$ is the historical catch, and $\Delta\text{MCP}_{\text{target}\,\Delta°\text{C}}$ is the projected percent change in MCP in the year that the target temperature is reached relative to the 2001–2010 period (Fig. 1, indicator ii).

Future ex-vessel prices were calculated using supply-demand models based on historical prices and the relative change in supply. We applied price flexibilities reported in table S4 that define a given percent change in price as a result of a 1% change in supply (i.e., MCP), such that

$$P_{\text{target}\,\Delta°\text{C}} = P_{2001-2010}{}^*(\Delta\text{MCP}_{\text{target}\,\Delta°\text{C}}{}^* - \text{Flex})$$

where $P_{\text{target}\,\Delta°\text{C}}$ is the projected price in the year when atmospheric temperature reaches target temperature, $P_{2001-2010}$ is the historical ex-vessel fish price, and Flex is the species-region–specific price flexibility.

Thus, projected landed values are a product of the relationship between the price and catch quantity and the interplay of that catch (or supply) on price. Changes to landed values may then be minimized as a result of a change in price. For example, a decrease in supply (MCP) will directly decrease FR (which is catch × price), but an increase in price due to a decrease in supply will offset the decrease in landed values, with the magnitude dependent on the price flexibility of the product. Changes in landed values in the year the target warming temperature is reached relative to 2001–2010 as a result of a change in supply and price were calculated for each warming scenario (+1.5° and +3.5°C). Changes to MCP (Fig. 1, indicator ii) and FRs (Fig. 1, indicator iii) due to meeting the Paris Agreement warming target were estimated by taking the difference in the changes in MCP and FR between scenarios

$$\Delta\text{MCP}_{\text{Paris}} = \Delta\text{MCP}_{1.5°\text{C}} - \Delta\text{MCP}_{3.5°\text{C}}$$
$$\Delta\text{FR}_{\text{Paris}} = \Delta\text{FR}_{1.5°\text{C}} - \Delta\text{FR}_{3.5°\text{C}}$$

where 1.5° and 3.5°C are the warming scenarios for the expected change in MCP and FR.

HSE and SWI

The economic multiplier is a factor that is multiplied by the output value from an economic activity (e.g., fisheries) to estimate the total direct and indirect economic contribution of this activity to the whole economy through other sectors and is used to emphasize that the fisheries industry has many linkages throughout the economy (16). After the fish is landed at the port, they are transported and sold in markets, delivered to the processing plants, and/or sold directly to retailers or restaurants before they are consumed. Along the value chain after fish is landed, a portion of the output value in each sector in this value chain can be traced back to capture fisheries. Economic impacts thus capture the value added along the value chain after a fish is landed, and this final value of seafood is what is paid by consumers, here termed HSE (Fig. 1, indicator v). A related income multiplier specifies the proportion of economic impacts that accrue to seafood-related workers as income throughout the value chain, termed here SWI (Fig. 1, indicator iv).

We applied the economic multipliers for each maritime country reported in (16); the authors used I-O analysis, a technique developed by Nobel Laureate, Wassily Leontief (38) to estimate the economic multiplier for each country (table S7), which was split by the level of development (table S8). The net multiplier is then equal to the Leontief multiplier minus one to take into account the fact that we estimated the multiplier effects using industry output rather than final demand (16), extracted I-O tables from the Global Trade Analysis Project (www.gtap.agecon.purdue.edu/) database at Purdue University, and obtained fisheries-related income and economic multipliers for each coastal country. The total HSE and SWI can be calculated using the following simple equations

$$\mathrm{HSE} = \sum_{i=1}^{n} (\mathrm{FR}_i * V_i)$$

$$\mathrm{SWI} = \sum_{i=1}^{n} (\mathrm{FR}_i * Z_i)$$

where FR_i is the FR, which represents the total industry output, of each country i. The parameters V_i and Z_i represent the economic impact and income multipliers for fisheries, respectively, for each country i.

Aquaculture

Since the 1980s, aquaculture production has been increasing rapidly, making it a big contributor to seafood supply to the global market. Hence, projections of the economics of fisheries should ideally take this into account because a lower supply of wild-caught fish could well be filled by farmed fish. Here, we decided to limit the scope of our analysis to marine fisheries for a number of reasons. First, the current analysis is already massive and could lay the foundation for a more comprehensive follow-up analysis. Second, a combined analysis of the wild and farmed fish sectors under climate change is worthy of a separate study. Third, Lam *et al.* (6) undertook an analysis of different production scenarios, including supply from fish farms. The authors found that, under high CO_2 emission levels (i.e., the Paris Agreement not implemented), global marine fisheries revenues could decrease by up to 15% with faster than the recent rate of aquaculture production and increase by up to 40% with slower than recent growth rates. Aquaculture growth was estimated at 4% in 2015, which is percentage points below the 6% mean growth estimated for the period 2001–2015 and well below the double digits recorded throughout the 1980s and 1990s (39). Hence, the latter scenario of slower aquaculture growth explored in (6) is more likely in the future, implying that our results may not be completely off even if aquaculture is taken into account.

Addressing uncertainties in model structures and parameter values

While integrated models such as the ones used in this study face uncertainties ranging from model structure and parameters across its biophysical and economic components (4), the conclusion presented here is expected to be reasonably robust to these uncertainties for a number of reasons. First, the uncertainties associated with the projected changes in MCP and the translation of radiative forcing to the two global warming scenarios have been previously tested and explored in detail. Hence, the broader-scale patterns of changes in MCP under the global warming scenarios, which are evaluated here, are generally more robust than projections for specific coastal waters that would require higher-resolution input data. Second, the pattern of changes in socioeconomic indicators is consistent across projections with outputs from different ESMs, suggesting that uncertainties are not substantially magnified from the biophysical to the economic submodels (40). Third, seafood economic dynamics are projected using empirical data and evaluated only within the range of projected MCP.

Fourth, we investigated the sensitivity of our three main economic indicators to deviations in price flexibilities. The scaling factor between deviations in price flexibilities and HSE is 1, and therefore, our conclusions for savings in HSE are robust as price flexibilities would need to deviate by >100% to reverse the trends observed (fig. S2). Outcomes for FR and SWI are also reasonably robust to deviations (scales close to 1) in price flexibility for globally aggregated data and for aggregated data by developed and developing regions (fig. S2).

Further, we chose three species that were ranked in the top five landed value list: anchoveta, yellowfin tuna, and a sea scallop (table S9), representing a low-priced species, a high-priced species, and a shellfish species, respectively. Sensitivity analyses show that FR and SWI for anchoveta and scallop are robust to deviations in price flexibilities (scales to less than 1). However, tuna is more sensitive to deviations in price flexibilities, and our FR results could be reversed with a 40% change in price flexibility estimates (fig. S2), which is still a robust result. The high price of tunas explains the sensitivity trends observed, and we expect that small deviations in price flexibilities for expensive commodities (e.g., tunas) will have greater downstream effects on the economy. All of the above suggests that our results are robust to deviations in price flexibility, but they are relatively more sensitive to deviations in biomass as shown with the ranges provided from the results of DBEM simulations with the different ESMs (table S9).

Having said the above, it is still worth cautioning the reader that even if there has been validation of the previous models based on past data, climate change itself is difficult to predict with strong certainty. Also, although the climate models capture some uncertainty, the results are based on a single type of ecological model (i.e., DBEM). Hence, it does not fully account for all the potential feedbacks that could emerge. Further, the resolution of GCMs (general circulation model) upon which the simulations are based are known to be poor at representing coastal regions, which are highly productive, and assessing this source of uncertainty requires further development of climate models, both regional and global. Regarding the supply-demand and multiplier components, one must be aware of the methods used to estimate input parameters and thus the suitability of source data for use within the assumptions of a model.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/5/2/eaau3855/DC1

Fig. S1. Projected differences taken between outcomes of meeting Paris Agreement targets.
Fig. S2. Sensitivity analysis of economic indicators (FR, SWI, and HSE) to changes in price flexibilities aggregated globally, by region, and for select species.
Table S1. Projected differences of indicators relative to 2001–2010 period between outcomes of meeting Paris Agreement targets (+1.5°C) and maintaining high greenhouse gas concentrations trajectory (+3.5°C) relative to preindustrial levels.
Table S2. Current (2001–2010 average) annual values for fisheries indicators of the top 10 revenue-generating species for each country, grouped by continent.
Table S3. Year in which target warming temperature is reached for each RCP within each ESM.
Table S4. Price flexibility by marine species group and country development group.
Table S5. Number of countries and their share in world marine capture catch, by share of exports volume in total domestic supply (2011–2015).
Table S6. Estimated and observed domestic price percent changes for fish with 13% decrease in world price.
Table S7. Multipliers used to determine impacts on SWI and HSE.
Table S8. List of countries by geographic region and FAO development grouping.
Table S9. Projected differences for the top 10 species by landed value globally taken between outcomes of meeting Paris Agreement targets (+1.5°C) and maintaining high emissions (+3.5°C).
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Benefits of the Paris Agreement to ocean life, economies, and people

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