ECOLOGY

Improved fisheries management could offset many negative effects of climate change

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The world's oceans supply food and livelihood to billions of people, yet species' shifting geographic ranges and changes in productivity arising from climate change are expected to profoundly affect these benefits. We ask how improvements in fishery management can offset the negative consequences of climate change; we find that the answer hinges on the current status of stocks. The poor current status of many stocks combined with potentially maladaptive responses to range shifts could reduce future global fisheries yields and profits even more severely than previous estimates have suggested. However, reforming fisheries in ways that jointly fix current inefficiencies, adapt to fisheries productivity changes, and proactively create effective transboundary institutions could lead to a future with higher profits and yields compared to what is produced today.

INTRODUCTION

Oceans provide enormous benefits to people (*1*). Each year, more than 80 million metric tons of seafood is harvested, providing more than 20% of needed animal protein to nearly 3 billion people and livelihood to 10% of the global population (*2*). However, climate change is already compromising these benefits through changes in both stock productivity and location (*3*, *4*). Previous estimates of climate change impacts on the world's fisheries have focused on the direct effects of ecosystem-level changes by comparing maximum potential food production today with that in the future (*4*). While instructive for assessing what could theoretically be possible, focusing on changes in maximum potential food production alone overlooks the effects of alternative human responses to climate change, which could either limit or exacerbate ecosystem changes. The actions of fishermen, management institutions, and markets can all influence the magnitude of fisheries benefits obtained from an ecosystem (*5*). Here, we ask: What are the potential benefits of adaptive fisheries management reforms that address anticipated consequences of changes in species productivity and distribution due to climate change? We examine how future global biomass, harvest, and profit of the world's fisheries might change over time if a range of potential human responses and climate change are considered together.

Considerable scope remains for increasing global fisheries yield, conservation, and profitability by improving current fishery management (*5*), but climate change could compromise these potential upside benefits (*4*, *6*). Although climate effects are diverse, the impacts on global fisheries can be clustered into two broad categories: changes in stock productivity, which affect potential yields and profits, and changes in stock distributions, which affect where fish can be caught and who might catch them. These changes pose distinct management challenges. Responding to changes in fisheries productivity requires harvest policies that are appropriately adaptive to changing demographics. For example, banded morwong and many other species in the Tasman Sea have already experienced noticeable changes in their population sizes driven by rapid warming (*7*, *8*). Failure to adequately address these changes can further exacerbate management failures. By contrast, changes in species distributions (*3*, *9*, *10*) can move stocks into and out of management jurisdictions, such as countries' exclusive economic zones (EEZs), altering management jurisdiction and incentives for those stocks. A perceived or anticipated decline of a stock due to a range shift out of one country creates an incentive to overharvest before it leaves the nation's waters (*11*). In contrast, as a stock enters a new EEZ or the high seas, a new and potentially unmanaged fishery emerges. If left unaddressed, these range shift challenges can drive overharvesting, even in fisheries that are currently managed effectively. For example, until 2009, North East Atlantic mackerel was well managed under a trilateral agreement between Norway, the Faroe Islands, and the European Union. However, because of shifts in migration patterns, Iceland suddenly became a key contender in the fishery and maximized its newfound access to a valuable fishery. Since countries could not agree on appropriate quota allocations, management was compromised. By 2010, mackerel harvest was 40% above safe biological recommendations (*12*). Solving these stock movement challenges requires the proactive development of effective transboundary institutions (*13*, *14*).

To explore the potential range of human responses to climate change, we analyze four management scenarios that bound human responses to the dual challenges of range and productivity shifts: (i) Full Adaptation, (ii) Range Shift Adaptation, (iii) Productivity Adaptation, and (iv) No Adaptation. The Full Adaptation scenario assumes that management addresses both productivity and range shift challenges. Thus, we apply an economically optimal harvest policy that maximizes long-term economic benefits to each stock (*5*). This dynamic harvest control rule optimally adjusts fishing mortality on the basis of available biomass and is therefore naturally adaptive to climate-driven productivity changes. In this scenario, we assume

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that management also addresses challenges posed by shifting stocks (for example, through new proactive institutions, such as effective transboundary agreements), ensuring that effective management does not degrade because of spatial shifts. Therefore, under this management scenario, all species, including those expected to shift across management boundaries, are managed with an optimized harvest control rule. Conversely, the No Adaptation scenario assumes that neither climate challenge is addressed. In this scenario, the current fishing mortality rate is initially applied to all stocks but is only maintained for those that do not shift across EEZs. Management for those that shift gradually transitions to open access, where fishing mortality is driven by short-term profits. Both the looming departure of a stock and the emergence of a new stock motivate this shift in management. The length of this transition for each stock depends on how quickly it is expected to experience a range shift across EEZs. The Full Adaptation and No Adaptation scenarios bookend the possible future outcomes for global fisheries.

The two intermediate scenarios separately address one of the two challenges explored in this paper. The Range Shift Adaptation scenario assumes that management addresses challenges posed by shifting stocks but lacks a response to changes in productivity. Under this management scenario, the current fishing mortality rate is maintained for all stocks, as it ensures that current management does not degrade because of spatial shifts and does not benefit from an optimal harvest rule. Productivity Adaptation manages for fisheries productivity changes that affect population dynamics and potential yields but takes no actions to address range shift challenges. Therefore, the economically optimal harvest rule is only applied to species for which climate change is not expected to cause border crossings. For all other stocks, we apply a harvest rule that gradually shifts from the economically optimal fishing mortality rate to the rate expected under open access (see the "Policy alternatives" section in the Supplementary Materials for details on all policies). These management scenarios, while broad and, in some cases, idealistic, can provide general insights into how a range of approaches to climate challenges might affect future biomass, harvest, and profit.

We apply the appropriate harvest rates prescribed by these four management alternatives to 915 single- and mixed-species stocks across the globe that have adequate data to both assess their current status and forecast their future distributions. The majority (779) consist of stocks of individual species (species stocks). The remainder (136) are mixed-species aggregations (NEI stocks—Food and Agriculture Organization Not-Elsewhere Included fisheries). Cumulatively, these 915 species stocks or NEI stocks (hereafter collectively referred to as "stocks") represent 67% of total current global catch (*2*). Changes in range for each species, projected under four different greenhouse

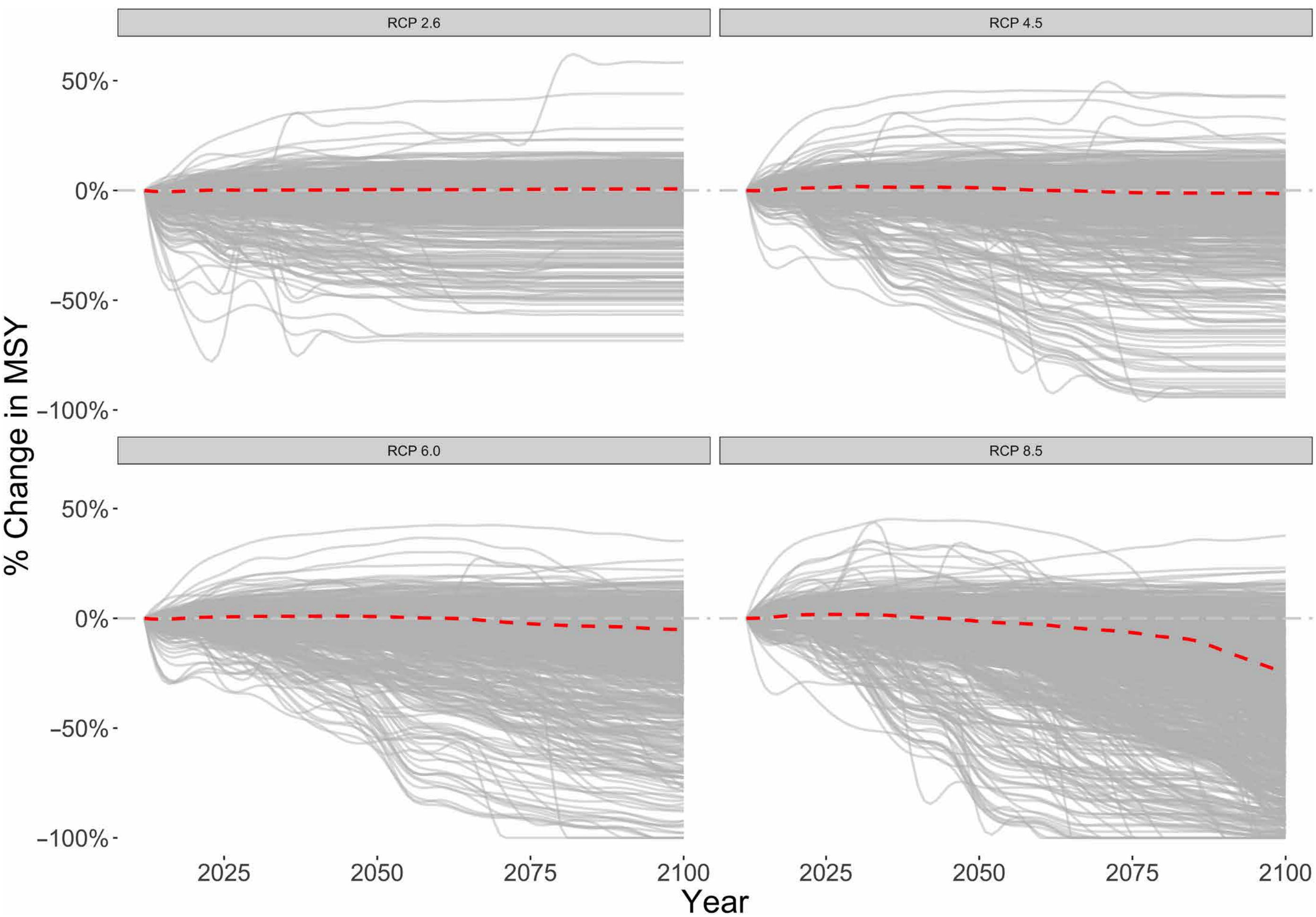

Fig. 1. Percent change in MSY under RCPs 2.6, 4.5, 6.0, and 8.5. The red dashed line indicates global percent change (weighted mean) in MSY. Gray lines represent change in MSY for all 915 global stocks.

gas concentration pathways [Representative Concentration Pathways (RCPs)] (*15*), determine how climate change will likely affect each stock's productivity and spatial range under several future climatic scenarios (table S1). We focus mostly on the moderately high-emission scenario, RCP 6.0, under which global mean temperature is expected to increase by 2.2°C by 2100 (*16*).

RESULTS

Fishery productivity changes

Total global fisheries maximum sustainable yield (MSY) does not change markedly by 2100 under three of the four RCPs. Global MSY (weighted mean) is expected to change by 1.0, −1.5, −5.0, and −25.0% under RCPs 2.6, 4.5, 6.0, and 8.5, respectively (Fig. 1). These modest global changes in productivity under the three lower RCPs, however, mask enormous variation in changes across stocks. While some stocks essentially go extinct (MSY declines by 100%), others increase by more than 35% under RCP 6.0. Overall, approximately 41, 53, 66, and 91% of global stocks experience a projected decline in total MSY by 2100 under RCPs 2.6, 4.5, 6.0, and 8.5, respectively.

Range shifts

The percentage of species stocks that shift across country boundaries by 2100 increases with the severity of the climate projection (Fig. 2). The percentage of individual species that will shift across EEZs ranges from 36% (RCP 2.6) to 81% (RCP 8.5). These shifting stocks comprise between 27.8 and 71.7% of the current global MSY. Under RCPs 6.0 and 8.5, most species that shift across EEZs experience shifts both into new and out of old EEZs (Fig. 2).

Future global projections

We find that adopting proactive and adaptive fishery management approaches today would lead to substantially higher global profits (154%), harvest (34%), and biomass (60%) in the future compared to No Adaptation (Fig. 3). Simultaneously addressing both range shift and productivity changes generates much greater benefits in profits, harvest, and biomass than focusing on either challenge alone. Similar trends are observed across all RCPs, where a fully adaptive strategy produces consistently large increases in all three parameters compared to No Adaptation (fig. S1). Productivity or Range Shift Adaptation alone produces intermediate benefits.

While these results show that adapting to climate change delivers far better outcomes than not adapting, we can also compare future outcomes to what is obtained today. Even in the presence of the net negative effects of climate change, the Full Adaptation policy could deliver higher total profit, harvest, and biomass (increases of 27, 16, and 29%, respectively) than what the oceans provide today (Fig. 4). Increases over today for all three indicators are only attained when both kinds of management changes are pursued together. Productivity Adaptation alone can slightly increase harvest but not profit or biomass, while Range Shift Adaptation alone can slightly increase biomass but not profit or harvest. No Adaptation results in far lower profits, harvest, and biomass compared to what is achieved today. Under the most extreme climate scenario (RCP 8.5), Full Adaptation can no longer generate outcomes that are better than today in all three metrics (Fig. 4 and fig. S1). These patterns of outcomes relative to today generally hold for alternative assumptions regarding global stock composition, the definition of a shifting stock, prices, and costs, and across the range of climate projections (figs. S1 and S5 to S7).

Individual stock projections—current status matters

Although Full Adaptation results in a global win across nearly all RCPs and all three indicators, not all individual stocks see improvements relative to today (Table 1). Whether a stock benefits in the future relative to today from climate-adaptive and proactive management depends on both ecosystem changes (projected magnitude and direction of productivity and range changes) and the fishery's current status. To highlight the role of current stock status, we categorize each species into one of four groups: (i) Healthy, (ii) Emerging, (iii) Recovering, and (iv) Overfished (see Fig. 5 for definitions). Under Full Adaptation, nearly all Healthy stocks see a decrease in biomass by 2100, because this group is currently underexploited relative to its maximum potential production. Although biomass decreases for these stocks, there is an increase in harvest as the species become fully exploited. Emerging stocks will almost exclusively see harvest decreases, even when climate change is inconsequential, because these stocks are currently in a "fishing down" period with harvests significantly higher than their MSY. Most Recovering stocks see increases in biomass and harvest, since stock recovery supports higher yields after the stock is rebuilt and subsequently fished sustainably. Most Overfished stocks see declines in harvest but increases in biomass, as current harvest levels are unsustainably high. Although only 22% of stocks will experience future increases in both harvest and biomass, this subgroup

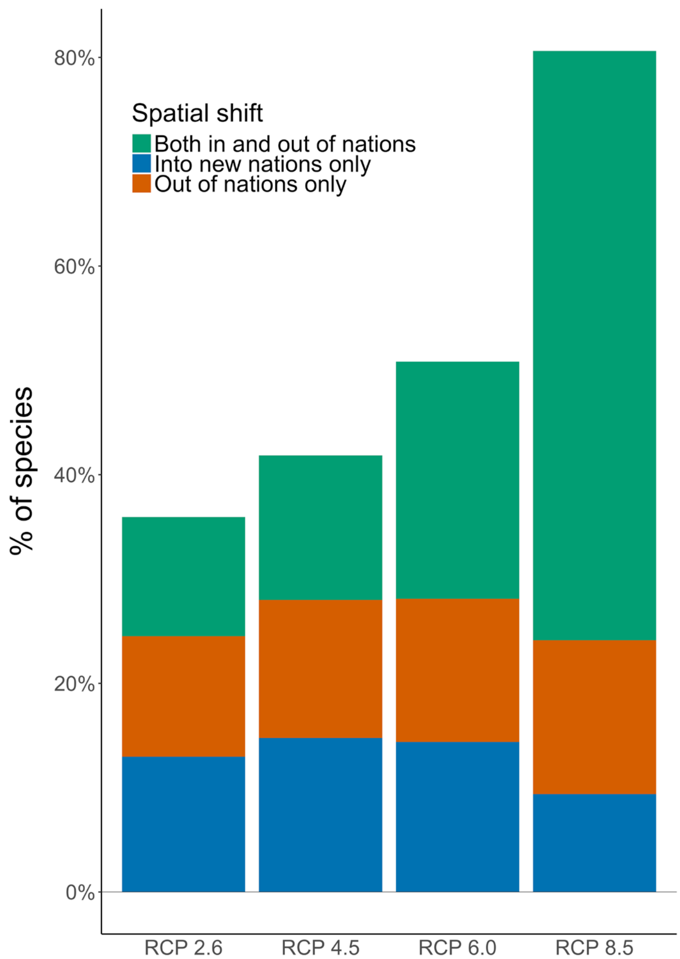

Fig. 2. Percentage of species stocks that move into, out of, or both into and out of one or more countries' EEZs by 2100 for each RCP.

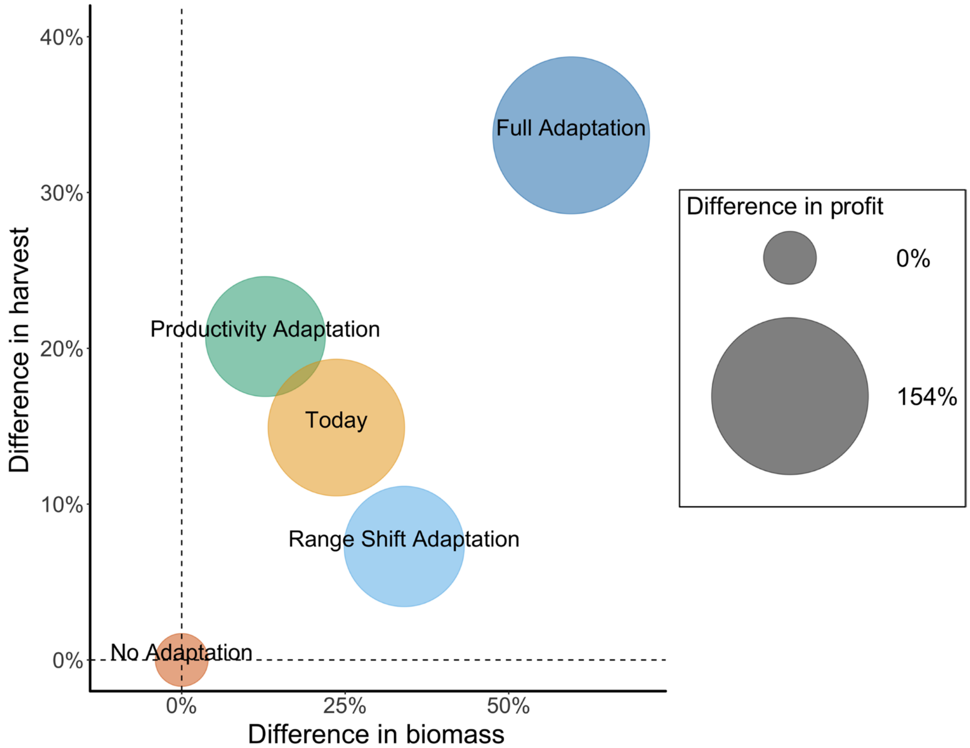

Fig. 3. Differences in harvest, profit, and biomass, relative to "No Adaptation" for RCP 6.0 in 2100 (see fig. S1 for results under the other RCPs).

includes some of the highest-yield stocks and cumulatively makes up about half of the total global yield.

DISCUSSION

Climate change will have diverse impacts on marine ecosystems and resources. Prior projections that climate change could reduce global fisheries revenues by as much as $10 billion a year compared to today garnered significant attention (*4*). However, taking human responses into account shifts our view of climate change and the world's oceans. We show that the future of global fisheries could actually be more prosperous than today, but only if management reforms addressing current mismanagement and looming challenges from climate change are implemented in the near future across a wide range of fisheries. This is true both globally and for nearly half of the individual stocks analyzed. The future of fisheries, however, could also be much worse than prior projections suggested if appropriate adaptations to potential productivity changes and climate-driven movement of species across management boundaries are not made. Maladaptive responses to the pending loss of a fishery or the arrival of a new fishery could exacerbate the previously projected direct effects of climate change.

These results suggest that climate change will force global fisheries to an important crossroads over the coming decades. Either we meet the challenges proactively with effective management or we risk undoing the significant progress that has been made in some countries (*17*, *18*) and further decimating fisheries in countries that have not yet enacted sound fishery reforms. The enormous contrasts between the four future management scenarios we explored suggest that the choice of management path will have profound consequences. One necessary choice will be how to reform current harvest policies. The possibility of a more prosperous future despite climate change depends on capturing the large untapped benefits from improving currently mismanaged fisheries.

Our analyses suggest that the benefits of enacting reforms today are cumulatively large enough to counter the future deleterious impacts of projected changes in fisheries productivity for most RCPs. Achieving this improved outcome is no small task since it involves reforms for many stocks with distinct fishery characteristics, each often fished by multiple countries. Management that flexibly adapts to productivity changes may require more frequent data collection and management updates, which can be costly. Fortunately, three factors help make a more prosperous future less daunting. First, case studies suggest that reform is possible for a range of fishery types, including high seas, large-scale, small-scale, data-rich, and data-poor. Pons *et al.* (*19*) found that high seas stocks under some form of management (generally commercially important species such as tuna) have shown improvements in biomass and decreases in fishing mortality over the last 10 years. In addition, management reforms in both large-scale fisheries (for example, Peru's individual vessel quota reform for the anchoveta fishery) and small-scale fisheries (for example, fishery reforms in Mexico and Chile) suggest that reform is possible in many contexts, although specific interventions might vary depending on fishery characteristics (*17*, *20*). These examples also suggest that even countries with more limited resources are capable of greatly improving their fisheries management. Second, the necessary fishery reforms do not require the threat of climate change as motivation. Adaptive harvest rules that respond to available biomass can provide large benefits in both static and changing climates (*5*, *21*). Therefore, reforms motivated purely by benefits today may also help buffer against negative productivity changes in the future. The third factor promoting improved global outcomes is the highly skewed distribution of fishery sizes. Because of the large variation in stock sizes,

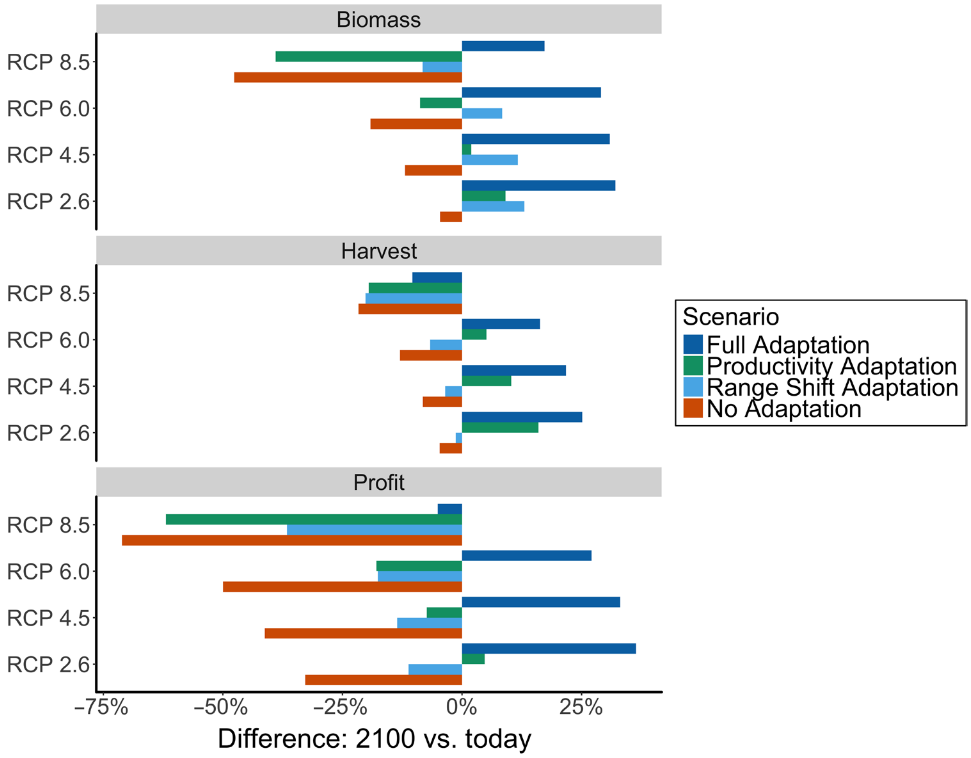

Fig. 4. Percent difference in biomass, harvest, and profit relative to today across RCP scenarios. Each color represents a different management scenario.

a large percentage of the potential global economic gains in this study can be achieved through the targeted reform of large overfished stocks. In our analysis, less than 10% of global stocks would need to adopt the most comprehensive reforms for future global profit to exceed current global profit. Therefore, although achieving the full benefits of global fisheries reform is an ambitious goal, strategic targeting of reform efforts could still generate major global benefits. Furthermore, a targeting approach that incorporates fishery size, value, and vulnerability to climate change may help to efficiently direct resources toward fisheries with the greatest potential for improved outcomes.

The second decision we will have to make is how to respond to shifting ranges. Spatial shifts across management boundaries can undermine well-designed policies and render promising management approaches unsuccessful. Transboundary fisheries already pose significant management challenges today and are often in worse shape than fisheries that reside entirely within individual countries' waters (*22*, *23*). As stocks begin to move more extensively, effective bilateral and multilateral cooperation will become increasingly important for effective management (*12*). Stock movement is ultimately beneficial to one country and detrimental to another, which changes the incentives to cooperate in effective management (*24*, *25*). Spatial shifts within a single country may also pose management challenges as stocks shift into and out of regional management zones—for example, the ongoing challenges from spatial shifts observed in stocks along the northeast United States (*26*). Designing institutions to address this inherently human challenge will be crucial given the extent of projected movement of fish stocks and the potentially enormous costs of inadequate responses. While it is encouraging that spatial and temporal stock structure is already measured in some cases, the existence of this information does not guarantee that this information will influence management decisions. In addition, accurately predicting where and when fish distributions will shift may be difficult. Therefore, international institutions and agreements will need to be flexible and robust in the face of uncertainty to effectively cope with these management disruptions as they arise. Improved international collaboration will be needed to adequately address climate-induced threats not only to fisheries but also to other natural resources for which climate change will have spatial and transboundary implications (*27*).

Table 1. Percentage of stocks where biomass, harvest, or profit is higher in the future (2100) than today when Full Adaptation is implemented.

	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Biomass	68.6%	67.2%	65.5%	57.3%
Harvest	42.2%	40.3%	37.6%	25.7%
Profit	55.0%	52.2%	48.6%	32.9%

Finally, although management responses can more than offset the projected direct effects of climate change on fisheries to create a more prosperous global future, there are three important qualifiers to this optimistic note. First, there are other potential direct (for example, acidification and other challenges to ocean productivity) and indirect (for example, novel species interactions) impacts of climate change that are not addressed by this analysis. These impacts will be important for assessing climate effects on fisheries at the local scale. Second, not everyone will share in these benefits. Globally, profits, yields, and biomass could increase, but for about half of the world's individual fisheries, this better future appears unattainable. Even under the most optimistic scenario for human responses, roughly half of the world's fisheries are projected to decline under a moderate climate

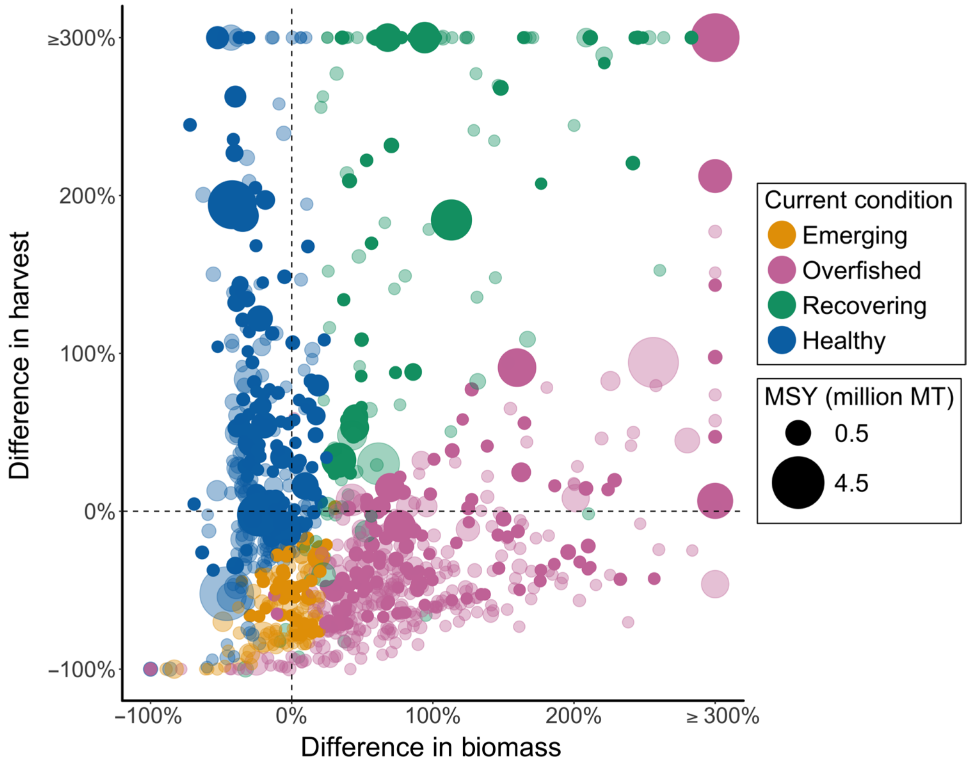

Fig. 5. Difference in harvest and biomass under the Full Adaptation strategy in 2100 relative to today for RCP 6.0. The bubble size corresponds to current MSY, and the colors indicate fishery category based on current biomass and fishing mortality rate relative to B_{MSY} and F_{MSY}, respectively. The fishery categories are defined as follows: Healthy ($F/F_{MSY} < 1$, $B/B_{MSY} \geq 1$), Emerging ($F/F_{MSY} \geq 1$, $B/B_{MSY} \geq 1$), Recovering ($F/F_{MSY} < 1$, $B/B_{MSY} < 1$), and Overfished ($F/F_{MSY} \geq 1$, $B/B_{MSY} < 1$). A transparent bubble indicates a decrease in maximum sustainable yield in 2100 relative to today, whereas a solid bubble indicates an increase (see fig. S2 for results under the other RCPs). MT, metric tons.

change scenario (RCP 6.0). Most latitudes in the tropics are not expected to obtain higher profits in the future compared to today under RCP 6.0 even with fully adaptive management (fig. S9). The distribution of winners and losers warrants considerably more attention to anticipate and potentially offset the likely food and livelihood losses that could ensue. Finally, future outcomes depend critically on the pace and magnitude of climate change. Under the most extreme scenario, RCP 8.5, both profit and harvest decline relative to today even under the most optimistic assumptions about global fisheries management reforms. This result highlights the fact that the future of fisheries will depend largely on activities that occur outside of the fishing industry and the importance of greenhouse gas emission mitigation (*28*). For fisheries to realize their potential, it is critical for the global community to reduce global greenhouse gas emissions; otherwise, even the most ambitious fishery reforms will fall short. Therefore, a more prosperous future for fisheries depends on both mitigation of climate change and proactive fisheries management reforms.

MATERIALS AND METHODS

We examined the implications of climate change and management reform for 779 species stocks and 136 NEI stocks (mixed-species fisheries aggregated at the country level) located across the globe (see the Supplementary Materials for aggregation methods). To make these projections, we required estimates of the fishery's current status and level of exploitation, as well as data on the current species' distribution to forecast responses to climate velocity. To conform to the spatial resolution of the climate velocity model, we modeled each species as a single "stock" and referred to these as "species stocks." The 779 species stocks are comparatively data-rich relative to the global pool of fisheries. To explore a more globally representative sample, we also included 136 stocks aggregated at the country level that represent NEI stocks, as defined in Costello *et al.* (*5*). Each stock's parameters, which include current biomass, fishing mortality rate, and carrying capacity, were determined through an aggregation method (see the Supplementary Materials) that calculates aggregated stock parameters using individual fisheries in a global fisheries database (*5*). Using recently published estimates of current stock status paired with bioeconomic projection models, rather than solely exploring changes in maximum potential productivity [for example, (*4*, *29*)], we examined how benefits and costs from potential management changes compare to potential losses from direct climate-driven changes.

We modeled future (2015–2100) species distributions by projecting changes from current (2012) presence-absence species distribution maps derived from AquaMaps (*30*) at 5-year intervals using a slightly modified version of the climate velocity model described in García Molinos *et al.* (*3*). This method assumes that species ranges track climate, expanding or contracting their range to keep up with changes in their thermal niche, conditioned to their inferred thermal and depth tolerances. To improve on the original model (*3*), species' trajectories were restricted based on the species' depth range (*30*) using global bathymetry data (ETOPO2v2 2-Minute Gridded Global Relief Data). Briefly, each cell within a species' range was spatially projected forward in time based on corresponding mean annual sea surface temperature isotherm trajectories (*31*). Isotherm trajectories were dictated by the speed and direction of cell-specific climate velocities

(*32*), based on multimodel ensemble means for the four Intergovernmental Panel on Climate Change RCPs: 2.6, 4.5, 6.0, and 8.5 (see the Supplementary Materials). Species' ranges were recalculated at the end of each 5-year interval based on those trajectories and species' thermal tolerance and depth range (see the Supplementary Materials).

Next, we converted projected changes in range size to changes in carrying capacity for each species stock over time (see the Supplementary Materials). An annual carrying capacity was calculated by interpolating between each 5-year interval. These changes in carrying capacity then drove predictable changes in maximum sustainable yield. Changes in range size cannot be projected for NEI stocks using the same methodologies, since they are composites of several species. To determine the carrying capacity trajectory for NEI stocks, we first aggregated total range by nation (including all species with range in a given nation) for each 5-year interval and then interpolated to obtain the annual aggregate range values for each nation. We then calculated annual changes in aggregate range for each nation, relative to year 2012. These relative changes were then applied to NEI stock carrying capacities. Finally, we projected future biomass, harvest, and profit under different management and climate scenarios using a bioeconomic model (*5*). This modeling approach was modified from the original by incorporating the unique stream of future carrying capacity values over time for each species and NEI stock (see the Supplementary Materials). Each year, biomass was calculated using a modified Pella-Tomlinson surplus production model, incorporating the projected carrying capacity in each time step (*33*) and the appropriate fishing mortality rate for the policy being modeled.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/4/8/eaao1378/DC1
Supplementary Materials and Methods
Supplementary Text
Fig. S1. Differences in harvest, profit, and biomass relative to No Adaptation for all RCPs.
Fig. S2. Differences in harvest and biomass under a Full Adaptation strategy in 2100 relative to today for all RCPs.
Fig. S3. Temporal changes in thermal envelopes within projected species ranges.
Fig. S4. Scatterplot and resulting regression lines from the linear models fitting biomass change to range size change for 11 unexploited marine species.
Fig. S5. Effect of the choice of different carrying capacity/range size ratios on harvest, profit, and biomass for each management alternative relative to No Adaptation for RCP 6.0.
Fig. S6. Differences in harvest, profit, and biomass relative to No Adaptation for all RCPs.
Fig. S7. Differences in harvest, profit, and biomass relative to No Adaptation for different assumptions regarding prices and costs under RCP 6.0.
Fig. S8. Differences in harvest, profit, and biomass relative to No Adaptation for all RCPs.
Fig. S9. Differences in profit by latitude.
Table S1. RCPs considered in this study along with the models used for computation of respective mean ensembles.
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