Global fishery prospects under contrasting management regimes

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Data from 4,713 fisheries worldwide, representing 78% of global reported fish catch, are analyzed to estimate the status, trends, and benefits of alternative approaches to recovering depleted fisheries. For each fishery, we estimate current biological status and forecast the impacts of contrasting management regimes on catch, profit, and biomass of fish in the sea. We estimate unique recovery targets and trajectories for each fishery, calculate the year-by-year effects of alternative recovery approaches, and model how alternative institutional reforms affect recovery outcomes. Current status is highly heterogeneous—the median fishery is in poor health (overfished, with further overfishing occurring), although 32% of fisheries are in good biological, although not necessarily economic, condition. Our business-as-usual scenario projects further divergence and continued collapse for many of the world's fisheries. Applying sound management reforms to global fisheries in our dataset could generate annual increases exceeding 16 million metric tons (MMT) in catch, $53 billion in profit, and 619 MMT in biomass relative to business as usual. We also find that, with appropriate reforms, recovery can happen quickly, with the median fishery taking under 10 y to reach recovery targets. Our results show that commonsense reforms to fishery management would dramatically improve overall fish abundance while increasing food security and profits.

fishery recovery | fishery reform | rights-based fishery management | bioeconomic model

Recent advances in our understanding of global fishery status (1–4) provide a foundation for estimating the targets for, and potential benefits from, global fishery recovery. Although existing aggregate estimates make a compelling general case for reform (5, 6) new data, models, and methods allow for more detailed analysis of the benefits and trade-offs of contrasting management regimes. Indeed, emerging empirical evidence shows that effective reforms and scientific assessments taken by some countries have already placed their fisheries on a positive path (1, 7). Reforms span a range of approaches, from scientifically informed harvest policies to institutional reforms that restructure the incentives in a fishery to align profits with conservation. In many cases, these changes have successfully reduced fishing effort to sustainable levels and stabilized overfished stocks (7, 8). These cases of successful management contain lessons that can be applied more broadly and also suggest that effects of fishery reform will differ across fisheries, nations, and reform policies. However, these new data, models, and lessons learned have never been synthesized to inform the future potential from global fishery recovery.

Here, we ask, what might be the future of global fisheries under alternative management regimes? In addition, what might happen if we undertook the reforms that previous studies have stressed are urgently needed? We couple the latest individual fishery data to bioeconomic models to estimate alternative scenarios of fishery recovery for individual fisheries, countries, and the globe. We seek to inform policy recommendations for recovering fisheries, including insights regarding the following: (*i*) what is the status of fisheries across the globe? (*ii*) Are there strong trade-offs or synergies between recovery efforts that emphasize fishery profits vs. catch vs. biomass conservation? (*iii*) In a world with limited resources to devote to fishery recovery, which countries provide the most compelling and urgent cases for fishery reform? In addition, (*iv*) how long will benefits of reform take to arrive?

We examined three approaches to future fishery management: (1) business-as-usual management (BAU) (for which status quo management is used for projections) (*SI Appendix*), (2) fishing to maximize long-term catch (F_{MSY}), and (3) rights-based fishery management (RBFM), where economic value is optimized. The latter approach, in which catches are specifically chosen to maximize the long-term sustainable economic value of the fishery, has been shown to increase product prices (primarily due to increased quality and market timing) and reduce fishing costs (primarily due to a reduced race to fish); these are reflected in the model. In all scenarios, we account for the fact that fish prices will change in response to levels of harvest.

For each fishery, we estimate future trajectories out to 2050 of catch, profit, and biomass under each policy. Other social objectives such as employment, equity, or biodiversity conservation are clearly important, and may be correlated with these outcomes, but are not explicitly modeled here. Aggregating across fisheries provides country and global estimates of the consequences and trade-offs of alternative policies for recovering fisheries. A strength of our approach is the ability to forecast effects for fisheries in the Food and Agriculture Organization (FAO) "not elsewhere included" (NEI) category (*SI Appendix*).

Bioeconomic theory provides some predictions for the trade-offs across alternative societal objectives of food, profit, and

Significance

What would extensive fishery reform look like? In addition, what would be the benefits and trade-offs of implementing alternative approaches to fisheries management on a worldwide scale? To find out, we assembled the largest-of-its-kind database and coupled it to state-of-the-art bioeconomic models for more than 4,500 fisheries around the world. We find that, in nearly every country of the world, fishery recovery would simultaneously drive increases in food provision, fishery profits, and fish biomass in the sea. Our results suggest that a suite of approaches providing individual or communal access rights to fishery resources can align incentives across profit, food, and conservation so that few trade-offs will have to be made across these objectives in selecting effective policy interventions.

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biomass conservation. Perhaps the most salient point is that the three objectives can go hand-in-hand, at least in comparison with a fishery in a depleted state. Consider, for example, a small-scale open-access fishery in the developing tropics, with biomass [scaled by biomass at maximum sustainable yield (MSY)] $B/B_{MSY} = 0.3$ (overfished) and fishing pressure (scaled by the fishing pressure that would generate MSY) $F/F_{MSY} = 1.7$ (overfishing). Such a fishery would be near bionomic equilibrium (9), so biomass and profit would be low, but stable from year to year. Because the stock has been overfished, the catch is also small—in this case, it is just one-half of MSY. Recovering such a fishery would eventually increase fish catch, profit, and fish biomass.

However, there are nontrivial cases in which trade-offs do exist. For example, consider a fishery with $B/B_{MSY} = 0.4$ and $F/F_{MSY} = 2.5$, where biomass is lower than optimal and still declining. Despite the low biomass, fishing mortality is so large that harvest remains high—in this case, it is MSY. Although such pressure will ultimately reduce the stock, the inevitable economic and food provision consequences of that overexploitation have yet to be realized. Implementing recovery in such a fishery is likely to increase biomass, and will almost surely increase profits and catches relative to their long-run values under BAU, but may not increase catches relative to their current levels (see *SI Appendix*, Fig. S1, for illustrative example).

Any given harvest policy will have effects that play out differently over time. By explicitly modeling the dynamics for each fishery under each harvest policy, we can examine the timing of effects in detail. To do so, we estimated the intrinsic growth rate, carrying capacity, and MSY for each fishery in our dataset, using a structural data-limited assessment approach (10). This arms us with a microlevel structural bioeconomic model for all fisheries in our database.

Timing of effects is particularly important when considering food provision and profit motives. For example, China, the country with the largest volume of fish catches, has proposed new goals to increase seafood consumption by 50% over the next 6 y (11). Our analysis allows us to examine the extent to which alternative management policies for wild fisheries can achieve such an objective for China. Similarly, if a country is interested primarily in the profitability to fishers, then it may focus on policies that emphasize profit recovery, which may involve adopting institutional reforms that improve economic efficiency. These harvest policies often call for sharp reductions in current fishing effort to allow rapid rebuilding of stocks (although, because we consider costs, it is rarely optimal to completely close the fishery during rebuilding). Such measures often impose significant short-run economic losses that are sometimes politically infeasible, but when such a policy is economically optimal, the long-run gains will outweigh the short-run costs.

Results and Discussion

We estimate that global MSY is 98 million metric tons (MMT) (after scaling up to account for data gaps), which is substantially larger than the 80 MMT reportedly caught across the globe in recent years (12), but is consistent with MSY calculations in ref. 6 (83–100 MMT) and ref. 5 (95 MMT). Our estimate reduces MSY of forage fish and assumes no unreported historical catch.

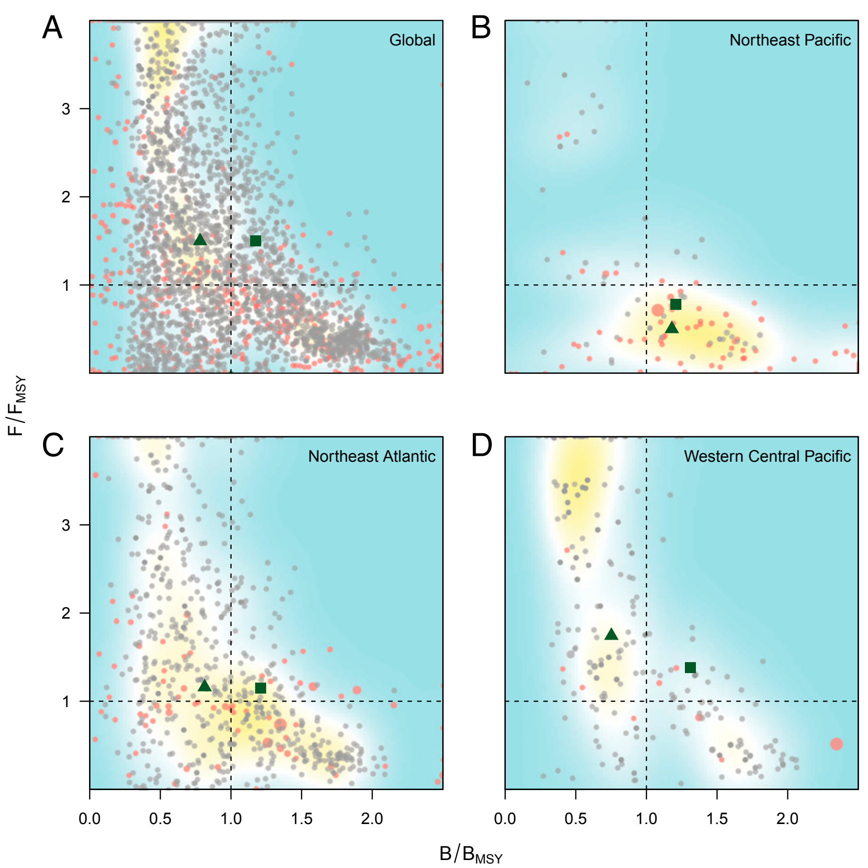

Fig. 1. Current fishery status ("Kobe") plots for four illustrative regions. Each dot represents a fishery. The red dots represent data from RAM database, and the black dots represent our estimates for unassessed fisheries. Dot size scales to fishery catch. Shading is from a kernel density plot. The green triangle is the median and the green square is catch-weighted mean, for the given region. Panels represent data from all global fisheries in our database (*A*), Northeast Pacific (*B*), Northeast Atlantic (*C*), and Western Central Pacific (*D*) regions.

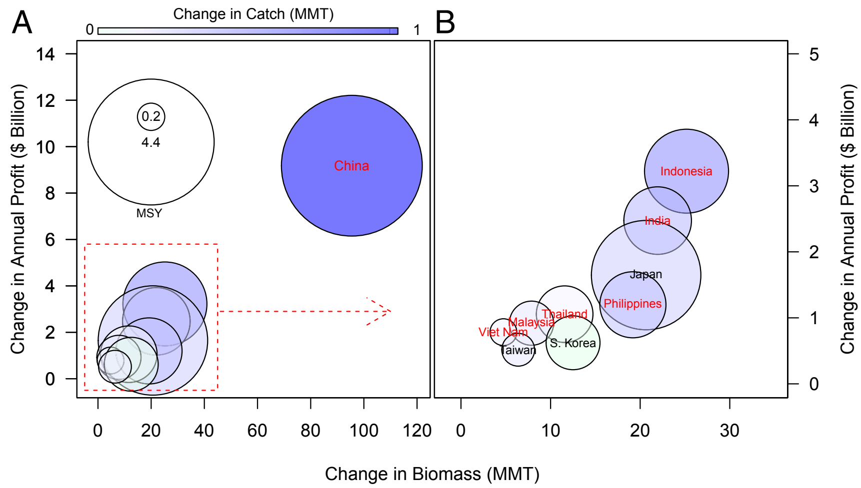

Fig. 2. Absolute changes in projected 2050 biomass, profit, and catch (color) for the 10 countries [China, Indonesia, India, Japan, Philippines, Thailand, Malaysia, Republic of Korea, Vietnam, and Taiwan (*A*); see *B* for exploded view of nine countries] with the greatest increase in profit under economically optimal harvest strategy (RBFM) compared with BAU for stocks of conservation concern for fisheries in our dataset. Size of circle indicates the *MSY* (in million metric tons) for stocks of conservation concern in the country. Country names in red indicate countries for which >50% increase in profit comes from fisheries in the FAO category "NEI."

Incorporating a recent global estimate of illegal fishing (23%) (13), our estimate of MSY would rise to 121 MMT. Our estimates of each fishery's current B/B_{MSY} and F/F_{MSY} are plotted in Fig. 1 for all global fisheries (Fig. 1*A*) and for three illustrative oceanic regions (Figs. 1 *B*–*D*). The Northeast Pacific is known to be well managed—our estimates accord with this (Fig. 1*B*). Many fisheries in the Northeast Atlantic are in poor condition, although 56% are on a path toward sustainability, as fishing pressure is below F_{MSY} (Fig. 1*C*). As a final illustration, we estimate very low biomass and continued high fishing mortality for the bulk of fisheries in the Western Central Pacific (Fig. 1*D*). The worse a fishery's current status, the larger the potential gains from reform. Overall, we estimate the global median fishing mortality is $F/F_{MSY} = 1.5$ (overfishing is occurring) and biomass is $B/B_{MSY} = 0.78$ (stocks are overfished); these are consistent with refs. 4, 5, and others.

Taking estimated current fishery status as a starting point, for each of the three future policies (BAU, F_{MSY}, RBFM), we consider two scenarios. The first scenario applies the policy only to stocks of "conservation concern" (i.e., the 77% of stocks for which we estimate $B/B_{MSY} < 1$ and/or $F/F_{MSY} > 1$, which roughly corresponds to the FAO definition of "fully exploited" or "overexploited"). Under that scenario, stocks not of conservation concern are assumed to maintain current biomass forever. The second scenario applies the policy to all stocks. Because the conservation concern scenario provides a less optimistic estimate of global benefits of reform, we adopt it as the default. There, we find that simultaneous gains for catch, profit, and biomass (RBFM relative to BAU) is a likely outcome for the majority of stocks (56%; Fig. 1), and countries (23 of the top 30 in harvest) of the world.

Focusing on the 10 countries with the greatest potential absolute increase in fishery profits relative to BAU also shows substantial gains in both conservation and catch (Fig. 2). China's immense fisheries show enormous potential (Fig. 2*A*); other prominent fishing nations in Asia, such as Indonesia, India, Japan, and Philippines, also secure large reform benefits along all three dimensions (Fig. 2*B*). Seven of these 10 countries derive >50% of profit increases from the NEI species groups (red, Fig. 2).

Although results thus far suggest that nearly every country in the world stands to gain from fishery recovery regardless of its objectives, some important distinctions emerge across recovery policies. Although all reasonable recovery policies are expected to give rise to increases in biomass of fish, albeit to different levels, we expect the RBFM class of policies, which focuses on economics returns, to achieve the highest levels of biomass (14). The F_{MSY} policy will have lower fish biomass, lower profits, and slower recovery times, but upon complete recovery, will ultimately generate the largest catch. The aggregated catch, profit, and biomass under each policy scenario illustrates that trade-offs across policies are small for the aggregated global fishery (Fig. 3).

Applying the stated policy only to stocks of conservation concern, the RBFM policy gives rise to annual increases of 2 MMT in catch, \$31 billion in fisheries profit, and 388 MMT in biomass compared with current levels (Fig. 3). These values rise substantially (to 16 MMT, \$53 billion, and 619 MMT) when all fisheries, not just those of current conservation concern, are managed more effectively and when comparing to BAU (Fig. 3); this accounts for fishing more aggressively on currently underexploited stocks. Each of these

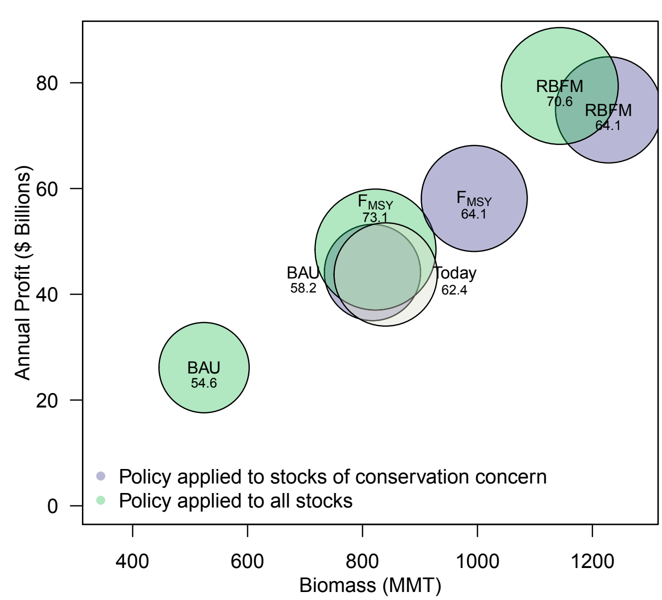

Fig. 3. Aggregate global effects on projected 2050 profit and biomass of alternative policies applied to fisheries in our dataset. Size and printed number indicate catch in baseline year ("Today" bubble) or in 2050 (all other bubbles).

values could reasonably be adjusted upward by an additional 28% because our database covers only the 78% of reported catch with adequate data. The largest gains accrue from fisheries with the most depleted status, although these gains may be limited if depleted fisheries have crossed tipping points beyond which recovery may not be possible (15). Even targeting reforms at just fisheries of conservation concern, global fishery profits are 29% higher under RBFM than under F_{MSY} (Fig. 3); this wedge grows to 64% when applying policies to all fisheries (Fig. 3). This increase in profits under RBFM relative to F_{MSY} has two components: an "optimization effect" (68% from optimizing the harvest policy) and a "pecuniary effect" (32% from price increases and cost decreases). Although we have not explicitly modeled effects of fishery reform on consumers, they are likely to benefit from the catch increases (and price decreases) that arise from fishery recovery. Consumers may also benefit from higher quality product under RBFM, albeit at a commensurately higher price.

Although the most suitable institutional reforms to achieve recovery will depend on social, economic, and ecological objectives and conditions, various approaches such as cooperatives (16, 17), territorial rights (18, 19), or individual transferable quotas (8, 20) could be used to improve economic results under a range of harvest policies. Although these all fall under the umbrella of RBFM, each will bring different benefits in different settings that must be weighed against the costs of reform. Although these costs have not been explicitly modeled here, experience from countries such as Iceland, New Zealand, and Australia suggest that they are likely to be only a fraction of the potential benefits identified here (21). Our results suggest that some of the greatest economic improvements in fisheries may come more from improving institutions than from improving the status of fished stocks. Furthermore, these gains in profit can occur quickly following institutional reforms, because they do not exclusively rely on stock recovery. Such rapid economic gains can help offset many of the necessary short-term costs associated with stock recovery when catches must temporarily decline to enable recovery.

To ensure model tractability and to apply it at a global scale, we made a number of simplifying assumptions. *SI Appendix* contains an extensive description and set of robustness checks and sensitivity analyses; we note a few here. First, because our entire analysis is built on estimates of the current fishery status, it is natural to ask how sensitive our results are to these uncertain estimates. We performed numerous routines to estimate our model's ability to predict out of sample, broken out by region and fishery size. Results suggest that our methods for estimating B/B_{MSY} and F/F_{MSY} are more robust for fisheries in the developed world that are not extremely overfished. The presence of low-to-moderate unreported fishing does not bias these estimates (although it will bias MSY estimates downward). Second, predictions of absolute economic effects rely on estimates of economic parameters (demand and costs). To this end, we built a price database derived from export values and other data. We transformed the data to ex-vessel equivalents and modeled demand with a constant elasticity of −1.15, consistent with refs. 22 and 23. We model costs by identifying the unassessed fisheries estimated to be in bionomic equilibrium and backing out the cost that drives profit to zero under open-access equilibrium. This procedure results in costs per MT that are consistent with those in ref. 24 and generates mean cost/revenue ratios of 67% in the current fishery. We conducted numerous sensitivity analyses examining the effects of a range of these biological and economic parameters; although these affect our quantitative predictions, our qualitative findings are largely unaffected. We also performed a historical analysis where catches for all assessed stocks from 1980 to 2012 were predicted using the model with data up to 1980 only. Actual catch compares extremely well with the model's prediction (correlation, 0.99; value of $P < 1\%$).

Our model allows us to make novel predictions of the timing of fishery status into the future under alternative management approaches (Fig. 4). If the BAU policy is applied to all fisheries, the proportion below a recovery target of $0.8B_{MSY}$ (see ref. 25 and *SI Appendix*) rises from 53% today to 88% in 2050 and the proportion experiencing fishing pressure above F_{MSY} rises from 64% to 84%. These values are consistent with those of Quaas et al. (26), who estimate declines under BAU for all stocks studied, with an estimated biological decline of about 77%. We find that, if reform efforts are put in place now, the median time to recovery would be just 10 y, and by midcentury, the vast majority (98%) of stocks could be biologically healthy and in a strong position to supply the food and livelihoods on which the world will increasingly rely.

Materials and Methods

We developed a novel approach combining several sources of data and models to conduct fishery-level analyses. Our database of 4,713 fisheries is drawn from both the RAM Legacy Stock Assessment database (27) and the FAO marine capture databases (species–country–FAO region triples) (28). Excluding fisheries that failed to meet minimum criteria (*SI Appendix*), this process accounts for 78% of reported global catch. Because data availability varies across these fisheries and by region, we used surplus production models consistently across all fisheries to estimate MSY-related parameters and predict future trajectories of biomass.

We extracted biomass and fishing mortality directly from stock assessments for the 397 fisheries included from the RAM database (43% of catch in our database). Status of the remaining 4,316 "unassessed" fisheries are estimated using a novel two-step process involving global regression analysis and a structural fisheries modeling approach (merging methods in refs. 4 and 10; *SI Appendix*), if available, or extracted from FAO State of World Fisheries and Aquaculture database (12). The structural modeling approach, catch-MSY (10),

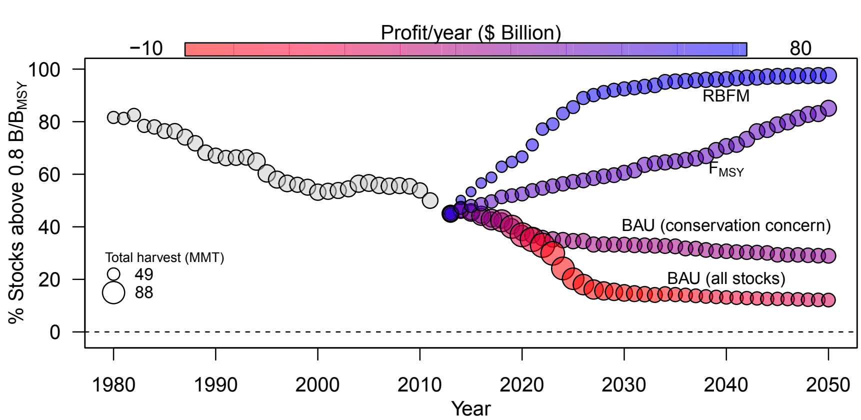

Fig. 4. Timing of projected recovery under alternative policies for recovering fisheries of conservation concern in our dataset. Size and color indicate global catch and profit by year, respectively.

assumes stationarity of MSY, F_{MSY}, and B_{MSY} parameters; see *SI Appendix* for further details including sensitivity analyses. The set of fisheries categorized as NEI by the FAO were handled with a two-step process using an appropriate comparison set of fisheries from the global database and imputing values to the NEI stock (*SI Appendix*); this could be improved with better reporting of catches of these species. Although trophic effects are not explicitly modeled, they may play a role in the potential benefits of rebuilding fisheries. In reality, each stock we have modeled exists within a larger ecosystem context that influences the dynamics of each species within it (e.g., ref. 15). Recovering predatory species increases predation on prey species. Consequently, reform projections from single-species models may be optimistic for ecosystems in which many piscivorous species are recovered. To partially account for this, we conservatively reduced MSY of all forage fish stocks, which provide a food source for many higher–trophic-level fish and mammals, by 25% (29).

We assessed the future trajectories of all individual fisheries up to mid-century (2050) using a Pella–Tomlinson surplus production model (30) with fishery-specific life-history parameters, described as follows:

$$B_{t+1} = B_t + \frac{\phi+1}{\phi} g B_t \left(1 - \left(\frac{B_t}{K}\right)^{\phi}\right) - H_t, \qquad \textbf{[1]}$$

where $((\phi+1)/\phi)g$ is the intrinsic rate of the growth for the species, K is the carrying capacity, and H_t is the harvest in year t. We assume stationarity in g and K parameters. We set the growth curve parameter ϕ at 0.188, per refs. 31 and 32, such that B_{MSY} occurs at 40% of K; alternatives are analyzed in *SI Appendix*. Estimates of MSY and g were also derived from the RAM database for assessed fisheries. In cases where only some of these values are provided, we used available data to calculate missing values (e.g., estimating MSY from $Catch$, B/B_{MSY} and F/F_{MSY}, and g as MSY/B_{MSY}) or performed a two-step process described above.

For each fishery, we modeled a range of fishing policies, each of which assigned a scaled fishing mortality rate tailored to that specific stock (i.e., a "control rule") for all possible realizations of biomass. Profit in a period is revenue (price times catch) minus the cost of fishing, which is an increasing function of the fishing mortality applied. Prices are adjusted each year from a global seafood demand curve with constant elasticity of −1.15. Our base case scenario assumed zero discounting (for which profit is optimized dynamically); higher discount rate scenarios are reported in *SI Appendix*. This allowed us to predict the annual catch, profit, and biomass of fish in the ocean across a range of alternative harvest policies, as reported above.

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