FISHERIES

Protecting marine mammals, turtles, and birds by rebuilding global fisheries

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Reductions in global fishing pressure are needed to end overfishing of target species and maximize the value of fisheries. We ask whether such reductions would also be sufficient to protect non–target species threatened as bycatch. We compare changes in fishing pressure needed to maximize profits from 4713 target fish stocks—accounting for >75% of global catch—to changes in fishing pressure needed to reverse ongoing declines of 20 marine mammal, sea turtle, and seabird populations threatened as bycatch. We project that maximizing fishery profits would halt or reverse declines of approximately half of these threatened populations. Recovering the other populations would require substantially greater effort reductions or targeting improvements. Improving commercial fishery management could thus yield important collateral benefits for threatened bycatch species globally.

Fisheries employ 260 million people and fish are a primary animal protein source for roughly 40% of the world's population (*1*). Recent studies suggest that more than half of the world's fisheries are overfishing (*2*), and rebuilding these fisheries could increase global fishing yields by ~15% and profits by ~80% (*2*, *3*). Fisheries also affect many protected, non–target species through bycatch (incidental capture), including ecologically important and charismatic megafauna such as marine mammals, sea turtles, seabirds, and sharks (*4*). Some of these bycatch species, such as Mexico's vaquita porpoise (*Phocoena sinus*) and New Zealand's Hector's dolphin subspecies (Māui dolphin, *Cephalorhynchus hectori maui*), face imminent extinction (*5*, *6*). For these reasons, ending overfishing and protecting threatened bycatch species are two of the main goals of modern marine conservation efforts.

At first glance, sustaining high fishery profits and yields can seem in conflict with bycatch species conservation. Unless targeting can become more selective through changing fishing technology or practices, reducing bycatch requires reducing target stock catch. However, because rebuilding overfished target stocks requires reducing fishing effort, bycatch populations should also benefit. Indeed, regions with the most severe bycatch—coastal fisheries of the developing world and, to a lesser extent, high-seas fisheries (*4*)—also experience some of the most severe overfishing (*2*) (Fig. 1 and fig. S1).

We quantify the trade-offs globally between protecting bycatch species and meeting economic fisheries objectives. To do this, we compare estimates of the changes in fishing pressure needed to maximize long-term profits [termed "maximum economic yield" (MEY)] for 4713 fish stocks, accounting for >75% of global catch (*2*), to the changes in bycatch mortality needed to reverse ongoing population declines of 20 populations substantially affected by fisheries bycatch, for which sufficient published information is available to calculate the reductions in mortality needed to prevent further declines (materials and methods and table S1).

Our sample includes 9 of 26 marine mammal populations, 6 of 8 sea turtle populations or species, and 3 of 22 seabird populations that the International Union for Conservation of Nature (IUCN) identifies as threatened, declining, and having bycatch as a primary threat (*7*). We also include the Northwest Atlantic loggerhead turtle (*Caretta caretta*) population, but it is not listed as threatened by the IUCN owing to uncertainty as to whether it remains in decline (*7*) (materials and methods). The IUCN last assessed olive ridley turtle (*Lepidochelys olivacea*) populations jointly (*7*), and we include two of these in our analysis (materials and methods). We restrict our analysis to marine mammals, sea turtles, and seabirds, because they are rarely retained or commercially valuable (*4*). However, future work could use similar methods to consider sharks, rays, and other taxa retained as both target and non–target catch (*8*).

Accounting for multiple uncertainties, we ask how likely it is that solely managing all target fisheries to MEY would reduce bycatch mortality sufficiently to halt each bycatch population's decline. We further ask how much long-term profit would need to be foregone, or how much more selective targeting would need to become, to ensure that each bycatch population's decline was halted. In other words, we assess whether there is currently a trade-off between maximizing long-term profit and halting each bycatch population's decline, and how severe the trade-off is, if one exists. In the supplementary materials, we explore trade-offs relative to maximum long-term catch [termed "maximum sustainable yield" (MSY)] and obtain results similar to those for MEY (figs. S2 to S4).

We assume that each population's annual rate of change (denoted Δ, e.g., $\Delta = -0.05\ \mathrm{year}^{-1}$ implies a 5% annual decline in abundance) can be approximately expressed as (materials and methods)

$$\Delta = \Delta_n - F_{\mathrm{e}} \qquad (1)$$

Here, Δ_n denotes the annual rate of change in abundance that would occur if there were no bycatch, and F_{e} denotes the "effective" annual bycatch mortality rate—the fraction of the population's total reproductive value removed by bycatch annually. Derived from age-structured

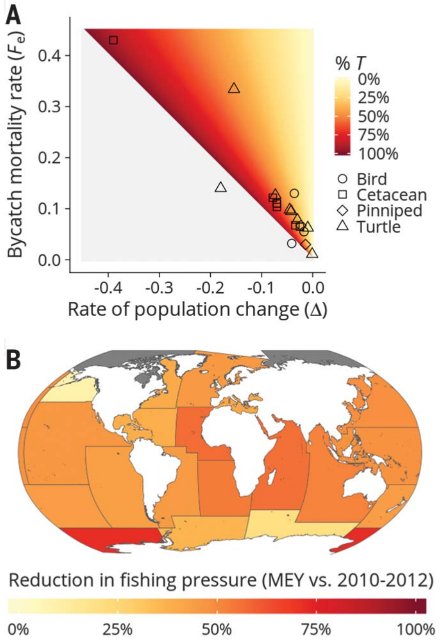

Fig. 1. Reductions in fishing pressure needed to meet profit and bycatch objectives. (**A**) Population decline (Δ) and bycatch mortality (F_{e}) rates, and reductions in bycatch mortality needed to halt population declines (%*T*), for 20 bycatch populations. (**B**) Projections (*2*) of average reductions in target stock fishing mortality (weighted by 2010 to 2012 expenditure), by FAO Major Fishing Area (except Arctic Sea, gray), under the MEY scenario [same color bar as in (A)].

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population models, reproductive value measures the relative contributions of individuals in each age group to overall population growth [e.g., see (*9*, *10*)]. We use this measure to standardize bycatch of different ages across fisheries, since fisheries primarily causing bycatch of breeding adults tend to have much larger population impacts than fisheries causing bycatch of small juveniles [e.g., (*10*)]. To keep the units of Eq. 1 consistent, we also measure Δ and Δ_n in reproductive-value units where possible, i.e., where a published age-structured assessment is available [e.g., (*10*)]. Otherwise, we assume that abundance and mortality trends measured in individual units reflect trends in reproductive value.

From Eq. 1, we calculate the percentage (denoted $\%T$) by which each bycatch population's mortality rate, F_e, would have to decrease to halt its population decline (i.e., $\Delta = 0$), if all other mortality sources remained constant:

$$0 = \Delta_n - \left(1 - \frac{\%T}{100}\right)F_e \qquad (2A)$$

$$\%T = 100\left(1 - \frac{\Delta_n}{F_e}\right) = 100\left(-\frac{\Delta}{F_e}\right)$$

$$= 100\left(\frac{\Delta}{\Delta - \Delta_n}\right) \qquad (2B)$$

Figure 2 illustrates the steps of our analysis for each bycatch population, using the relatively data-rich Northwest Atlantic loggerhead turtle as an example. Materials and methods and table S1 describe our analysis for all populations. First, we obtain point estimates and approximate uncertainty for two of Δ, Δ_n, and F_e, from the literature. From these, we calculate point estimates and distributions for $\%T$ using Eq. 2B (Figs. 1A and 2B and fig. S2). We also use information from the literature to infer which target fisheries may be contributing to bycatch mortality (Fig. 2, A and C).

We then perform a Monte Carlo simulation that defines 1000 different "states of the world." In each state, we randomly draw a value of $\%T$ from its distribution (Fig. 2B), as well as an allocation of bycatch mortality among target fisheries from the set of identified target fisheries. We weight allocation probabilities by the fisheries' relative efforts, measured by 2010 to 2012 fishing expenditures (Fig. 2C). We assume that bycatch mortality (F_e) responds proportionally to changes in target stock mortality. Thus, the percentage reduction in bycatch mortality in a given state of the world is equal to the average change in sampled target stock fishing mortality at MEY relative to 2010 to 2012 rates (*2*).

In some states of the world, the projected reduction in bycatch mortality at MEY is greater than $\%T$. The bycatch population's decline is thus already halted under economically optimal conditions and current targeting, implying that zero cost or targeting improvement is required. In states of the world where the projected reduction in bycatch mortality is less than $\%T$, we calculate the total cost of reducing bycatch mortality by $\%T$ according to principles of economic efficiency (i.e., additional reductions in target stock mortality beyond MEY are ordered in ascending order of marginal cost). We calculate the required targeting improvement as the additional percentage change in bycatch mortality required beyond MEY. When $\%T \geq 100$, fishing or bycatch must cease entirely, so the required cost or targeting improvement is 100%. Our Monte Carlo analysis thus yields distributions of $\%T$ and expected reductions in bycatch mortality (Fig. 2D), as well as costs (Fig. 2E) and targeting improvements (Fig. 2F) required to halt the decline of each bycatch population.

In 95% of simulated states of the world, halting the declines of 7 to 13 populations (median 10) is fully accomplished by managing target stocks to MEY, or requires only minor loss in total profit (<5%) (Figs. 3 and 4 and figs. S2 and S3). In >50% of states of the world, this includes seven turtles, one pinniped, one cetacean, and two birds (Fig. 3). Required costs are often substantial (>50%) for the remaining populations. Even eliminating bycatch completely is insufficient to halt declines of one turtle and one bird in most states of the world, owing to other mortality sources. Targeting improvements required for recovery are always slightly larger than required profit losses (Figs. 3 and 4 and fig. S4), because long-term profits are insensitive to small deviations from the exactly optimal fishing pressure [(*11*) demonstrates

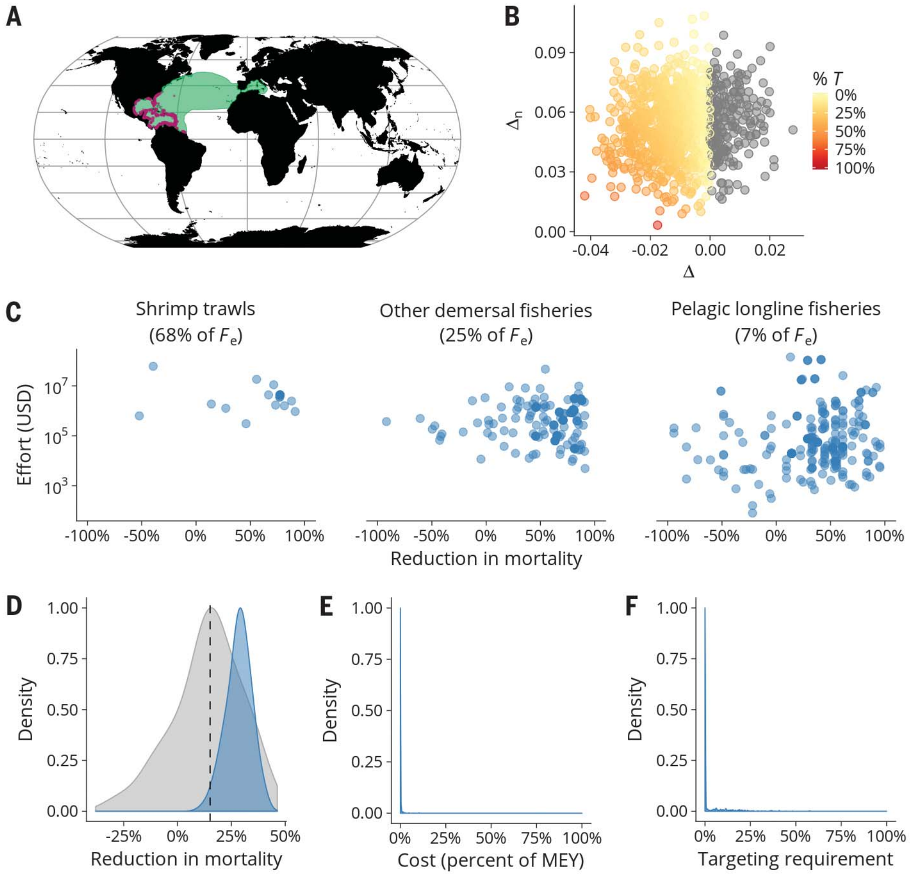

Fig. 2. Analysis. The steps of our analysis are illustrated using the Northwest Atlantic loggerhead turtle population. From the literature, we determine (**A**) its geographic range (green, nesting sites in purple) (*18*, *19*), (**B**) the joint distribution of its rates of abundance change currently (Δ) and without bycatch (Δ_n)—from which we sample the mortality reduction needed ($\%T$) (dots, gray indicates $\%T < 0$)—and (**C**) the target stock groups implicated in bycatch and their relative contributions to mortality. (C) The effort (measured as average 2010 to 2012 fishing expenditures) and projected reduction in mortality under MEY in each target fishery (*2*). From this information, we use Monte Carlo simulation to estimate distributions on (**D**) $\%T$ (gray) and the percentage reduction in bycatch mortality under MEY (blue), (**E**) the fraction of cumulative MEY that would need to be forgone, or (**F**) the improvement in targeting ("targeting requirement") needed to halt the population's decline.

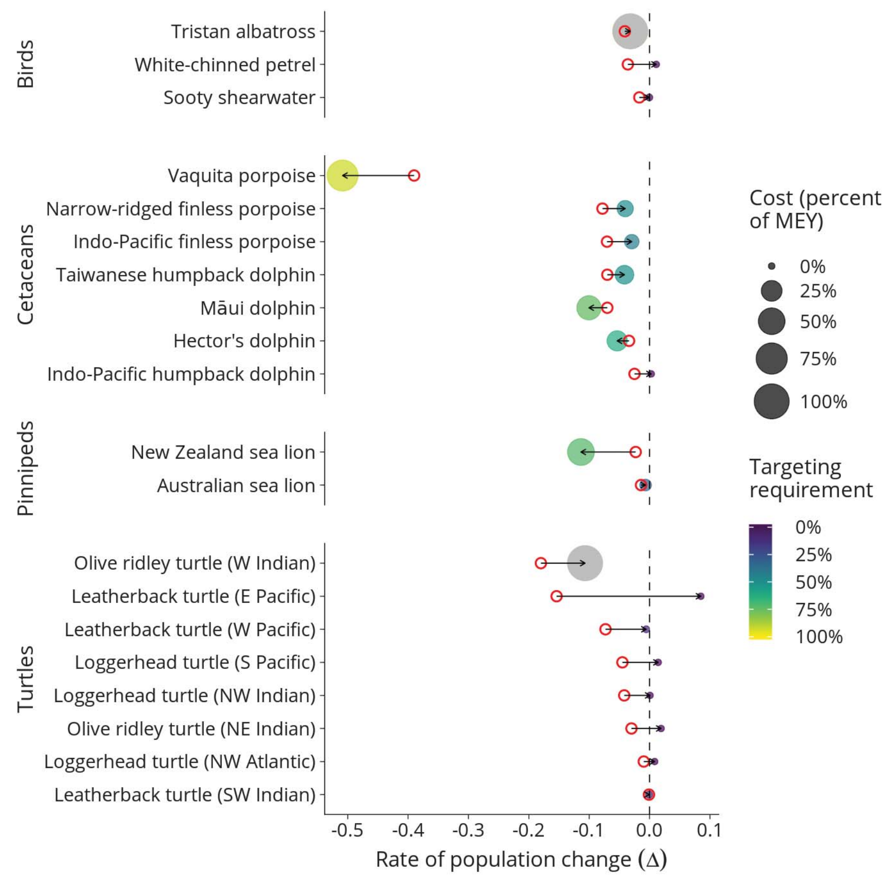

Fig. 3. Trade-offs. For each bycatch population, we compare the median projected rates of population change (Δ) under current conditions (open red circles) and with all target stocks fished at the profit-maximizing rate (denoted F_{MEY}) (filled colored circles). Arrows illustrate the effect of transitioning to MEY. Bycatch populations whose target stocks are currently fished at lower rates than F_{MEY} on average experience greater mortality at MEY (left-facing arrows), and vice versa (right-facing arrows). Sizes and colors of filled circles respectively represent median required costs (as a percentage of MEY) and median targeting requirements (percentage reduction in bycatch mortality, starting from MEY). Gray color indicates that the decline would continue even if bycatch were completely eliminated.

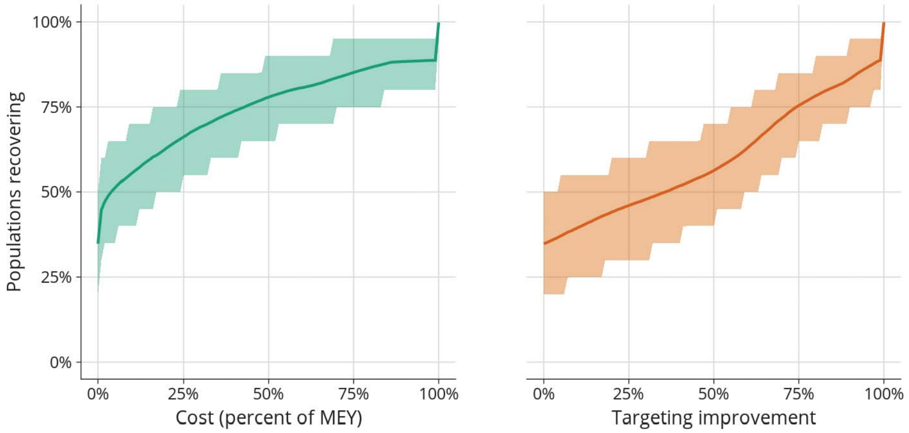

Fig. 4. Summary. At each cost level (% of MEY, green) and targeting improvement level (%, orange), the fraction of populations increasing in abundance is shown. Lines represent means; shaded regions represent 95% of states of the world.

this principle for catch]. Efficiently ordering reductions in fishing pressure among fisheries to minimize costs enhances this insensitivity (fig. S5).

Given the data limitations associated with both fisheries bycatch (*4*) and assessing the status of target fisheries lacking formal stock assessments (*2*), we urge cautious interpretation of our results for any specific bycatch population, some of which have a large uncertainty (figs. S2 to S4). Each population would benefit from a locally tailored follow-up study. However, several broader conclusions are robust to both these uncertainties and a wide range of sensitivity analyses (materials and methods and figs. S6 to S8).

First, our results suggest that recovery of approximately half of the world's marine mammals, turtles, and birds most threatened by fishery bycatch could be achieved as a collateral benefit to ending overfishing of target stocks. Given that achieving MEY and MSY would respectively require 52% and 33% reductions in fishing mortality for the median target stock (*2*), it makes sense that this alone could allow many threatened bycatch populations to recover. Marine turtles and cetaceans in developing-world waters stand to benefit in particular (Fig. 3). These populations are caught in coastal trawl and gillnet fisheries targeting shrimp and finfish (*12*, *13*), which are estimated (*2*) to need the greatest average reductions in fishing effort to achieve MEY (Fig. 1B and fig. S1). However, MEY reference points for shrimp fisheries may need to be refined to account for their highly variable, environmentally driven recruitment (*14*).

Second, we project that recovery of some bycatch populations would require substantial profit losses or targeting improvements. These bycatch populations tend to be caught in fisheries whose target stocks are already sustainably harvested [e.g., the New Zealand sea lion (*Phocarctos hookeri*)], require total or near-total elimination of bycatch to persist (e.g., the vaquita porpoise), or both (e.g., the Māui dolphin). Such bycatch populations should thus receive high priority in efforts to improve fishery targeting. Recent progress in bycatch mitigation efforts suggests that substantial targeting improvements are achievable (*15*). In many cases, non–fishery-related threats to these populations will also need to be addressed.

Ending overfishing can benefit fisheries and fishers. Our results suggest that it can also contribute substantially to reducing global bycatch of threatened species. Of course, ending overfishing is not easy. In many places, it will require new institutions and infrastructure, combined with increases in science and enforcement capacity (*16*). Substantially reducing fishing pressure can create short-term hardship for fishing communities until stocks recover (*2*). Rebuilding target stocks may also have important—sometimes negative—indirect effects on bycatch populations, and vice versa [e.g., via competition for prey (*17*)]. These issues deserve attention in future studies. Nonetheless, our conclusions enhance the motivation for continued global progress in sustainable fisheries reforms.

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/359/6381/1255/suppl/DC1
Materials and Methods
Figs. S1 to S8
Table S1
References (*20–110*)

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