RESEARCH ARTICLE SUMMARY

FISHERIES

Seventy years of tunas, billfishes, and sharks as sentinels of global ocean health

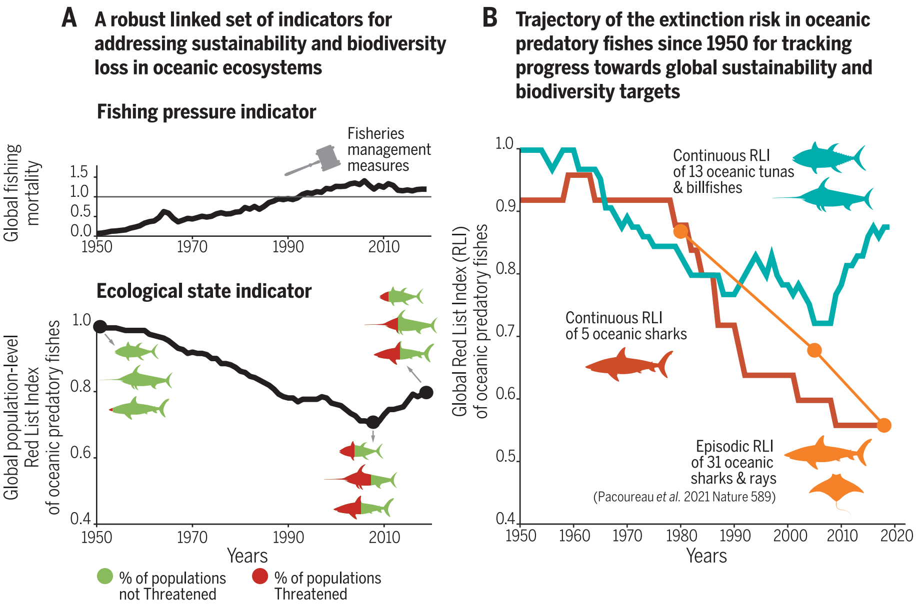
Maria José Juan-Jordá*, Hilario Murua, Haritz Arrizabalaga, Gorka Merino, Nathan Pacoureau, Nicholas K. Dulvy

INTRODUCTION: Recent biodiversity assessments show unprecedented loss of species, ecosystems, and genetic diversity on land but it remains unclear how widespread such patterns may be in the oceans. There is an urgent need to develop surveillance indicators to track the health of ecosystems in the marine realm, including changing extinction risk of marine species. These will allow evaluation of progress toward achieving global goals and commitments established by the Convention of Biological Diversity (CBD) and Sustainable Development Goals (SDGs) to halt and reverse marine biodiversity loss.

RATIONALE: Highly monitored oceanic fisheries comprising iconic predatory tunas, billfishes, and sharks yield an opportunity to support the development of linked sets of pressure and ecological state indicators capable of measuring progress toward global biodiversity and sustainability targets. We derived a continuous Red List Index (RLI) based on International Union for Conservation of Nature (IUCN) Red List categories and criteria for tracking yearly changes in extinction risk of oceanic tunas, billfishes, and sharks over the past 70 years to assess the health of oceanic biodiversity. Furthermore, by assessing the sensitivity and responsiveness of the RLI (state indicator) to fishing mortality (pressure indicator) and assessing the alignment between the most recent Red List status and fishery exploitation status of tunas, billfishes, and shark populations, we offer decision-makers a robust set of linked pressure-state indicators for tracking biodiversity loss and recovery in oceanic ecosystems.

RESULTS: We find that since 1950, the global extinction risk of oceanic predatory fishes has continuously worsened as a result of rising and excessive fishing pressure, up until the late 2000s when management actions reduced fishing mortality, allowing for recovery of tunas and billfishes. However, sharks remain undermanaged and their extinction risk continues to rise. Our findings reveal a core problem and ongoing challenge in the management of oceanic multigear and multispecies fisheries. Whereas target species are increasingly sustainably managed to ensure maximum yields, the functionally important shark species being captured incidentally by the same fisheries continue to decline as a result of insufficient management actions. Furthermore, our study also connects annual changes in global extinction risk with changes in fishing mortality over the last 70 years, demonstrating how the global RLI trajectory of oceanic predatory fishes is highly sensitive and responsive to fishing mortality.

CONCLUSION: Although halting biodiversity loss by rebuilding highly valuable commercial tuna and billfish species has been achieved, the next challenge is to halt declines in shark species by setting clear biodiversity goals and targets as well as implementing science-based conservation and fishery management measures and international trade regulations. Unless an effective mitigation hierarchy of management actions to reduce shark mortality is urgently implemented (and adapted to the complexity of each fishery and shark species), their risk of extinction will continue to increase. Furthermore, we demonstrate a high alignment and complementarity between the current population-level Red List status and fishery exploitation status of tunas, billfishes, and sharks, when applied at the same scale. Although we do not propose that the RLI be used to manage fish populations, this strong alignment eliminates any technical barrier for use of the RLI by policy-makers for tracking CBD and SDG targets. ■



Global Red List Index (RLI) of oceanic predatory fishes for tracking progress toward global biodiversity and sustainability targets. (**A**) The global population-level RLI (state indicator) closely tracks changes in fishing mortality (pressure indicator) for 52 oceanic tuna, billfish, and shark populations over the last 70 years, thus providing decision-makers with a linked set of pressure-state indicators for tracking the health of oceanic biodiversity. The population-level RLI was reversed in 2008 following a reduction in fishing mortality after implementation of fisheries management measures in tuna regional fisheries management organizations. The horizontal gray line denotes F/F_{MSY} =1, F_{MSY} being fishing mortality (F) which produces the maximum sustainable yield (MSY). (**B**) Global continuous species-level RLI of tunas, billfishes, and oceanic sharks (seven, six, and five species, respectively) tracking yearly changes in extinction risk over 70 years and the global episodic RLI of oceanic sharks and rays (21 and 10 species, respectively) estimated in 1980, 2005, and 2018. An RLI value of 1 indicates that a given taxa qualifies as least concern (that is, not expected to become extinct in the near future), whereas an RLI value of zero indicates that all taxa have gone extinct.

The list of author affiliations is available in the full article online.
*Corresponding author. Email: mjuan@azti.es
Cite this article as M. J. Juan-Jordá *et al.*, Science **378**, eabj0211 (2022). DOI: 10.1126/science.abj0211

READ THE FULL ARTICLE AT
https://doi.org/10.1126/science.abj0211

RESEARCH ARTICLE

FISHERIES

Seventy years of tunas, billfishes, and sharks as sentinels of global ocean health

Maria José Juan-Jordá[1]*, Hilario Murua[2], Haritz Arrizabalaga[1], Gorka Merino[1], Nathan Pacoureau[3], Nicholas K. Dulvy[3]

Fishing activity is closely monitored to an increasing degree, but its effects on biodiversity have not received such attention. Using iconic and well-studied fish species such as tunas, billfishes, and sharks, we calculate a continuous Red List Index of yearly changes in extinction risk over 70 years to track progress toward global sustainability and biodiversity targets. We show that this well-established biodiversity indicator is highly sensitive and responsive to fishing mortality. After ~58 years of increasing risk of extinction, effective fisheries management has shifted the biodiversity loss curve for tunas and billfishes, whereas the curve continues to worsen for sharks, which are highly undermanaged. While populations of highly valuable commercial species are being rebuilt, the next management challenge is to halt and reverse the harm afflicted by these same fisheries to broad oceanic biodiversity.

Recent global biodiversity assessments show unprecedented human-driven declines in abundance of wild species, compromising the integrity and functioning of ecosystems on Earth (*1*, *2*). However, the scale of damage upon oceanic ecosystems remains unclear. Fishing activity is increasingly monitored by satellites (*3*) and fishery statistics (*4*), but its effects on ocean biodiversity are not similarly tracked. The Convention of Biological Diversity (CBD) and the Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development together established a framework of agreed-upon targets and actions for governments to reduce the current rate of biodiversity loss at the global, regional, and national scale. This requires linked sets of pressure and ecological state indicators capable of measuring progress toward achieving global marine biodiversity and sustainability targets (*5*, *6*).

Several major oceanic predatory fishes—tunas, billfishes, and sharks—exhibit three features that make them strong candidates for assessment of the trajectory of oceanic biodiversity (Fig. 1, fig. S1, and table S1). First, they are among the largest (100 to 500 cm) megafaunal predators and most functionally unique species in pelagic ecosystems, and they play a critical role in regulating the structure, function, and stability of oceanic ecosystems (*7*). Second, they exhibit differential resilience to overfishing and span a range of fisheries categories from economically valuable target species to ecologically important incidental catch (*8*, *9*). Third, they are routinely monitored and assessed by the five tuna regional fisheries management organizations (tuna RFMOs) with the mandate to conserve and manage transboundary large migratory fish species (table S2 and fig. S2). Time series of biomass and fishing mortality rates derived from fish stock assessments are available for 52 populations of 18 species, encompassing 60% of oceanic predatory fish diversity (Fig. 1 and figs. S3 to S6). This data richness enables the development of linked sets of pressure and ecological state indicators capable of tracking global targets.

The International Union for the Conservation of Nature (IUCN) Red List Index (RLI) is a well-established ecological state indicator adopted as one of the official UN SDG and CBD indicators (*5*). The RLI is based on the IUCN Red List categories and criteria, which uses one of five quantitative criteria (A to E) to classify species into one of eight categories of extinction risk: extinct (EX), extinct in the wild (EW), critically endangered (CR), endangered (EN), vulnerable (VU), near threatened (NT), least concern (LC), and data deficient (DD) (*10*, *11*). The RLI shows trends in the overall extinction risk for a group of species by measuring how the number of species in each Red List category changes over time scaled from 1 (all species LC) to 0 (all species EX). The RLI has already been estimated from the episodic application of the IUCN Red List categories and criteria to the world's birds, mammals, amphibians, corals, cycads, and oceanic sharks and rays (*2*, *9*) by Red List Authorities and Specialist Groups of the IUCN Species Survival Commission. These episodic Red List assessments occur every 4 to 10 years, thus far yielding time series of 2 to 4 data points spanning up to four decades.

We first derive a novel continuous year-on-year RLI using a Bayesian framework to model population time series and estimate probabilistic extinction risk applying the IUCN Red List A criterion (fig. S7) (*12*, *13*). Then, we develop a global continuous RLI for 18 oceanic predatory fishes of tunas, billfishes, and sharks from 1950 to 2019 to assess the state of oceanic biodiversity. Finally, we assess the sensitivity and responsiveness of the RLI trajectory to fishing pressure, providing decision makers with an integrated linked set of pressure-state indicators for tracking biodiversity change.

We illustrate our six-step method to estimate extinction risk with its application to the Southern Bluefin Tuna (*Thunnus maccoyii*; Fig. 2 and figs. S7 to S9) (*14*). Criteria A classifies extinction risk based on exceeding a threshold of population decline over the greater part of 10 years or three generation lengths (GL). First, we defined the GL of the given species (12 years) and extracted abundance time series from the most recent fish stock assessment (Fig. 2A, fig. S5, and table S3). Second, we calculated the total percent change in population biomass over three GL by estimating the average annual rate of population change over the

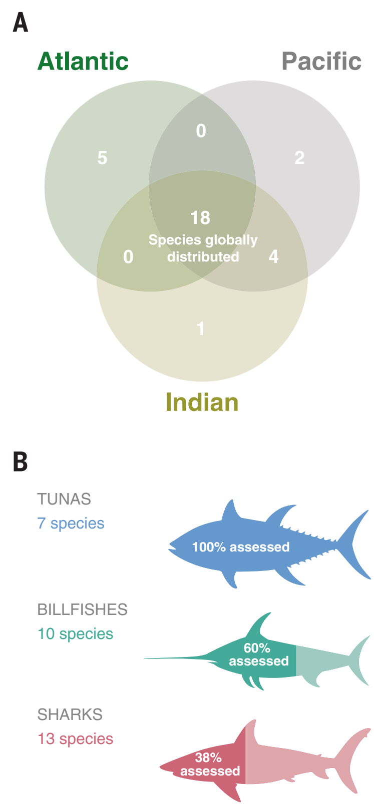


Fig. 1. Oceanic predatory fishes of the world. (**A**) Total number of oceanic tunas, billfishes, and sharks distributed globally and by ocean (table S1). (**B**) Proportion of species with at least one population assessed with fish stock assessment models by major taxa (table S2).

[1]AZTI, Marine Research, Basque Research and Technology Alliance (BRTA). Herrera Kaia, Portualdea z/g, 20110 Pasaia, Gipuzkoa, Spain. [2]International Seafood Sustainability Foundation, Pittsburgh, PA, USA. [3]Earth to Ocean Research Group, Department of Biological Sciences, Simon Fraser University, Burnaby, British Columbia, Canada.
*Corresponding author. Email: mjuan@azti.es

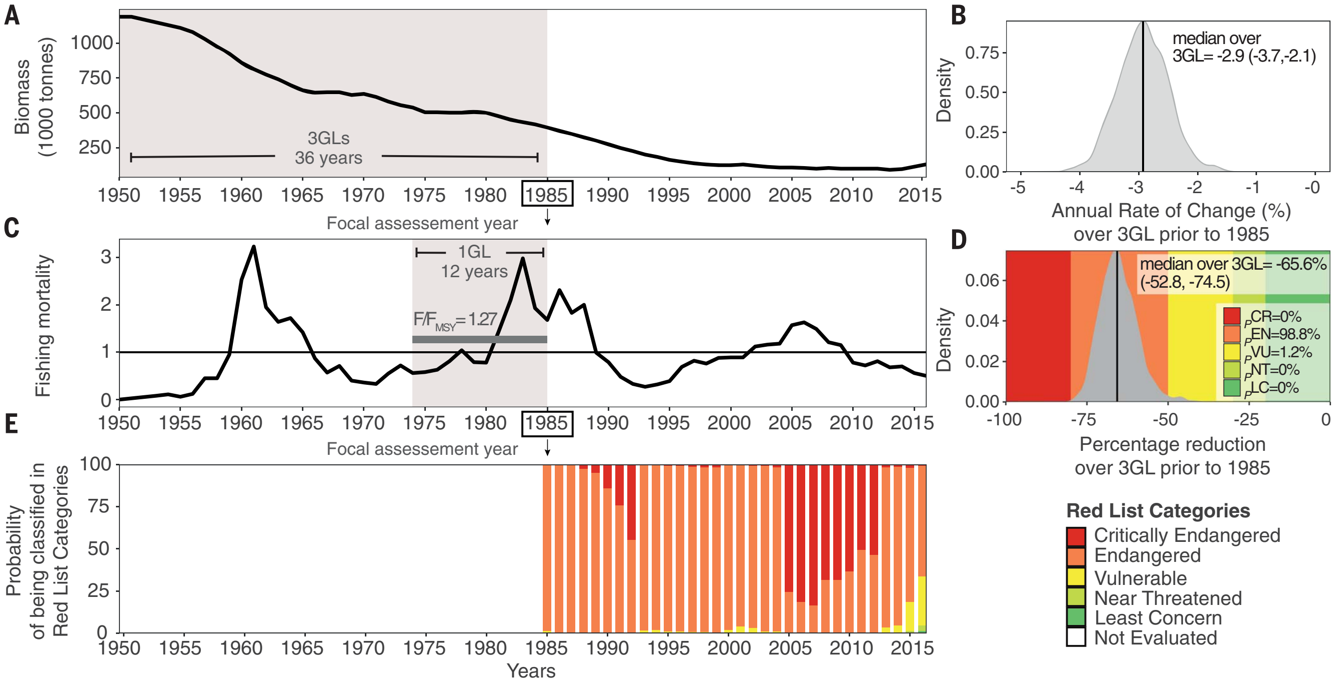


Fig. 2. Illustrative example of a continuous Red List assessment using Criterion A for Southern Bluefin Tuna from 1985 to 2016. (**A**) Time series of biomass from the latest fish stock assessment (table S2). The shaded rectangle shows the three GL window used to estimate the Red List category for 1985. (**B**) Posterior probability distribution and median (vertical black line) of the estimated average annual rate of change (percent) in population size over the previous three GL in 1985. (**C**) Time series of fishing mortality rate relative to F_{MSY}. The shaded rectangle shows the average fishing mortality over a one GL window before 1985, showing that the species is not being sustainably managed—hence application of the A2 thresholds. (**D**) Posterior median (vertical black line) and probability distribution of the estimated total reduction over three GL in 1985. The posterior probability is overlaid on the Red List category A2 thresholds. (**E**) The probability of being classified in the Red List categories in 1985 and at each subsequent year between 1985 and 2016.

three GL window using an intercept-only hierarchical Bayesian model (*14*). These models allow for nonlinearity in population trends and account for the hierarchical structure of the data as some species trends are based on multiple population estimates from multiple fish stock assessment models (fig. S5). We estimated that by 1985, Southern Bluefin Tuna had a median population reduction of 65.6% [95% credible interval (CI) 52.8, 74.5], equivalent to an annual rate of change of −2.9% (CI −3.7, −2.1) (Fig. 2B). Third, we classified status using either A1 thresholds, when the species is sustainably managed worldwide (i.e., the causes of decline are reversible, and understood, and have ceased) in at least 90% of its range, or A2 thresholds otherwise. Specifically, A1 thresholds for population reduction (VU = 50 to 69%, EN = 70 to 89%, and CR ≥ 90%) are applied to sustainably managed species. In operational terms, a fish species is considered sustainably managed when the average fishing mortality (F) on the species is below the fishing mortality corresponding to the maximum sustainable yield (MSY) ($F/F_{MSY} \leq 1$) for the previous one GL in at least 90% of its range in accordance with IUCN guidelines (*15*). Otherwise, for unsustainably managed species ($F/F_{MSY} > 1$), the A2 thresholds (VU = 30 to 49%, EN = 50 to 79%, and CR ≥ 80%) are applied. In our illustrative example, the Southern Bluefin Tuna was not being sustainably managed (F/F_{MSY} = 1.27) in 1985 based on the average fishing mortality over the one GL window before 1985, hence application of the A2 threshold (Fig. 2C). Fourth, we assigned Red List category probabilities because the Bayesian estimation framework allows us to propagate the uncertainty in population reductions into probabilistic classifications for each of the Red List categories (*12*). Based on a population reduction value of 65.6%, Southern Bluefin Tuna was classified as EN (probability $_P$EN=98.7% and $_P$VU=1.3%) in 1985 (Fig. 2D). The fifth step consisted of a year-on-year estimation of Red List status for the entire time series, which reveals how Southern Bluefin Tuna became increasingly threatened over time to the point where in 2005 it was classified as CR ($_P$CR=76% and $_P$EN=24%; Fig. 2E). As fishing mortality was reduced from 2006 onward, the biomass of Southern Bluefin Tuna stabilized at low levels and has recently started to increase—this is closely tracked by a reduction in extinction risk in the most recent years ($_P$CR=0%, $_P$EN=66%, $_P$VU=29%, $_P$NT=4%, and $_P$LC=1% in 2016; Fig. 2E). This is a case for which we have one population representing the whole species. An example of a species composed of multiple populations and how they are combined to the species level is available in the supplementary materials (fig. S10 and table S4). Last, we aggregated the Red List status hierarchically across populations (fig. S8) and then species (fig. S9) to derive the global RLI of oceanic predatory fishes (*14*).

Since 1950, the global RLI trajectory of oceanic predatory fishes worsened by ~27% (95% CI 24.4, 31.1) reflecting the increasing extinction risk of the whole assemblage until recovery became apparent in 2008 (Fig. 3A). In that year, 10 species were classified as threatened, with Southern Bluefin Tuna and Oceanic Whitetip Shark (*Carcharhinus longimanus*) classified as CR; Blue Marlin (*Makaira nigricans*), Silky Shark (*Carcharhinus falciformis*), Porbeagle Shark (*Lamna nasus*), and Swordfish (*Xiphias gladius*) as EN; and Bigeye Tuna (*Thunnus obesus*), Yellowfin Tuna (*Thunnus albacares*), Pacific Bluefin Tuna (*Thunnus orientalis*), and Striped Marlin (*Kajikia audax*) as VU (fig. S9). The most recent recovery of the RLI since 2008 reflects improvement (from CR to VU) of Southern Bluefin Tuna, and improvement of five species into NT and LC [Yellowfin Tuna, Swordfish, Blue Marlin, Striped Marlin, and Black Marlin (*Makaira indica*); fig. S9]. However, the RLI trajectory varies among major taxa (Fig. 3, B and C). For tunas, the RLI started to improve in the 1990s and end of the 2000s whereas the RLI for billfishes deteriorated until the early 2000s, improving only during the past decade. However, the RLI of sharks has worsened continuously. Our continuous RLI is robust to the choice of different time windows for calculating fishing mortality metrics and population range–based scenarios to determine whether a species is being sustainably managed throughout its entire range (figs. S11 to S13) (*14*).

To understand how changes in population-level fishing mortality underlie the RLI, we derived a global population-level RLI for the 52 assessed populations (Fig. 4 and fig. S14). The 58-year decline and recent recovery in the population-level RLI of oceanic predatory fishes closely tracks the historical trend of fisheries development and implementation of fisheries management in these species. Since the 1950s, global average fishing mortality has been increasing, exceeding sustainable levels in 1993 and then peaking in 2006 (Fig. 4A). Over this same period, the average biomass of oceanic predatory fishes declined

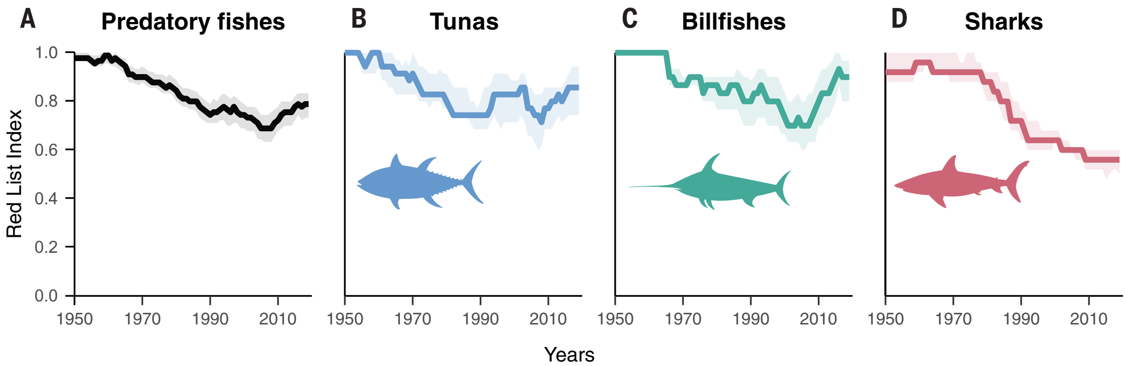


Fig. 3. RLI of oceanic predatory fishes. (**A**) The global RLI includes 18 species of oceanic tunas, billfishes, and sharks and is disaggregated by major taxon: (**B**) tunas, (**C**) billfishes, and (**D**) sharks. The solid line denotes the median and the shaded polygons denote the 95% CI. An RLI value of 1.0 indicates that all species qualify as Least Concern (that is, not expected to become extinct in the near future) whereas an RLI value of 0 indicates that all species have gone extinct.

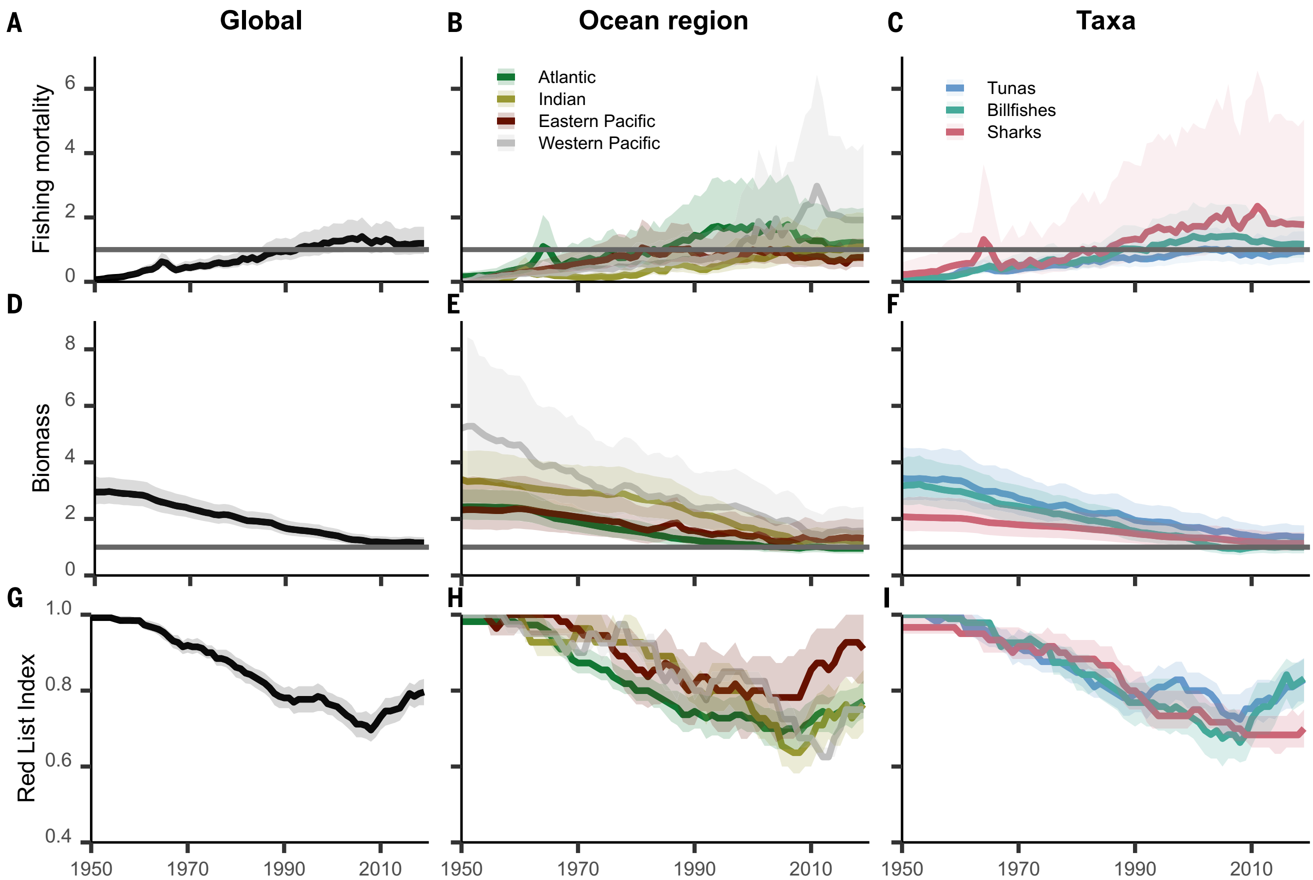


Fig. 4. Trends in overall fishing mortality and their impact on population biomass and population-level RLI trajectory of oceanic predatory fishes. (**A**) Global average fishing mortality rates relative to F_{MSY} and is disaggregated by major ocean regions (**B**) and taxon (**C**). (**D**) Global average biomass relative to B_{MSY} and is disaggregated by major ocean regions (**E**) and taxon (**F**). (**G**) Global population-level RLI and is disaggregated by major ocean regions (**H**) and taxon (**I**). The solid line denotes the median and the shaded polygons the 95% CIs. The horizontal gray lines denote the F_{MSY} and B_{MSY}. Interpretation of RLI values can be found in Fig. 3.

and then approached the MSY (B_{MSY}; Fig. 4D). Consequently, the population-level RLI of oceanic fishes worsened steadily since the 1950s, reaching its lowest value in 2008, 2 years after the maximum value of fishing mortality (Fig. 4G). When fishing mortality started to decrease after 2006, the population-level RLI reversed shortly after, reflecting the reclassification of many populations into less threatened categories (fig. S8).

The extent and timing of management measures implemented by tuna RFMOs differ markedly among ocean regions and taxa, influencing overall fishing mortality, biomass, and population-level RLI trajectories (Fig. 4). Regionally, the RLI trajectories track the historical increase in fishing mortality following the development of industrial tuna fisheries, which began first in the Atlantic and eastern Pacific before expanding to the Indian and western Pacific oceans during the 1980s (Fig. 4B). The lowest RLI values observed in the Indian and western Pacific around the 2010s (Fig. 4H) were due to the steep decline in biomass (Fig. 4E) resulting from the rapid increase in fishing mortality. We also find that the different timing in the stabilization pattern of overall biomass levels around the management target of MSY in the four ocean regions has resulted in the observed region-level reductions in extinction risk. The RLI has been reversed in all oceans through reductions in fishing mortality (Fig. 4H). When examining population-level RLI trajectories by major taxon, we confirm that the declining RLI trajectory has not only been halted but also reversed for tunas and billfishes (Fig. 4I). We attribute these recoveries to a reduction in overall fishing mortality (Fig. 4C) and hence the recovery of biomass toward sustainable levels (Fig. 4F) following effective management measures. However, we caution that the threatened status of some tunas and billfishes (e.g., Indian Ocean Yellowfin and Atlantic Bigeye Tuna) require strengthened management measures (fig. S8). Historically, sharks have been the incidental catch of these tuna and billfish fisheries and have declined steeply (Fig. 4, F and I) as fishing mortality is twice that of the sustainable level (Fig. 4C). Despite increasing scientific evidence and public concern, undermanaged populations of oceanic sharks continue to worsen along a path of increasing extinction risk (Fig. 4I).

By next demonstrating the correlation between fishing mortality and the RLI and evaluating the alignment between fishery exploitation status and Red List status, we offer decision-making tools for tracking and tackling biodiversity loss in oceanic ecosystems thus supporting UN CBD and SDG processes (*6*). First, we assess the sensitivity and responsiveness of the RLI trajectory to fishing pressure using a prewhitened cross-correlation analysis for removing the autocorrelation and trends in the time series. We show that the RLI closely tracks changes in fishing mortality and find a significant negative cross-correlation between fishing mortality and the RLI (Fig. 5A), suggesting that the RLI is sensitive (sensitivity = −0.34) and responsive to fishing mortality (with a significant time lag of only 2 years) (*14*) (figs. S15 to S17). The pressure-state relationship is reversible and symmetric, with the RLI recovering as fishing mortality decreases, tracking back (green points) along the same path as the decline trajectory (red points, Fig. 5A). Second, we assessed alignment by comparing the fishery exploitation status [whether populations are considered overfished ($B < B_{MSY}$) or not ($B \geq B_{MSY}$), derived from the latest fish stock assessments and the corresponding population-scale Red List status (*14*) (table S5). We find that the fishery exploitation status and Red List status are aligned in 76.6% of the assessments (true positives and negatives; Fig. 5B and table S6). Therefore, a sustainable fishery will have low extinction risk, and conversely in an unsustainable fishery, an overfished population will likely have a higher extinction risk. However, some overfished populations were categorized in the low-risk category of LC by the Red List assessment (a "miss" of 12.8%; Fig. 5B), as they may not be considered threatened when their abundance declines have been stabilized at low levels and the causes of decline are understood and have ceased. Furthermore, there were few "false alarms" (10.6%) in which the Red List criteria classified a population as threatened although it was not being estimated as overfished, offering an early warning for those populations with relatively large biomass declining rapidly toward target levels (fig. S5). These false alarms are transient and disappear if populations are stabilized at target levels. Altogether, this harmony in criteria sets is highly consistent with all other modeling and meta analyses comparing the Red List status with fishery exploitation status over a wide range of marine fishes (*16*–*18*) and provides further evidence of alignment among both classification systems when applied at the same scale. Although we do not propose that the RLI be used to manage populations, there should be no concerns that a threatened listing is inconsistent with fishery management advice as these mismatches can often be understood and explained. Hence, our findings of strong alignment demonstrate that both criteria sets are complementary and eliminate any technical

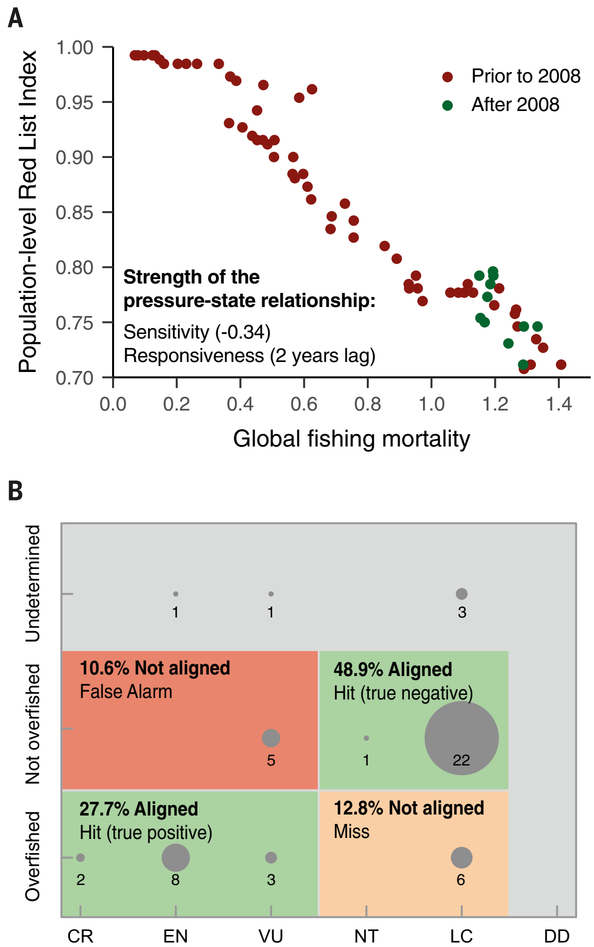


Fig. 5. Effects of fishing mortality on the state of oceanic predatory fishes. (**A**) Prewhitened cross-correlation between global average annual fishing mortality and population-level RLI for the assessment of sensitivity and responsiveness of the RLI to fishing. (**B**) Alignment between the population-level Red List status in relation to fishery exploitation status. Current fishery exploitation status, whether the population is considered overfished ($B_{current} < B_{MSY}$) or not ($B_{current} > B_{MSY}$), derived from the most current fishery assessments (*y* axis) and the Red List status for the same assessment year (*x* axis). Circle size is proportional to the number of populations classified in each category.

barrier for use of the RLI by policy-makers for tracking CBD and SDG targets.

Our continuous RLI of oceanic predatory fishes advances and complements episodic RLI as calculated for other animal and plant groups (Fig. 6) as it allows for tracking of status and trends in extinction risk on much finer time scales. In a half a century, industrial fisheries have reduced oceanic pelagic biodiversity to levels similar to those brought about for other terrestrial taxa over the course of centuries (*19*). The initial warnings now seem timely and appropriate given how rapidly the RLI of oceanic tunas, billfishes, and some sharks have recovered to levels more typical of terrestrial vertebrates. This provides evidence that decisive action by fisheries agencies can recover exploited fishes, but we have yet to take similarly decisive action for sharks. Furthermore, our continuous RLI trajectories for tunas (Fig. 3B) and sharks (Fig. 3D) are highly consistent with the recently published episodic IUCN Red List assessments for oceanic tunas and sharks (*8*, *9*, *20*), showing that the RLI for oceanic tunas has recovered between 2011 and 2021 and that the global extinction risk for sharks continues to worsen. For data-rich taxa, both the episodic and continuous RLI are highly aligned because both Red List assessments are driven by the same data, though we note that the episodic formal IUCN Red List assessments process has scope to diverge as it considers other criteria (B to E), threats, use and

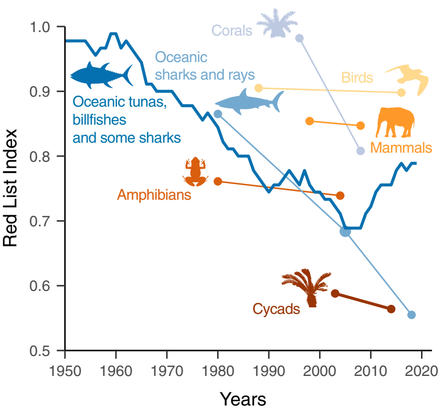


Fig. 6. Decline and recovery of the RLI of oceanic predatory fishes in the context of increasing risk of extinctions in major taxa groups. Our species-level RLI of oceanic tunas (n = 7 species), billfishes (n = 6), and sharks (n = 5) adds to the already monitored episodic RLI trajectories of marine taxa groups (illustrated with tones of blue): oceanic sharks and rays (n = 31; 5 of these species are included in our continuous RLI for sharks), and corals (n = 704). Terrestrial taxa groups are illustrated with earthy tones: mammals (n = 4556), birds (n = 9869), amphibians (n = 4355), and cycads (n = 307) (*2*, *9*).

trade, and conservation actions to categorize species in addition to the population reduction analysis used here. Finally, our continuous RLI could be applied to other marine fishes and any other taxa with time series of population data, which would increase the temporal and spatial resolution of both global and regional Red List and RLI assessments. We reaffirm the need to expand the representation of marine species on the Red List to monitor marine biodiversity because most marine taxa remain unassessed (*21*).

Our study connects annual changes in fishing mortality and extinction risk globally over the past 70 years for oceanic tunas, billfishes, and sharks and reveals how effective management for highly valuable commercial species of tunas and billfishes has reversed the biodiversity loss curve while the extinction risk of undermanaged sharks continues to increase. Our vignette of oceanic predator fisheries reveals the biggest challenge of global multigear and multispecies fisheries management, as target species are increasingly being brought to sustainable levels to ensure maximum yield. However, the shark species incidentally captured by the same fisheries continue to decline to the point where there is increasing risk of biodiversity loss due to insufficient management actions (*22*, *23*). Driven by policy complexity, insufficient data and monitoring, socioeconomic concerns, and lack of political action, oceanic sharks remain undermanaged and a lower priority in tuna RFMOs despite repeated and increasingly intense warnings based on their high intrinsic sensitivity to overfishing, increasing catches, and the high international trade value of their meat and fins (*9*, *24*). To date, conservation and management measures in tuna RFMOs for sharks remain largely focused on mitigating the effects of fishing on incidental catches through gear modification (e.g., banning shark leaders), safe handling and release practices (e.g., devil rays caught in purse seines), prohibition of retention (e.g., thresher and hammerheads sharks), and establishing requirements for data reporting to support their assessments (*24*). However, there seems to be high resistance to any measure that might meaningfully curb fishing mortality for sharks. Unless an effective mitigation hierarchy of management actions to reduce shark mortality—including international trade regulation—are urgently implemented and adapted to the complexity of each fishery and shark species, their trajectories will continue worsening in the future (*25*). We show that reversing the curve of oceanic biodiversity loss is possible in the case where fishery sustainability goals and effective management measures are implemented, even in the challenging context of international fisheries management. Defining new priorities and setting clear biodiversity goals and targets to halt and reverse broad oceanic biodiversity loss remains the next management challenge to achieve progress for both people and oceanic biodiversity.

Materials and Methods

Compilation of population data from fish stock assessments

We compiled the most recent (as of June 2020) fish stock assessments for 52 populations (18 species) of tunas, billfishes, and sharks from the five tuna RFMOs (fig. S2 and table S2) (*14*). For each fish stock assessment, we extracted the following: (a) the estimated time series of biomass or time series of biomass relative to the biomass that produces the MSY [B/B_{MSY}] (fig. S5), (b) the estimated time series of fishing mortality relative to the fishing mortality that produces the MSY [F/F_{MSY}] (fig. S6), and (c) the standard biological reference points used to determine population status, generally the current adult biomass relative to the adult biomass producing MSY ($B_{current}/B_{MSY}$) and current fishing mortality rate relative to the fishing mortality that maintains MSY ($F_{current}/F_{MSY}$) (table S2). This data was extracted from the assessment models (and model runs) used to determine population status and provide management advice by the Scientific Committees of each of the tuna RFMOs (*14*).

Compilation and estimation of generation lengths

We also collated the GL for each species (and populations) of tunas, billfishes, and sharks from the published literature or as approved for use by the IUCN Tuna and Billfish Specialist Group or the IUCN Shark Specialist Group (table S3). In some cases we also estimated GL for populations using age-structured life tables (*14*).

Estimation of Red List status

We applied the IUCN Red List categories and criteria to calculate the extinction risk for 18 species of tunas, billfishes, and sharks (fig. S7) (*14*). All species of oceanic tunas, billfishes, and sharks were assessed under IUCN Red List Criterion A "population reduction." Criterion A was applied to both the taxonomic unit of population and the taxonomic unit of species, to assign a Red List category to each population and species of tunas, billfishes, and sharks between 1950 and 2019 (figs. S8 and S9). For each species and population, we estimated the total percent change in biomass within the past three GL yearly between 1950 and 2019, and then we assigned a Red List category using Criterion A1 or A2 thresholds, depending on whether the species/population was being effectively and sustainably managed. A fish species/population is considered sustainably managed when the average fishing mortality

(F) on the species or population is below the fishing mortality corresponding to the maximum sustainable yield (MSY; $F/F_{MSY} \leq 1$) for the previous one GL in at least 90% of its range according to IUCN guidelines (*15*). When estimating the total percent change for species with multiple populations, we weighted the estimated total percent change in biomass of each population by their MSY to account for the contribution of different population sizes to the global species (table S2). We calculated the total percent change in population biomass over the past three GL by estimating the average annual rate of population change over the three-GL window using an intercept-only hierarchical Bayesian model (*14*). At the end, we were able to assign Red List categories to the taxonomic unit of population (fig. S8) and the taxonomic unit of species (fig. S9) annually between 1950 to 2019 (fig. S10 shows two illustrative examples of Red List status calculations). Because of the Bayesian estimation framework, we assigned Red List category probabilities allowing us to propagate the uncertainty in population reductions into probabilistic classifications for each of the Red List categories. The application of A1 or A2 thresholds for assigning the most likely Red List category requires to determine on an annual basis whether a population and species is being sustainably managed. We conducted two different sensitivity analyses for evaluating the impact of calculating in different ways whether a population and species is being sustainably managed on the determination of extinction risk (figs. S11, S12, and S13) (*14*).

Estimation of RLI

We calculated a continuous RLI for oceanic predatory fishes between 1950 and 2019 using the estimated extinction risk of the 18 species of tunas, billfishes, and sharks (figs. S7 and S14) (*14*). We also disaggregated the global species-level RLI by major taxon (tunas, billfishes, sharks). Traditionally, the RLI is calculated from the episodic application of the IUCN Red List categories and criteria to species groups, and this usually occurs episodically involving Red List Authorities and Specialist Groups of the IUCN Species Survival Commission. Instead, here, we calculated a continuous RLI using a Bayesian framework by classifying species into the extinction risk probabilistic categories using time series analyses of population data derived from fish stock assessments (*14*). The Bayesian estimation framework improved the characterization of uncertainty in the RLI, which facilitates the communication of uncertainty and probabilistic statements to conservation practitioners (*12*).

We also calculated a global population-level RLI in order to examine the effects of global fishing pressure (here expressed as fishing mortalities), which is monitored at the level of population, on the population-level RLI trajectories. We calculated the global population-level RLI using the Red List status of the 52 populations of tunas, billfishes, and sharks as the basic unit of assessment (instead of using species as the unit of assessment) assigning equal weighting to all populations (fig. S7 and S14) (*14*).

Estimation of the overall trajectories of biomass and fishing mortalities

We calculated the global overall trajectory of biomass and fishing mortality across the 52 populations of oceanic predatory fishes from 1950 to 2019 by fitting a Bayesian generalized linear model where the fishing mortality or biomass values were treated as the response variable with a Gamma likelihood and an identity link function, and the years were the fixed predictors (treated as factors) (*14*). In this way, the estimated average biomass or fishing mortality had balanced data as each year had the same number of populations and each population weighted equally.

REFERENCES AND NOTES

1. "Secretariat of the Convention on Biological Diversity (2020) Global Biodiversity Outlook 5 – Summary for Policy Makers" (UN Convention on Biological Diversity, 2020).
2. "Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services" S. Díaz *et al*., Eds. (IPBES secretariat, 2019).
3. D. A. Kroodsma *et al*., Tracking the global footprint of fisheries. *Science* **359**, 904–908 (2018). doi: 10.1126/science.aao5646
4. FAO, *The State of World Fisheries and Aquaculture 2020.* (FAO, 2020); www.fao.org/documents/card/en/c/ca9229en.
5. G. M. Mace *et al*., Aiming higher to bend the curve of biodiversity loss. *Nat. Sustain.* **1**, 448–451 (2018). doi: 10.1038/s41893-018-0130-0
6. T. H. Sparks *et al*., Linked indicator sets for addressing biodiversity loss. *Oryx* **45**, 411–419 (2011). doi: 10.1017/S003060531100024X
7. E. L. Hazen *et al*., Marine top predators as climate and ecosystem sentinels. *Front. Ecol. Environ.* **17**, 565–574 (2019). doi: 10.1002/fee.2125
8. B. B. Collette *et al*., High value and long life - Double jeopardy for tunas and billfishes. *Science* **333**, 291–292 (2011). doi: 10.1126/science.1208730
9. N. Pacoureau *et al*., Half a century of global decline in oceanic sharks and rays. *Nature* **589**, 567–571 (2021). doi: 10.1038/s41586-020-03173-9; pmid: 33505035
10. S. H. M. Butchart *et al*., Improvements to the Red List Index. *PLOS ONE* **2**, e140 (2007). doi: 10.1371/journal.pone.0000140; pmid: 17206275
11. IUCN Red List Categories and Criteria: Version 3.1 (IUCN Species Survival Commission, 2012); https://portals.iucn.org/library/sites/library/files/documents/RL-2001-001-2nd.pdf.
12. R. B. Sherley *et al*., Estimating IUCN Red List population reduction: JARA—A decision-support tool applied to pelagic sharks. *Conserv. Lett.* **13**, e12688 (2020). doi: 10.1111/conl.12688
13. N. K. Dulvy, S. Jennings, S. I. Rogers, D. L. Maxwell, Threat and decline in fishes: An indicator of marine biodiversity. *Can. J. Fish. Aquat. Sci.* **63**, 1267–1275 (2006). doi: 10.1139/f06-035
14. Materials and methods are available as supplementary materials.
15. Guidelines for Using the IUCN Red List Categories and Criteria, Version 14 (IUCN Standards and Petitions Committee, 2019); https://www.iucnredlist.org/resources/redlistguidelines.
16. N. K. Dulvy, H. K. Kindsvater, in *Conservation for the Anthropocene Ocean*, L. P. S, M. R. Poe, Eds. (Academic Press, 2017), pp. 339–340.
17. P. G. Fernandes *et al*., Coherent assessments of Europe's marine fishes show regional divergence and megafauna loss. *Nat. Ecol. Evol.* **1**, 0170 (2017). doi: 10.1038/s41559-017-0170
18. S. Millar, M. Dickey-Collas, Report on IUCN assessments and fisheries management approaches. ICES CM 2018/ACOM:60 (2018).
19. D. J. McCauley *et al*., Marine defaunation: Animal loss in the global ocean. *Science* **347**, 1255641 (2015). doi: 10.1126/science.1255641
20. The IUCN Red List of Threatened Species, (IUCN, 2015); www.iucnredlist.org.
21. T. J. Webb, B. L. Mindel, Global patterns of extinction risk in marine and non-marine systems. *Curr. Biol.* **25**, 506–511 (2015). doi: 10.1016/j.cub.2014.12.023; pmid: 25639240
22. R. Hilborn *et al*., Effective fisheries management instrumental in improving fish stock status. *Proc. Natl. Acad. Sci. U.S.A.* **117**, 2218–2224 (2020). doi: 10.1073/pnas.1909726116; pmid: 31932439
23. M. G. Burgess *et al*., Protecting marine mammals, turtles, and birds by rebuilding global fisheries. *Science* **359**, 1255–1258 (2018). (2018). doi: 10.1126/science.aao4248
24. M. J. Juan-Jordá, H. Murua, H. Arrizabalaga, N. K. Dulvy, V. Restrepo, Report card on ecosystem-based fisheries management in tuna regional fisheries management organizations. *Fish Fish.* **19**, 321–339 (2017). doi: 10.1111/faf.12256
25. H. Booth, D. Squires, E. J. Milner-Gulland, The mitigation hierarchy for sharks: A risk-based framework for reconciling trade-offs between shark conservation and fisheries objectives. *Fish Fish.* **21**, 269–289 (2019). doi: 10.1111/faf.12429
26. M.-J. Juan-Jordá, N. Pacoureau, mjuanjorda/RLI_tunas_billfishes_sharks, Github (2022); https://github.com/mjuanjorda/RLI_tunas_billfishes_sharks.

ACKNOWLEDGMENTS

We thank all the authors of the fishery stock assessments used in our analysis, which were performed by the five tuna regional fisheries management organizations independent of this paper. We also thank A. B. Cooper, and the Earth to Ocean Research Group from Simon Fraser University, Canada for their highly constructive comments and feedback at the early stages of this study. **Funding:** M. J. J-J. received funding from the People Programme (Marie Curie Actions) of the European Union's Seventh Framework Programme (FP7/2007-2013) under REA grant agreement [628116], and a fellowship from "la Caixa" Foundation (ID 100010434). The "la Caixa" fellowship code is (LCF/BQ/PR20/11770005). N.K.D. was supported by the Natural Sciences and Engineering Research Council of Canada and the Canada Research Chairs Program. This paper is contribution 1130 from AZTI, Marine Research, Basque Research and Technology Alliance (BRTA). **Author contributions:** M. J. J-J. and N.K.D. conceptualized the analysis. M. J. J-J., H. M., H.A., and G. M. compiled and curated the time series data. M. J. J-J. and N.K.D. visualized the data and wrote the first draft. M. J. J-J. and N.P. conducted the statistical analysis with input from all authors. M. J. J-J. created figures with input from all authors. M. J. J-J., H. M., H.A., and N.K.D. acquired the funding. All authors discussed the time series data, developed the methodology, discussed analysis and results, contributed to writing the manuscript and oversaw the project. **Competing interests:** The authors declare no competing interests. **Data and materials availability:** Data and code used in our analysis will be available on GitHub. All other data needed to evaluate conclusions in the paper are present in the paper or the supplementary materials.

SUPPLEMENTARY MATERIALS

science.org/doi/10.1126/science.abj0211
Materials and Methods
Figs. S1 to S17
Tables S1 to S6
References (*27*–*47*)
MDAR Reproducibility Checklist

Submitted 27 April 2021; resubmitted 10 December 2021
Accepted 27 September 2022
10.1126/science.abj0211

Science

Seventy years of tunas, billfishes, and sharks as sentinels of global ocean health

Maria José Juan-JordáHilario MuruaHaritz ArrizabalagaGorka MerinoNathan PacoureauNicholas K. Dulvy

Science, 378 (6620), eabj0211. • DOI: 10.1126/science.abj0211

Conservation works
Tuna and billfishes are large species that have long been targeted by fisheries, whereas sharks, which are also large fishes, have tended to be considered as by-catch or nontarget species. Juan-Jorda *et al*. used an approach that monitors yearly changes in the International Union for Conservation of Nature Red List status to estimate population status for these three groups (see the Perspective by Burgess and Becker). After almost three decades of decline, tuna and billfishes have begun to recover because of proactive fisheries management approaches. Sharks, however, which have received much less conservation attention, have continued to decline. These results both reinforce the value of conservation and management and emphasize the need for immediate implementation of these approaches for sharks.
—SNV

Science (ISSN) is published by the American Association for the Advancement of Science. 1200 New York Avenue NW, Washington, DC 20005. The title *Science* is a registered trademark of AAAS.