CONSERVATION

Global shark fishing mortality still rising despite widespread regulatory change

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Over the past two decades, sharks have been increasingly recognized among the world's most threatened wildlife and hence have received heightened scientific and regulatory scrutiny. Yet, the effect of protective regulations on shark fishing mortality has not been evaluated at a global scale. Here we estimate that total fishing mortality increased from at least 76 to 80 million sharks between 2012 and 2019, ~25 million of which were threatened species. Mortality increased by 4% in coastal waters but decreased by 7% in pelagic fisheries, especially across the Atlantic and Western Pacific. By linking fishing mortality data to the global regulatory landscape, we show that widespread legislation designed to prevent shark finning did not reduce mortality but that regional shark fishing or retention bans had some success. These analyses, combined with expert interviews, highlight evidence-based solutions to reverse the continued overexploitation of sharks.

Sharks and their relatives (class Chondrichthyes) have persisted as powerful ocean predators for over 400 million years, yet many shark species are recently threatened by overfishing, raising serious concerns about species extinction (*1*) and associated consequences for ocean ecosystems (*2*, *3*). Large numbers of sharks have historically been caught incidentally by the world's pelagic tuna fisheries, and elevated mortality has been linked to increasing demand for their fins, a valuable commodity in Asian markets (*4*, *5*). In response, protective regulations were introduced by national governments and regional fisheries management organizations (RFMOs). Most regulations aimed to eliminate the wasteful practice of shark finning, in which valuable fins are retained and shark carcasses are discarded at sea (*6*). These efforts were further supported by changing market forces (*7*), international agreements to limit the trade of threatened species (*8*), sustained nongovernmental organization (NGO) advocacy to address pelagic fisheries bycatch (*9*), and public awareness campaigns intended to curb demand for shark fins (*10*). No studies to date have investigated whether such shark finning and fishing regulations have successfully reduced shark fishing mortality globally.

In this study, we calculated global patterns of shark fishing mortality at 1° by 1° resolution from 2012 to 2019 and contrasted these patterns with relevant regulations adopted during this time. We took a synthetic approach, collating and analyzing all available shark-catch data and regulatory data reported by individual fisheries, countries, and RFMOs (fig. S1 and tables S1 to S6). Fishery- and country-level data were derived from detailed, spatially explicit catch reconstructions based on United Nations Food and Agriculture Organization (FAO)–reported catches combined with regional data and expert sources informing estimates of unreported catches and discards that are not included in the FAO statistics (*11*). Publicly available RFMO shark-catch data recorded by scientific observers or self-reported by fishers were collated, evaluated, and spatially allocated by using a recently developed Random Forest machine learning approach (*12*) (tables S7 to S10). All catch data were converted to fishing mortality estimates by using species-, gear-, and, where available, location-specific shark-catch fate and postrelease mortality information (figs. S1 to S7). We further conducted in-depth interviews with 22 experts, whose deep knowledge helped contextualize current trends in shark finning and mortality and the mechanistic drivers of these trends and served to validate our quantitative assessment (full details on data sources and processing are found in materials and methods).

Tracking changes in the regulatory landscape (Fig. 1, A to C, and tables S3 to S5), we documented a >10-fold increase in international (Fig. 1A) and national (Fig. 1B) management measures addressing shark fishing and finning since 2000. As of 2022, 29 countries and overseas territories (hereafter "jurisdictions") have declared shark sanctuaries, no-take protected areas, or other protective measures that prohibit shark fishing within their national waters. Most jurisdictions, however, have focused shark conservation efforts on measures to eliminate shark finning rather than to curtail fishing or retention of sharks outright. Currently, 94 jurisdictions and one RFMO have finning regulations that require fishers to land whole sharks with their fins naturally attached. A further four jurisdictions and two RFMOs have regulations requiring that sharks and their fins are landed in a prescribed fin-to-carcass ratio, and 27 jurisdictions and one RFMO have mixed finning regulations that differ by shark species. There are 16 jurisdictions with unspecified finning regulations and 75 jurisdictions with no relevant measures on record (Fig. 1D and tables S4 to S5). Regulatory attempts to eliminate shark finning and associated fishing mortality currently occur in nearly 70% of maritime jurisdictions globally; few such regulations existed 20 years ago (Fig. 1). Concomitantly, we observed a rapid increase in trade-restricted shark species listed under the Convention on International Trade in Endangered Species (CITES) (Fig. 1, A and B, red lines; and table S1). Likewise, there has been a rapid increase in the number of pelagic tuna fishing companies seeking Marine Stewardship Council (MSC) ecocertification and engaging in related fishery improvement projects, two prominent market-based measures that prohibit shark finning on board certified vessels (Fig. 1C and table S6).

Mapping spatial patterns of shark fishing mortality, we found that current hotspots of mortality are concentrated in coastal environments such as the Atlantic coast of North and South America; West Africa; the northern Indian Ocean; and the Coral Triangle, a particularly biodiverse region spanning the national waters of Indonesia, Malaysia, Papua New Guinea, and the Philippines (Fig. 2A). This distribution also holds broadly for species designated as threatened with extinction by the International Union for the Conservation of Nature (IUCN) (Fig. 2B). Individual taxa have fishing mortality hotspots primarily in pelagic (e.g., silky shark, Fig. 2C) or coastal environments (e.g., hammerhead sharks, Fig. 2D), respectively, depending on their preferred habitat and intersection with fisheries (see fig. S8 for other taxa).

From 2017 to 2019, national waters accounted for 95% of shark fishing mortality by number of individuals and 71% of catch by tonnage (tables S14 and S15). Global fishing mortality increased from 76 million sharks in 2012 to more than 80 million in 2017, averaging 79 million from 2017 to 2019 (table S15). The number of threatened shark species caught during this timeframe fluctuated between 22 million and 28 million each year (Fig. 2B). From 2012 to 2019, fishing mortality increases were observed in 35% of nonzero shark catch cells and decreases in 65%, with an overall increase in mortality of 3.6% in national waters and a 7.4% decrease in pelagic fisheries managed by RFMOs (Fig. 2E). This decrease coincides with the introduction of new RFMO regulations prohibiting the retention of

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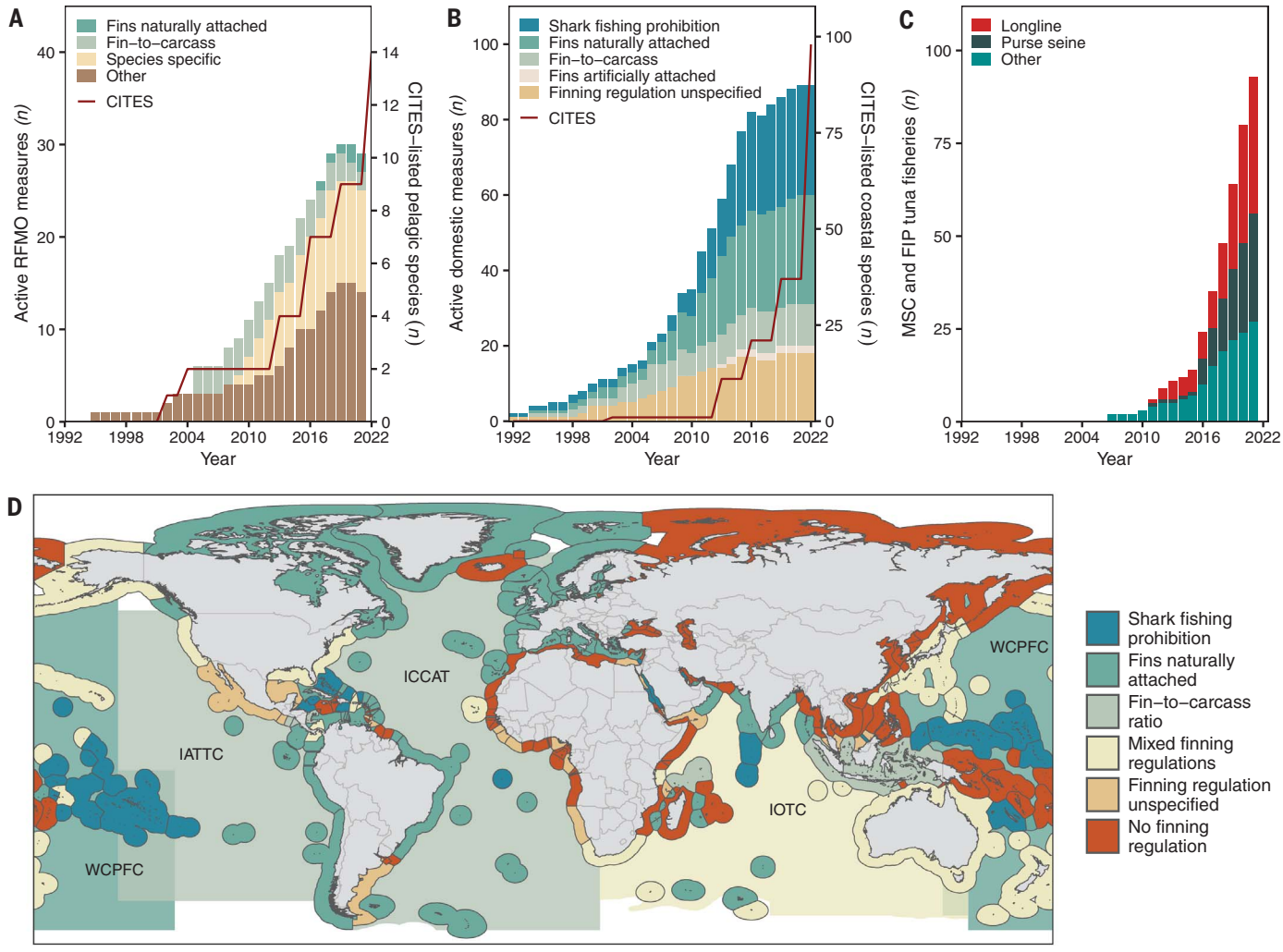

Fig. 1. Global regulatory landscape. (**A** and **B**) Increasing trends in number of shark fishing and finning regulations adopted (A) internationally through tuna regional fisheries management organizations (RFMOs) and (B) nationally through domestic laws and policies. Number of CITES-listed threatened shark species additionally regulated through international trade restrictions are superimposed as red lines. New listings introduced in 2022 are not yet fully implemented. (**C**) Trends in tuna fisheries involved with MSC ecocertification and related fishery improvement projects (FIPs). (**D**) Spatial pattern of active shark regulations in 2022. WCPFC, Western & Central Pacific Fisheries Commission; IATTC, Inter-American Tropical Tuna Commission; ICCAT, International Commission for the Conservation of Atlantic Tunas; IOTC, Indian Ocean Tuna Commission.

specific threatened species (Fig. 1A), particularly those listed under CITES. Indeed, available species-specific data indicate a decrease in retention and an increase in observed live release for hammerhead, thresher, and oceanic whitetip sharks across various RFMOs (fig. S9). In addition, although longline vessels fishing for tuna, billfish, and sharks have the widest spatial footprint of all shark-related fishing gears (*13*), most mortality hotspots coincide with coastal gears such as gillnets and trawls (Fig. 2F), both of which are known to incur substantial shark mortality (*14*).

When we analyzed the relationship between shark fishing mortality rates and prevalent regulations by country (Fig. 3A), we found that only shark fishing prohibitions and accountable governance, as measured by the World Bank's Voice and Accountability index (*15*), were associated with reduced mortality of sharks. The main drivers predicted to increase mortality were total catch (combined tonnage of all species landed) and overall fishing effort [total kilowatt vessel hours, a measure of fishing intensity (*13*)]. Established finning regulations had little effect on mortality (Fig. 3A) and may have even increased it, possibly by incentivizing full use of sharks and creating additional markets for shark meat and cartilage, among other products (*16*–*18*). Comparing shark mortality standardized by fishing effort across all countries reveals the complexity of assessing regulatory effectiveness, with the same regulation in some cases resulting in both positive outliers—that is, locations with lower-than-expected shark mortality given their regulations and fishing intensity—and negative outliers, where outcomes for sharks are worse than expected (e.g., the shark sanctuaries of Sint-Maarten and the Dominican Republic, respectively; Fig. 3B).

Interviews with a globally diverse group of shark science, conservation, fishery, and industry professionals independently corroborate and contextualize the above trends (Fig. 4A and tables S11 to S13). Almost all interviewees perceived that shark finning had declined over the past two decades, whereas trends in fishing mortality were perceived differently among regions (Fig. 4B), and 45% noted a concurrent increase in the demand for shark meat. One NGO representative suggested, "Shark finning legislation particularly didn't have an impact on reducing overall shark mortality [because]

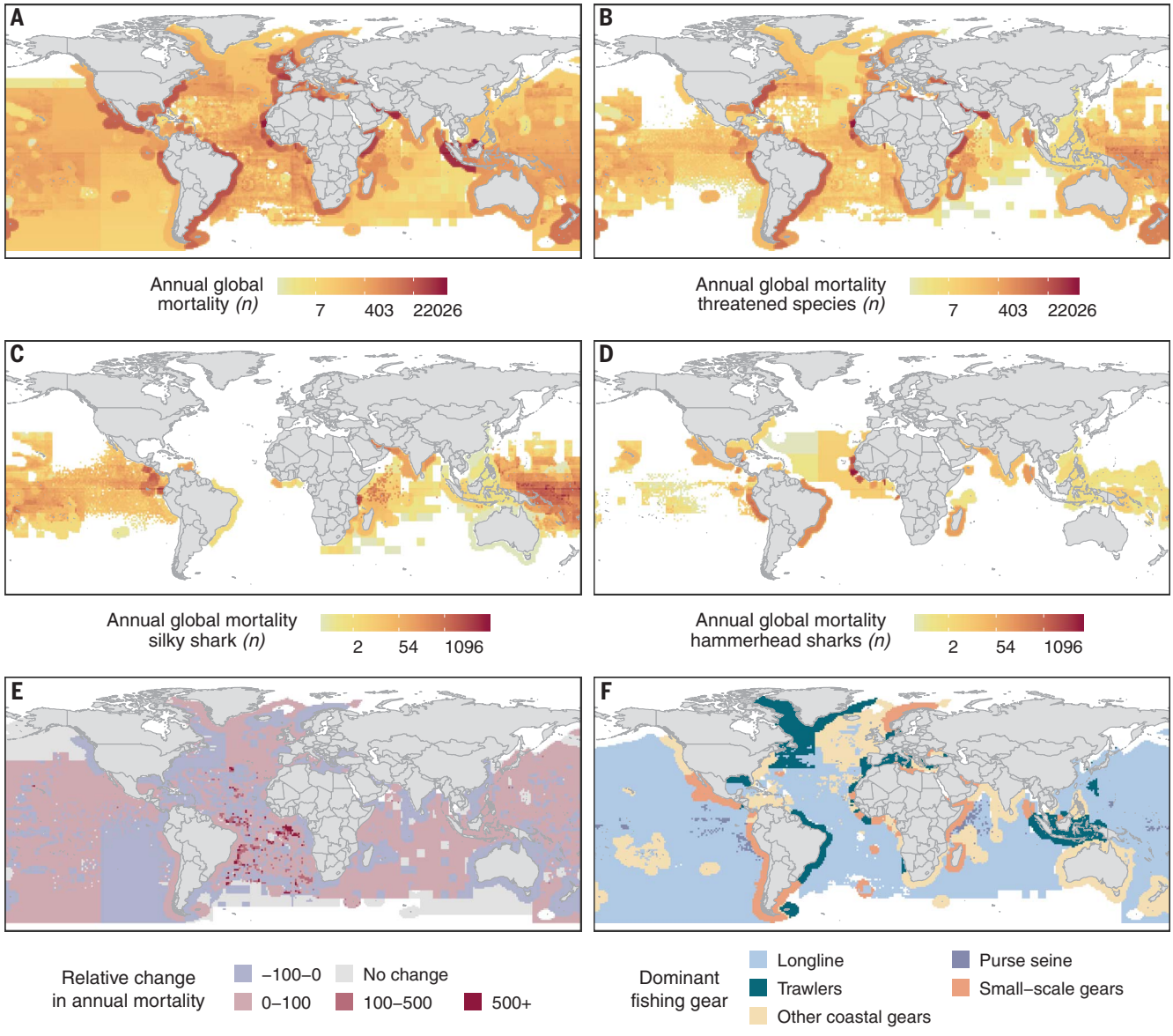

Fig. 2. Global patterns of shark fishing mortality. Shown are average annual mortalities per 1° by 1° grid cell from 2016 to 2018 for (**A**) all sharks, (**B**) threatened species (IUCN critically endangered, endangered, or vulnerable), (**C**) silky sharks (*Carcharhinus falciformis*), and (**D**) hammerhead sharks (*Sphyrna* spp.). (**E**) Relative trend in annual mortality (percent increase or decrease) for all sharks from 2012 to 2019. (**F**) Fishing gear type that dominates shark mortality for each cell (further details about fishing gear categories are shown in table S19).

after the prohibitions [countries that were finning sharks] just landed the sharks whole, [which] resulted in new markets for shark meat, oil, and other products in countries that didn't consume shark meat previously" (Interviewee NGO-3; table S11). Many interviewees further perceived that fisheries are now catching smaller sharks, including juveniles (*19*), because of declines in the fin trade, regional declines in the abundance of large sharks, and increasing demand for shark meat (table S11). Almost two-thirds of experts (64%) highlighted regions of the Indian Ocean or Indo-Pacific as primary areas of shark bycatch concern, with West Africa identified as an additional hotspot by 23% of experts. In terms of fishing gears, 91% highlighted gillnets as key contributors of shark mortality because of their unselective nature and their unregulated use in many coastal fisheries.

Regarding the reduction of shark finning, domestic and RFMO finning regulations were perceived as being most effective (54 and 45%, respectively), followed by public awareness campaigns and pressure from large seafood retailers for sustainable seafood products (Fig. 4C and tables S12 and S13). One industry representative noted, "We are seeing a big push from [the] market side, which is having a bigger impact at this stage relative to the regulatory side [because] if you lose your [eco-]certification, it would be diabolical for business and a huge company risk" (Interviewee IND-2; table S11). All three industry representatives and 18% of all interviewees perceived that RFMO retention prohibitions had effectively reduced the catch of CITES-listed species (e.g., silky, hammerhead, oceanic whitetip; fig. S9). Conversely, domestic fisheries management, catch monitoring, and enforcement were deemed to be most in need of improvement (Fig. 4C and tables S12 and S13). Multiple interviewees also suggested that improved engagement by government agencies with coastal fishers was essential, especially where shark meat is contributing to local food security.

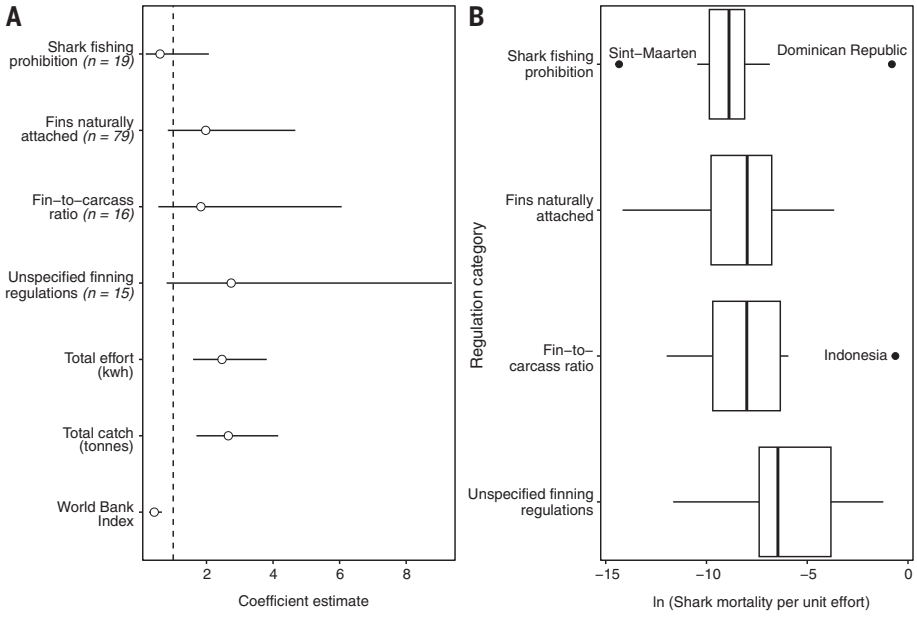

Fig. 3. Linking shark fishing mortality to regulation. Shown are (**A**) slope coefficients [± 95% confidence interval (CI)] from a generalized linear model predicting shark fishing mortality for all countries' national waters as a function of active shark conservation regulations. The vertical hatched line denotes a neutral effect, with points (unfilled circles) to the right signifying increased and points to the left decreased shark fishing mortality given the regulation; points are the exponentiated coefficient estimates, and horizontal lines are the 95% CIs. Total catch refers to the combined tonnage of all species landed and total effort to the number of kilowatt vessel hours observed fishing. World Bank Index refers to the Voice and Accountability composite index, with higher scores indicating improved democratic governance. (**B**) The distribution of (natural log-transformed) shark fishing mortality per kilowatt fishing hour and regulatory regime for each country. Outliers of lower-or-higher-than-expected mortality were 2 SDs below or above the mean and are labeled (black circles).

Our analyses represent a first global synthesis of spatial and temporal trends in shark fishing mortality in the context of widespread regulatory change. Although finning regulations have been successful in reducing waste and animal cruelty, there is little evidence that they have reduced shark mortality overall (Figs. 2E, 3A, and 4B). Indeed, domestic measures adopted to eliminate the fin trade were insufficient to halt overexploitation, and interviewees suggested that they even contribute to incentivizing retention of whole sharks and, by extension, markets for their meat. This is consistent with results from our regulatory analyses (Fig. 3) and mapping exercise (Fig. 2 and tables S14 and S15), which suggest that shark mortality is increasingly concentrated in coastal hotspots. We found that territorial waters of just six coastal nations incurred 50% of global shark mortality from 2017 to 2019 (table S15), four of which (Indonesia, Brazil, Mauritania, and Mexico) were also highlighted by interviewees as places where high shark fishing mortality coincides with insufficient regulatory capacity. It is noteworthy that these countries are also major international suppliers or domestic consumers of shark meat, reflecting growing markets for nonfin shark products (*17*).

These findings suggest a shifting global landscape of shark fishing mortality that is moving away from finning of larger pelagic species (*4*) toward full use of smaller coastal species, presenting new regulatory and conservation challenges. On the positive side, shark mortality under the oversight of the tuna RFMOs appears in decline overall, most notably in the Atlantic and Western Pacific, where species-specific retention bans and comprehensive observer coverage on purse seine fishing vessels combine with strong incentives to provide ecocertified tuna to global markets. It is yet unclear whether this is enough to reduce pelagic shark threat status similarly to that of tuna and billfish, the traditional target of improved management (*20*). In this regard, it is notable that only since 2019—50 years after its establishment—have member states of the International Commission for the Conservation of Atlantic Tunas (ICCAT) been legally mandated to manage sharks in the Atlantic in the same way that they manage target tuna species. Across national waters, some small island nations lead the charge with respect to reducing shark fishing mortality. Shark sanctuaries in the Bahamas and Maldives, for example, have managed to maintain relatively healthy shark populations (*21*), which fuel successful dive tourism industries (*22*, *23*). Other measures, such as large no-take protected areas in the Pacific Remote Islands Marine National Monument south of Hawaii, also appear successful in maintaining relatively low shark fishing mortality, although outcomes are variable (Fig. 3A). Nations that are more democratic are also consistently associated with better outcomes for sharks (Fig. 3A), echoing similar results from a global analysis of reef shark abundance (*21*). Yet, our analysis suggests that when viewed through a global lens, current risks for coastal sharks still appear to be escalating on average, a conclusion that is supported by recent IUCN assessments (*1*, *24*).

We caution that data quality and transparency were key limitations for our analyses. Catch data are rarely reported with uncertainty estimates, although there are many known uncertainties and data gaps (*25*). The detailed catch reconstructions used here (*11*) acknowledge this uncertainty by cross-referencing multiple data inputs and assigning a data-source specific, qualitative uncertainty score to all catch estimates (tables S14 and S15). Mapping the catch-weighted uncertainty across coastal and high-seas areas highlights hotspots of high shark catch and high uncertainty where more comprehensive and reliable data are critical for improving global estimates of shark mortality (figs. S10 to S12). Likewise, although our RFMO catch models are specifically designed to overcome spatio-temporal observation biases arising from incomplete reporting, catches are still largely self-reported by fishing countries and almost certainly underestimate total fishing mortality, especially for rare and endangered species (*26*). We provide upper and lower 95% confidence limits around RFMO shark catch estimates to explicitly account for this uncertainty and to highlight areas with particularly poor data reporting (tables S16 to S19 and figs. S11 and S12). We further present expert interviews as an independent source of data to further mitigate these uncertainties (Fig. 4 and tables S11 to S13). We offer a detailed discussion of data uncertainty in the materials and methods and make all data and models publicly available for future work that could make use of new and improved reporting (data S1 to S5).

We further caution that country-level shark catch is also likely underestimated because 24% of the annual catch from national waters is being reported at the subclass (Elasmobranchii) level (fig. S3), preventing meaningful analysis of these data at the species level. Including these taxonomically unresolved elasmobranch catches (which include rays and skates in addition to sharks) and assuming a similar proportion of true sharks as in the taxonomically resolved data (71%) would increase our global shark mortality

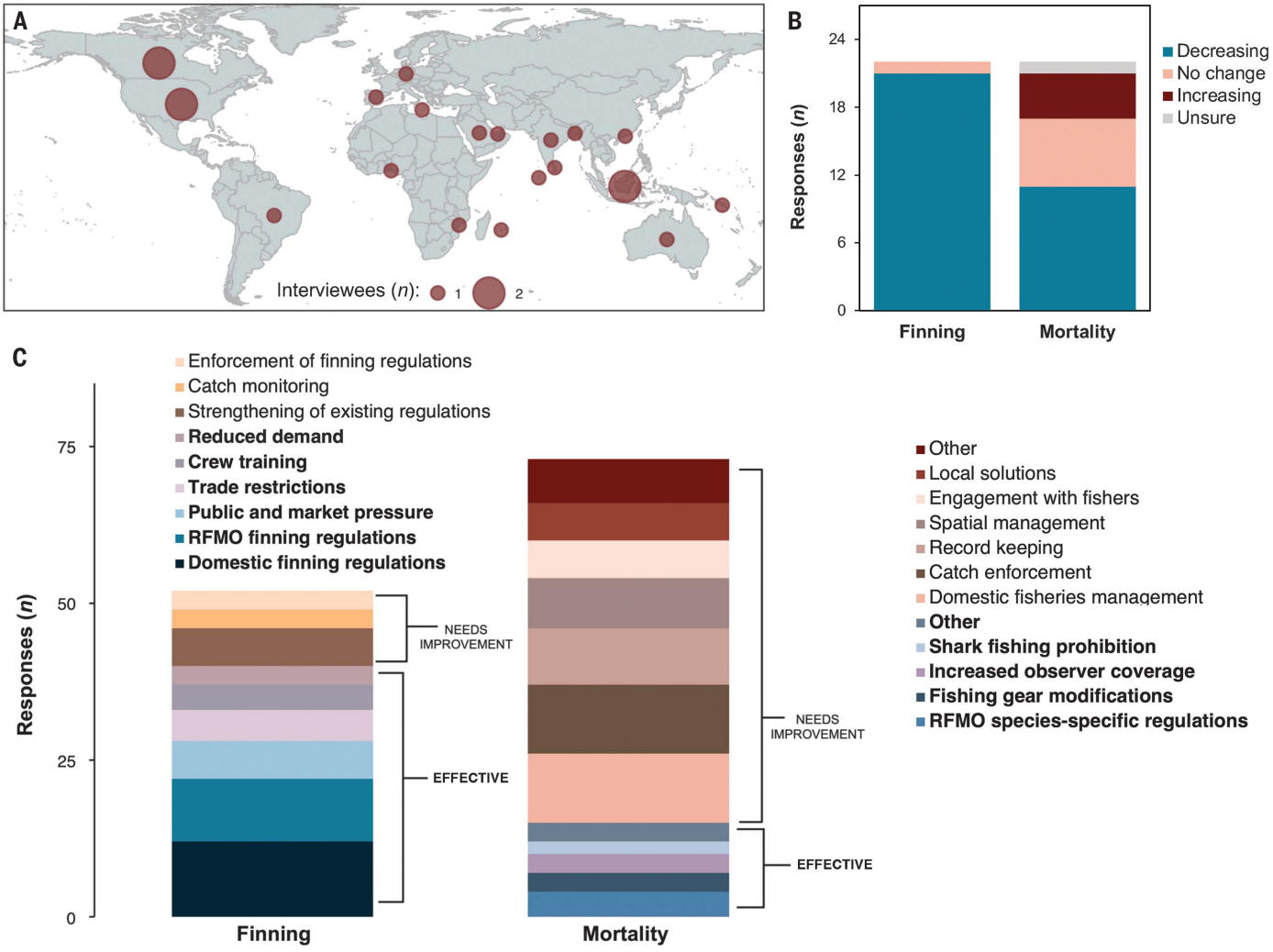

Fig. 4. Expert perceptions on shark fishing and regulation. (**A**) Geographical location of 22 regional experts interviewed for this study. (**B**) Interviewee perceptions on current trends in shark finning (left) and shark mortality (right). (**C**) Interviewee perceptions on effective (in boldface) and insufficient regulatory and market measures affecting trends in shark finning and mortality (see tables S11 to S13 for detailed interview data summaries).

estimate to 101 million sharks (in 2019). This figure represents a 4% increase over previous global fishing mortality estimates for the year 2010 (*5*).

These results highlight the importance of improved data reporting. Market and regulatory pressures to enhance reporting requirements and data dissemination are expected over time, and trends of decreasing shark fishing mortality in industrial tuna fisheries should be scrutinized further when more data are available. Additional datasets that more comprehensively document discarding practices are also required to improve mortality estimates, especially for poorly observed longline fisheries (fig. S9). Lastly, illegal, unreported, and unregulated (IUU) shark fishing is only in part captured by our analyses but is very evident both from expert interviews (table S11) and from the literature (*19*, *27*). Combined, these data indicate that our estimate of total shark fishing mortality is conservative.

Our analysis shows that shark fishing continues to present a substantial threat to shark populations over much of the world, despite the widespread adoption of antifinning legislation and related measures. This regulatory shortfall needs to be addressed through a combination of area-based conservation (*28*) and improved shark-specific fisheries management measures (*29*) that address overcapacity and disincentivize retention of overfished and threatened species. Science-based harvest control rules have been recently adopted for most tuna stocks under RFMO oversight (*7*, *30*) and should be used to address overexploitation of pelagic sharks, most of which lack catch limits. Effective bycatch mitigation is a pressing issue in this regard, both for management bodies and for fishing companies seeking ecocertification, especially given the recent expansion of CITES listings to include 54 species of requiem and hammerhead sharks (Fig. 1, A and B, and table S1). Our findings signal that such measures can be effective when paired with other regulations in international fisheries (fig. S9) and also highlight the importance of similarly expanding improved regulation and oversight in national fisheries. Increased transparency and accountability of fishing companies, fleets, and management bodies are needed to support successful implementation of these measures. We observe that some of the most effective regional solutions have been spearheaded by low-income countries with a high dependence on a healthy marine environment for food and livelihood security. Such localized efforts are part of an emerging trend in ocean sustainability (*31*) and demonstrate that positive change can be achieved where the long-term needs of both nature and people

are adequately valued. As these solutions are more widely adopted, our analyses can provide a spatially explicit baseline against which future progress in recovering threatened shark populations can be assessed, supporting timely efforts to rebuild resilient ocean ecosystems and sustainable fisheries.

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SUPPLEMENTARY MATERIALS

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Materials and Methods
Figs. S1 to S12
Tables S1 to S19
References (*34*–*78*)
MDAR Reproducibility Checklist
Data S1 to S5

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Editor's summary

Over the past decade, the plight of the world's sharks has received much attention, resulting in increased regulation and finning bans. However, whether this increased attention has translated into improved outcomes for sharks is unclear. Worm *et al*. estimated fishing-induced mortality globally and found that, overall, it has continued to increase over the past 10 years. Finning bans had little impact, but fishing regulations did reduce mortality. —Sacha Vignieri

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