Half a century of global decline in oceanic sharks and rays

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Summary: Overfishing is the primary cause of marine defaunation, yet individual species declines and rising extinction risk are difficult to measure, particularly for the largest predators found in the high seas[1–3]. We calculate two well-established indicators to track progress towards Aichi Biodiversity Targets and Sustainable Development Goals[4,5], the Living Planet Index (a measure of changes in abundance aggregating 57 abundance time-series for 18 oceanic shark and ray species), and the Red List Index (a measure of extinction risk calculated for all 31 oceanic shark and ray species). We find that, since 1970, the global abundance of oceanic sharks and rays has declined by 71% due to an 18-fold increase in Relative Fishing Pressure. This depletion elevated global extinction risk to the point where three-quarters of this functionally important assemblage of iconic fishes are now considered threatened with extinction. Strict prohibitions and precautionary science-based catch limits are urgently needed to avert population collapse[6,7], avoid disruption of ecological function, and promote species recovery[8,9].

Over the United Nations 'Decade of Biodiversity' from 2011–2020, governments committed to improve human well-being and food security by safeguarding ecosystem services and halting biodiversity loss[10]. The Sustainable Development Goals, adopted by all United Nations Member States, and the 20 Aichi Biodiversity Targets of the Convention on Biological Diversity, provide a framework to track progress towards the 2020 deadline[4,5,10]. Seafood sustainability is an integral part of these commitments, and wild capture fisheries remain an essential nutritional and economic resource for millions of people globally[11,12]. Yet beneath the ocean surface, it is difficult to assess changes in the state of biodiversity and ecosystem structure, function, and services[13].

Elasmobranchs (sharks and rays, hereafter 'sharks') offer a unique window into the state of the oceans. Together with closely related chimaeras, they are one of the only marine lineages completely assessed on International Union for Conservation of Nature (IUCN) Red List of Threatened Species[14]. Sharks also make up one of the most evolutionarily distinct vertebrate radiations[15] and occupy a range of ecological roles throughout the world's oceans, notably functioning as apex and mesopredators that shape food web structure[16]. The first IUCN global status assessment estimated that one-quarter of shark species were threatened with extinction (classified as Critically Endangered, Endangered or Vulnerable according to Red List criteria) and only a third (37%) qualified as Least Concern[14], making sharks the most threatened vertebrate lineage after amphibians[14,17,18]. Long generation times and low intrinsic population growth rates of many sharks make them inherently susceptible to overexploitation[1,7,19]. Globally, targeted and incidental shark catches rose steadily, reaching a peak in the early 2000s, before declining due to overfishing[6]. In the peak year, 63–273 million sharks were landed for meat, fins, gill plates, and liver oil[20,21]. Concern over associated damage to shark populations and ecosystems has been increasing in recent decades[1,6]. The first warnings that 'sharks may be headed toward extinction' were based on boom and bust catch patterns and rising international trade in shark fins[22,23]. Starting in the 1990s, assessments of shark population status for the Gulf of Mexico and Northwest Atlantic[24] region, conducted separately by government and independent scientists, resulted in decline estimates that, though often varying by degree, signaled depletion[25]. In subsequent years, serious declines in many oceanic and coastal shark populations have been confirmed in this region[26,27], and revealed elsewhere using datasets from diverse sources, such as coastal bather-protection nets in South Africa[28] and bather-protection drum line programs in Australia[29]. Shark population assessments for many regions have since become increasingly robust[8,30,31]. Until now, however, these have not yet been synthesised to provide a global perspective on shark population trends.

Here, we calculate for oceanic sharks two Biodiversity Indicators established by the Convention on Biological Diversity: the Living Planet Index (LPI)[5,32] and the Red List Index (RLI)[5,33]. These indicators quantify progress toward Aichi Targets 6 (manage marine resources for sustainability) and 12 (prevent extinction), and UN Sustainable Development Goal 14 (conserve and sustainably use the oceans). The LPI is a quantitative metric that estimates global population changes since 1970 by aggregating time-series of relative abundance. The RLI tracks the relative change in the overall extinction risk of a group of species based on the changes in the number of species in each threat category on the IUCN Red List of Threatened Species over time. Finally, we develop three lines of evidence to attribute decreasing abundance and rising extinction risk for oceanic sharks to overfishing.

First, we used a Bayesian state-space framework[34,35] to estimate trends in relative abundance of 18 species from 57 time-series compiled from peer-reviewed papers and stock assessments. These trends were reviewed at an expert workshop convened by the IUCN Species Survival Commission's Shark Specialist Group (IUCN SSC SSG). Using these trends, we calculated the global LPI for oceanic sharks from the reference year 1970 (which was set at 1) to 2018 — and then extrapolated each time-series to 2020 to encompass the Aichi Target assessment year — by hierarchically aggregating the annual rates of change from each time-series for a species by region (see Text box 1 and Extended Data Figure 1 for an example). Second, we combined a retrospective Red List assessment (1980) with two recent assessments (~2005 and 2018) for all 31 species of oceanic sharks to build the RLI (see Text box 1) and visualise the spatial distribution of status change. Finally, we attributed the cause of decreasing abundance (shown by the LPI) and elevated extinction risk (shown by the RLI) to overfishing using three lines of evidence: (i) increasing Relative Fishing Pressure over time (measured as changes in catch relative to the changes in the LPI), (ii) increasing probability over time that that oceanic sharks around the globe are overfished below biomass or abundance levels that could produce Maximum Sustainable Yield (MSY, which is the equilibrium state of the exploited population that can sustain the greatest yield [catch] over long time periods[36]), and (iii) the near-absence of significant threats other than fishing reported in each species' current IUCN Red List assessment.

Declining abundance index

We find that, globally, abundance of oceanic sharks declined by 71.1% (95% credible interval [CI]: 63.2–78.4% decline; Fig. 1) from 1970 to 2018, at a steady rate averaging 18.2% per decade (see Extended Data Figure 2b). Over the half-century from 1970–2020, the projected LPI predicts that abundance will have declined by 70.1% (CI: 62.8–77.2%, see Extended Data Figure 2a). The declining trend of the LPI trajectory is robust to the exclusion of any individual species (Extended Data Figure 3).

The global trend index can be disaggregated into trajectories for each ocean and species, as well as for functional groups that share similar ecological or life history traits. In the Atlantic Ocean, the decline of oceanic shark abundance began to stabilize at low levels from 2000 onwards following a long period of decline since 1970 (with an overall decrease of 46.1%; CI: 30.7–61.1%; Fig. 2a). In the Pacific Ocean, abundance decreased steeply prior to 1990, and then declined at a slower rate thereafter (overall decline of 67.0%; CI: 53.6–79.4%; Fig. 2c). Oceanic sharks continue to decline steeply in the Indian Ocean (overall decline of 84.7%; CI: 75.9–92.1%; Fig. 2b). Despite more resilient life histories, tropical oceanic sharks declined more steeply than their temperate relatives (respective, overall declines of 87.8%; CI: 79.8–94.3% and 40.9%; CI: 30.4–50.5%, Fig. 2d). Overfishing of sharks induced a distinct pattern of serial depletion, starting with the largest species, which dropped steeply prior to the 1980s. Steady declines of medium-sized species, and eventually relatively small species (including some devil rays, *Mobula* spp.), followed (Fig. 2e). Late-maturing species initially declined more steeply than those with shorter generation times but showed some improvement in recent years (Fig. 2f, g). The segment of very long-lived sharks of the LPI index comprises three species: Dusky Shark *Carcharhinus obscurus*, White Shark *Carcharodon carcharias*, and Porbeagle *Lamna nasus*, with the latter two showing signs of population rebuilding since the early 2000s (see Extended Data Figure 7). All species, apart from the Smooth Hammerhead (*Sphyrna zygaena*), decreased in abundance over the last half-century (Fig. 2g). Devil ray abundance has declined by at least 85% in the past 15 years in the Southwest Indian Ocean (Fig. 2e). Although sparse, the available data are representative of the repeated, rapid depletions and local extinctions suspected based on high fishing pressure in many parts of their historical range driven by target fisheries (see Supplementary Information Discussion 1 and Population section in Supplementary Red List assessments). While large body size is usually correlated with sensitivity to overexploitation in sharks, the relatively small-bodied devil rays tend to have very low annual reproductive output (typically one pup per year or every other year)[19] and small localized populations, leaving them particularly ill-equipped to withstand fishing pressure[7].

Rising extinction risk

Overall, the risk of extinction of all 31 oceanic shark species has substantially worsened since 1980. The RLI declined from a retrospective estimate of 0.86 (range: 0.74–0.90) in 1980 to 0.56 in 2018 (Fig. 3a). We find that the rate of decline of the RLI is steeper in recent years (since 2005) than in the previous period (1980–2005) (Fig. 3a). We estimate that in 1980 two-thirds (*n*=20) of shark species fell into the IUCN Red List category of Least Concern, and only nine were threatened (Critically Endangered, Endangered or Vulnerable). The Basking Shark (*Cetorhinus maximus*) was the only species retrospectively classified as Endangered. In contrast, more than three-quarters (*n*=24) of these species are threatened now based on steep population reductions (IUCN Red List Criterion A). Some formerly abundant, wide-ranging sharks have declined so steeply that they are now classified in the two highest IUCN threat categories: three are Critically Endangered (Oceanic Whitetip Shark *Carcharhinus longimanus*, Scalloped and Great Hammerhead *Sphyrna lewini* and *S. mokarran*), and four are Endangered (Pelagic Thresher *Alopias pelagicus*, Dusky Shark, Shortfin and Longfin Mako *Isurus oxyrinchus* and *I. paucus*; Fig. 3b). Adding in these recently declined species brings the total to half (15 of 31) of oceanic shark species are Critically Endangered (n=3) or Endangered (n=12). Species have undergone population reductions of 50–80% over three generation times to warrant an Endangered listing and more than 80% to warrant a Critically Endangered listing. Half of the species are unquestionably far below half of their former abundance.

The RLI has only worsened globally since 1980, evidenced by the absence of increases which would be shown in orange (Fig. 4b). There is considerable uniformity in high extinction risk. While it is useful to convey the broad spatial scale of risk, this pattern also serves to mask considerable variation in fishing pressure and management progress (see Fig. 4 and text boxes). The spatial pattern of the RLI reveals latitudinal differences in risk. Decreases in RLI are consistently greater in the tropics, especially in enclosed seas like the Gulf of Mexico, Red Sea, and Arabian/Persian Gulf along oceanographic frontal features near the coasts (Western Central Atlantic, Western Indian, and central Indo-Pacific Oceans), where species richness is greatest. The only RLI values equal to 1 (green) are where the Salmon Shark (*Lamna ditropis*), which is categorized as Least Concern, occurs in the cooler waters of the Bering Sea in the North Pacific.

Connecting abundance declines and extinction risk to overfishing

We attribute oceanic shark population declines and elevated extinction risk to overfishing based on three lines of evidence. First, the last half-century has seen more than a two-fold increase in fishing with longlines and seine nets, the gears that catch the most oceanic sharks[37] (Fig. 5a; black lines). The associated rise in oceanic shark catch has been three-fold since 1970 (Fig. 5a; grey line and polygons). We demonstrate an 18-fold increase in Relative Fishing Pressure (changes in catch relative to the changes in the LPI; Fig 5b). This correlation suggests fishing drove declines in abundance with a striking breakpoint in 1990 that we hypothesize coincides with increasing retention of sharks to meet new market demand (specifically for fins)[38] (Fig. 5c). Second, the role of fisheries in driving declines is thoroughly addressed in the growing number and quality of fisheries stock assessments (see Extended Data Figure 10). The declining LPI is consistent with a vanishing global probability over time that populations and species are fished sustainably, i.e. at a level of biomass or abundance equal to or greater than that which could produce MSY. By 2018, there was only a 21% probability that assessed species were sustainably fished (Fig. 6). Most species (6 of the 8) and over half the populations (9 out of 15) have been fished down to biomass or abundance levels below MSY (Extended data Figure 11). Third, we compiled expert knowledge on the causes of the decline reported in Red List assessments (Fig. 5d). The Red List assessment process includes a structured approach to classifying threats into 11 primary classes, ranging from Human Intrusions and Disturbance, to Pollution, and to Climate and Severe Weather[39]. While there are numerous pressures that influence sharks, e.g. climate change, every single Red List assessment for the 31 oceanic sharks concluded that the major threat was 'Biological Resource Use' and, more specifically, 'Fishing and Harvesting Aquatic Resources', while other threats are reported for only two species (Fig. 5d).

Discussion

We document an alarming, ongoing, worldwide decline of oceanic shark populations across the world's largest ecosystem over the past half-century, resulting in an unprecedented elevation in marine extinction risk. The tremendous increase in Relative Fishing Pressure is mirrored by the general consistency in the rate and extent of declines across species' body sizes and generation times. The low reproductive output of these slow growing species is clearly no match for the intense fishing pressure they currently encounter.

It's important to note that our analysis is intentionally conservative. There are three reasons why the true abundance trend index values are likely to be lower and the calculated percent declines worse than estimated here. First, our baseline for 1970 likely represents the already depleted state for several species compared to unfished levels[29]. Some shark populations were fished down prior to 1970, often due to incidental catch in fisheries targeting highly valued large oceanic teleosts (primarily tunas and billfishes). Some, notably the Porbeagle in the Northwest Atlantic, had already collapsed by the 1960s[40]. We also estimated a 25% chance that species were already below MSY by the 1970s, underscoring that fishing levels were already unsustainable half a century ago. Therefore, our LPI is likely to be a conservative estimator of the degree of decline. Second, unreported catches (landings and/or discards) are not included in our time-series dataset, which can result in underestimates of relative abundance (although trends in abundance may be unaffected if the under-reporting rate remains constant)[41]. Third, very high mortality of Shortfin Mako in the Northwest Atlantic revealed using satellite telemetry suggests that traditional stock assessments could underestimate fishing mortality for this species, and that this problem may be more widespread[42].

Overfishing of oceanic shark populations has far outpaced the implementation of fisheries management and trade regulation[43]. Despite great strides in shark conservation commitments over the last three decades, relatively few countries impose catch limits specific to oceanic sharks, and fewer still can demonstrate population rebuilding or sustainable fisheries for these species. Obligations under international wildlife treaties (e.g., Convention on the Conservation of Migratory Species of Wild Animals, Convention on International Trade in

Endangered Species of Wild Fauna and Flora, see[7]) to prohibit retention or restrict international trade of select species have not yet been well-implemented[44]. The world's four major Regional Fishery Management Organizations focused on tunas (tRFMOs) have, to varying degrees, prohibited retention of inherently sensitive oceanic shark species that are also of relatively low value to the associated pelagic fisheries, e.g., (1) Bigeye Thresher (*Alopias superciliosus*) in the Atlantic, (2) Devil rays in the Pacific and Indian Oceans (with some exceptions), (3) the Oceanic Whitetip Shark in all major ocean basins (see Supplementary Red List assessments), and (4) species taken mainly in fisheries not affected by the management action (e.g. hammerhead sharks *Sphyrna* spp., with the exception of *S. tiburo* in select Atlantic pelagic fisheries of non-developing countries). The first and still only international shark fishing quotas (for Atlantic Blue Sharks, *Prionace glauca*) were not adopted until late 2019. For the other shark species making up a significant portion of high seas fleets' catch, the tRFMOS have set only a few species-specific measures (e.g., as suite of landing condition options for Atlantic Shortfin Mako, bycatch limits for Silky Sharks (*Carcharhinus falciformis*) in the Eastern Tropical Pacific, and gear restrictions in the Western and Central Pacific), in addition to finning bans. While Ecosystem-Based Fisheries Management (EBFM) is often touted as a remedy for bycatch problems, tRFMOs' efforts to manage sharks using EBFM have been evaluated as inadequate with respect to scientific advice and implementation[45,46]. Moreover, sharks, particularly Shortfin Mako and Blue Sharks, are increasingly targeted or welcomed as secondary catch by high seas longliners. The Red List status of many oceanic sharks was worse than previously anticipated and shows that these species are facing nearly the same threat level as Cycads (palm-like plants), the most threatened, completely assessed group of species on Earth[47] (Fig. 3a). When looking at the RLI for oceanic sharks from the global assessments conducted around 2005 (*n*=554), we note a greater extinction risk than the latest global assessments for birds, mammals, and corals (Fig. 3a). Some oceanic sharks listed as globally Near Threatened or even Vulnerable may still be able to sustain modest levels of fishing, , if managed immediately and carefully throughout their range[7]. For species classified as Critically Endangered or Endangered, however, strict measures to prohibit landings and minimize bycatch mortality (by avoiding hotspots, modifying gear, and improving release practices) are urgently needed to halt declines and rebuild populations.

There are some encouraging findings. We note that the White Shark historically declined by an estimated 70% worldwide over the last half-century, but is now recovering in several regions with the help of retention bans[48]. Hammerhead shark populations also appear to be rebuilding in the Northwest Atlantic, owing to relatively low and strictly enforced quotas throughout their U.S. range. The Blue Shark has declined less than other species despite being reported to be at significantly greater risk due to the high overlap with heavily fished areas[42]. This is likely due to the Blue Shark's relatively high reproductive rate (compared to other pelagic sharks). Blue Sharks dominate the shark catches of high seas longline vessels; while the value of Blue Shark meat and fins has been relatively low, management is warranted on a global scale as market interest and targeted fishing increase. It is possible to reverse shark population declines, even for slow-growing species, if precautionary, science-based management is implemented throughout a species' range [8,49] before depletion reaches a point of no return.

The ecosystem consequences of oceanic shark declines are uncertain because of the complexity and scale of marine food webs[50]. Nevertheless, profound effects of depleting predatory species are becoming apparent around the world. For example, the decline of predatory sharks and tunas is associated with increases in mesopredators, including teleosts and smaller-bodied shark species[51], indicating fundamental functional changes to marine food webs[52]. Of further concern is the associated threat to food security and income in many poor and developing nations[7], many of which have fished sharks for hundreds of years[53]. The development of alternative livelihood and income options could significantly ease transitions to sustainability.

Conclusion

We demonstrate that — despite ranging farther from land than most species — oceanic sharks are exceptionally threatened from overexploitation. It is clear that the Sustainable Development Goals and specific Aichi targets (to reverse population declines and use marine resources sustainably) will not be met by 2020 for these species. Based on the revelation that the extinction risk of oceanic sharks is similar to the most threatened terrestrial organisms on Earth, we underscore longstanding calls to prioritize shark conservation. Action is needed immediately to prevent shark population collapses and myriad negative consequences for associated economic and ecological systems. Specifically, there is a clear and urgent need for governments to adopt, implement, and enforce — at domestic and regional levels — science-based catch limits for oceanic shark species that are capable of supporting sustainable fisheries, and retention prohibitions along with bycatch mitigation for those that are not[7,8]. These steps are imperative for long-term sustainability, including potentially increased catch once populations are rebuilt[9,54], and a brighter future for some of the most iconic and functionally important animals in our oceans.

Materials and methods

Data collection of oceanic shark time-series and expert selection

Time-series data on relative abundance (*n*=57) for 18 species (see Supplementary Information Table S1) were gathered from peer-reviewed publications and the grey literature, including government reports. Relative abundance indices, and associated uncertainty estimates when available, included formal stock assessment outputs (trends in biomass), as well as standardized or nominal catch per unit effort (CPUE) or sightings per unit effort (SPUE) from scientific surveys, fisheries data, or bather protection nets (see Supplementary Information Table S1 and Extended Data Figure 4 to 9). Entry of original time-series (in the database available at www.sharktraits.org) was conducted by J.S.Y., checked by N.K.D. and subsequently independently checked by C.L.R. and N.P. All datasets underwent extensive checks prior to analyses, their reliability was reviewed and assigned to ocean regions (North, South Atlantic Ocean; Indian Ocean; North, South Pacific Ocean) by experts during an IUCN SSC SSG workshop (Dallas, Texas, USA, 5–9 November 2018). Stock assessment outputs were preferred over standardized, then nominal CPUE or SPUE time-series when multiple data sets were available for the same species and region. Stock assessment models integrate the catch history, abundance trends and life history information to infer population dynamics, whereas CPUE or SPUE represents the trend in relative abundance of the sampled fraction of the population. The details and rationale for the selection of datasets, where pertinent, are presented in the Population section of the relevant Red List assessment (see Supplementary Red List assessments). Two stock assessments were updated[27,55] after the workshop and are thus included in our analysis.

Data collation and calculation of ecological and life history traits

Shark age parameters and maximum size can vary regionally, as well as between studies and across regions. Where possible, estimates of generation time (GT) were based on observed rather than theoretical maximum age. Within regions, preference was given to studies that used: validated ages; the widest size range; and, age estimates that included repeat readers, measuring precision and bias. The validated age estimates from the closest region were used in cases where there was not a published age and growth study for a region, or validated ages from a region[56–58]. Generation time is defined as the median age of parents in the current cohort[59]. Species- and regionally-specific GT (Supplementary Information Table S1) were calculated from female median age at maturity (A_{mat}) and maximum age (A_{max}) as $GT = \left((A_{max} - A_{mat}) * z\right) + A_{mat}$. The constant z depends on the mortality rate of adults and is typically around 0.3 for mammals[59,60]. We chose to assume a more conservative value of z=0.5 to account for the likelihood that age structure had already been truncated by overfishing by the time it was measured[28,29] and that ages of sharks have been systematically underestimated[58]. The details of GT were presented to the workshop for review and the final choices were used in the published IUCN Red List assessments and associated supplementary material for each species (see Supplementary Red List assessments, Supplementary Methods 2).

Modeling population dynamics

To analyze oceanic shark trend data, we used a Bayesian population state-space model designed for IUCN Red List assessments (Just Another Red List Assessment, JARA[35]), which builds on the Bayesian state-space tool for averaging relative abundance indices by Winker et al.[34] and is available open-source on GitHub (www.github.com/henning-winker/JARA). Each relative abundance index (or time-series) was assumed to follow an exponential growth defined through the state process equation:

$$\mu_{t+1} = \mu_t + r_t$$

where μ_t is the logarithm of the expected abundance in year *t,* and r_t is the normally distributed annual rate of change with mean $\bar{r}$, the estimable mean rate of change for a time-series, and process variance σ^2. We linked the logarithm of the observed relative abundance indices to the logarithm of the true expected population trend using the observation equation (eqn. 16) from Winker et al.[34]. Multiple time-series for a species in a same region (North, South Atlantic Ocean; Indian Ocean; North, South Pacific Ocean) were analysed in a single run and treated as indices following [34]. We used a non-informative normal prior for $\overline{r} \sim N(0{,}1000)$. We used an approximately uniform prior on the log scale for the process variance $\sigma^2 \sim \frac{1}{gamma(0.001{,}0.001)}$.

For each time-series, we also projected model estimates from the last data point to 2020 to be able to estimate trajectories for the LPI up to the final year of assessment for progress towards the Aichi Targets. These projections were based on the posteriors of the estimated changes across all years in the observed time-series (see [61] for details):

$$\overline{r} = \frac{1}{n}\sum_{t=1}^{n} r_t$$

Three Monte Carlo Markov chains were run for each dataset with different initial values. Each Markov chain was initiated by assuming a prior distribution on the initial condition centred around the first data point in each abundance time-series. In each chain, the first 5,000 iterations were discarded (‘burn-in’), and of the remaining 50,000 iterations, 10,000 were selected for posterior inference (‘thinning rate’ = 5). Thus, posterior distributions were estimated from 30,000 iterations. Convergence of each parameter was checked with the Gelman and Rubin diagnostics[62]. Analyses were performed using R Statistical Software v3.5.2[63] and via the interface from R (‘R2jags’ package v0.5-7;[64]) to JAGS (‘Just Another Gibbs Sampler’ v4.3.0;[65]). The Highest Posterior Density interval was used as the interval estimator of 95% credible intervals.

Calculation of Living Planet Index

The LPI for oceanic sharks is a quantitative mean index of year-to-year rate of change of all species that occur in a given region and finally aggregated to a global scale (see Text box 1). The annual rate of change d_t for each species in a region is the logarithm of the growth rate of the time-series in a given year (t) :

$$d_t = \log_{10}\left(\frac{I_t}{I_{t-1}}\right)$$

where I_t denotes the posteriors of the estimated abundance trend in a given year (t) obtained from the Bayesian state-space model outputs.

To calculate the global LPI, the annual rates of change d_t for each species in a region were then aggregated to provide a single annual rate of change for each region (see Extended Data Figure 1 for an example), and the same procedure was applied across regions in the same Ocean (if subdivided in south and north regions), and finally across the three Oceans to generate a global year-to-year rate of change. We also computed a global LPI for each species separately, by Oceans and by time-series with similar ecological lifestyle or life history traits: geographical zone (temperate or tropical), body size (maximum total length) and generation time (following IUCN definition[59], see Supplementary Information Table S1). We back-transformed the log values to the linear scale to generate index values for the range of scales (global, by ocean, by species or trait-groupings of time-series):

$$LPI_t = LPI_{t-1} \times 10^{\overline{d}_t}$$

where LPI_t is the Living Planet Index at a given year (t), with $LPI_{t=1} = 1$.

The global index started in 1970 and was modelled until 2018 using each year-to-year rate of change for the available time-series. In a second step, the global index was extrapolated through to 2020 using each year-to-year rate of change for the available time-series, and their projections after their last data point (see Extended Data Figure 1 for an example).

Although the overall extent of change in the LPI is an indicator of status and trends in biodiversity, the trend may be driven by the data-rich species in our dataset. We evaluated the sensitivity of the LPI to the subset of species, using a jackknife procedure in which we sequentially dropped individual species and recalculated the index (see Extended Data Figure 3).

Calculation of Relative Fishing Pressure

To investigate the underlying drivers of the abundance trend decline, we calculated the

Relative Fishing Pressure, the changes in catch from 1970 to 2014 (end of the available data) , relative to abundance (LPI) over the same time period, and scaled by the Relative Fishing Pressure in 1970. First, we extracted the total Sea Around Us Project reconstructed reported and unreported catch data[66] by species for 14 of our 18 focal species — catch data were not available for 4 of the species: *A. pelagicus*, *M. alfredi*, *M. kuhlii*, *P. violacea*, and thus were not included in this analysis. To account for the disproportionately high catch of some species (e.g., Blue Shark) in the total catch that could affect the overall pattern, we scaled the catch data at the species level (*sp*) to the first catch value in each time-series before summing across species. The Relative Fishing Pressure (RFP) was then calculated as:

$$RFP_t = \frac{\frac{\sum_{sp} catch_t}{LPI_t}}{\frac{\sum_{sp} catch_{t=1970}}{LPI_{t=1970}}}$$

with LPI_t being the LPI of the 18 oceanic sharks in year *t*. We also calculated the RFP with the LPI_t of only the 14 species for which catch data were available and this was not credibly different from the RFP for all 18 species (see Extended Data Figure 12).

Calculation of Red List Index

We calculated the RLI based on the proportion of the 31 oceanic shark species in each IUCN Red List category in 1980, 2005 and 2018 (see Supplementary Information Table S2). The categories used in the assessments were Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Near Threatened (NT), and Least Concern (LC). No species of oceanic shark were assessed in the categories Extinct (EX), Extinct in the Wild (EW), Not Applicable (NA), or Not Evaluated (NE) categories. The statuses in 2018 were assigned by the IUCN SSC SSG (Dallas, Texas, USA, 5–9 November 2018). For the RLI of 2005, we used the assessments published between 2000 and 2010. Red List assessments for ~2005 and 2018 are published on the IUCN Red List of Threatened Species website[67] (also in supplementary material for the 2018 Red List assessments: Supplementary Red List assessments). Species previously assessed as Data Deficient (DD) were retrospectively assigned a data-sufficient category (see Table S2). No assessment was available in the 1980s and experts involved in the IUCN SSC SSG workshop (Dallas, Texas, USA, 5–9 November 2018) retrospectively determined Red List statuses for 1980, as well as missing statuses in ~2005. To take into account the uncertainty around a retrospective assessment, we used a bootstrap-like method to iteratively resample 10,000 times each species' status from its retrospective assigned status or one category better, or one category worse, denoted by the error bar (the range of bootstrap-like results) in Fig. 3a around the retrospective RLI in 1980 (black dot).

The RLI value of a particular year (*t*) is calculated by multiplying the number of species (s) in each Red List category by the category weight (*W*) (0 for LC, 1 for NT, 2 for VU, 3 for EN, 4 for CR, and 5 for EX), then summing the product and dividing by the maximum possible product (number of species (*N*) multiplied by the maximum weight 5), and subtracted from 1 to have an index between 0 (where all species are EX) and 1 (where all species are LC)[33]:

$$RLI_t = 1 - \frac{\sum_s W_{c(t,s)}}{W_{EX} * N}$$

To make the RLI in 2018 spatially explicit, we calculated 100,000 km^2 hexagonal cells in the world's oceans[68] using the IUCN Red List status of species that are distributed in each unique cell (based on IUCN distribution maps for each species, see Supplementary Red List assessments). We analyse the difference of RLI between 1980 and 2018 in the same way, assuming the distribution of species did not change in between those years. All spatial data described were processed using ESRI ArcGIS v10.7[69] and R Statistical Software v3.5.2[63] in Eckert IV equal-area Projection.

The stand-alone point labelled 'Global sharks' in Figure 3 indicates the starting point for the global Chondrichthyans (sharks, rays and chimaeras) Red List Index calculated from the Red List status as reported in 2006 (the median date of available Red List assessments at this time)[14].

Sustainability of stocks of oceanic sharks

In order to represent the status of stocks (population) of oceanic sharks, we compiled total biomass or abundance, relative to Maximum Sustainable Yield (MSY), provided by authors or extracted from the latest available stock assessment reports (the reference of the source and the trajectory used are in Supplementary Information Table S3). A stock assessment is the process of employing statistical models to quantify the population dynamics of a fished stock in response to fishing based on the best available catch, abundance, and life history information. No stock assessment exists for any of the oceanic rays and one of the Blue Shark stock assessments could not be included because no estimates of MSY-related quantities were available$^{\text{see page 2 of 70}}$. We thus used the eight species (Oceanic Whitetip Shark, Dusky Shark, Shortfin Mako, Porbeagle, Scalloped Hammerhead, Great Hammerhead, Smooth Hammerhead, and Blue Shark) with published biomass or abundance trajectories relative to MSY (15 stocks in total) to produce the global probability — over time — that these species were at levels above the biomass or abundance achieving the MSY (i.e., $p(\mathrm{B}>\mathrm{B}_{\mathrm{MSY}})$), and thus not overfished (Figure 6b). Each stock's biomass or abundance relative to MSY was transformed into a binary variable, indicating if the stock was above (1) or below (0) MSY. To represent the status of species with several stocks, we calculated the proportion — over time — of stocks above or below MSY. We finally calculated the global probability — over time — that these species were at levels above the biomass or abundance achieving the MSY by calculating the proportion of the species' status that were above MSY for each year.

In a stock assessment, scientists attempt to estimate the amount of fishing mortality (F) over time, and the fishing mortality that will achieve MSY ($\mathrm{F}_{\mathrm{MSY}}$). Using available stock assessments, we compiled the latest value of fishing mortality relative to the fishing mortality at MSY ($\mathrm{F}/\mathrm{F}_{\mathrm{MSY}}$) and plotted them against the latest value of biomass or abundance trajectories relative to the MSY, in the 'four quadrant, red-yellow-green' Kobe plot style

(Extended Data Figure 11).

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Data and materials availability: Upon publication, the data will be available on www.sharktraits.org.

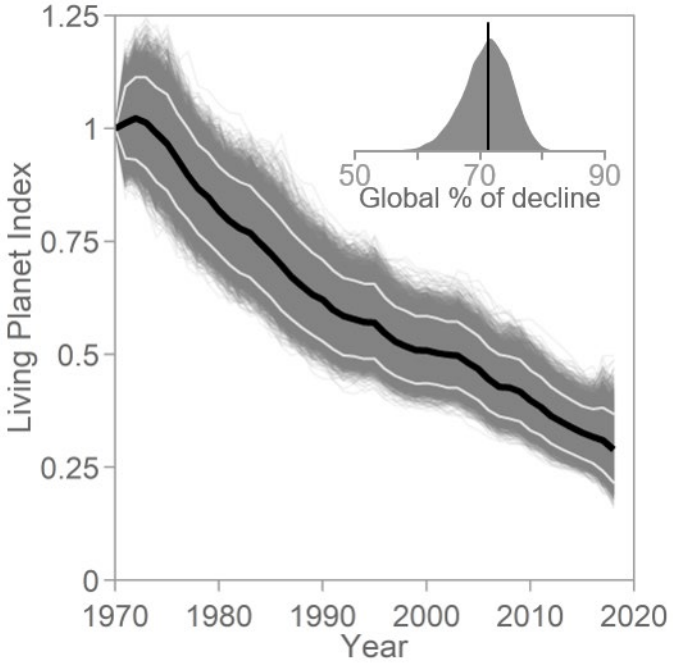


Figure 1 | Global Living Planet Index (LPI) for 18 oceanic sharks estimated from 1970 to 2018. The global percentage (%) of decline was calculated from the posteriors of the LPI around the final assessment year relative to the posteriors for 1970. The black line denotes the mean, the white lines the 95% credible intervals and the grey lines each iteration.

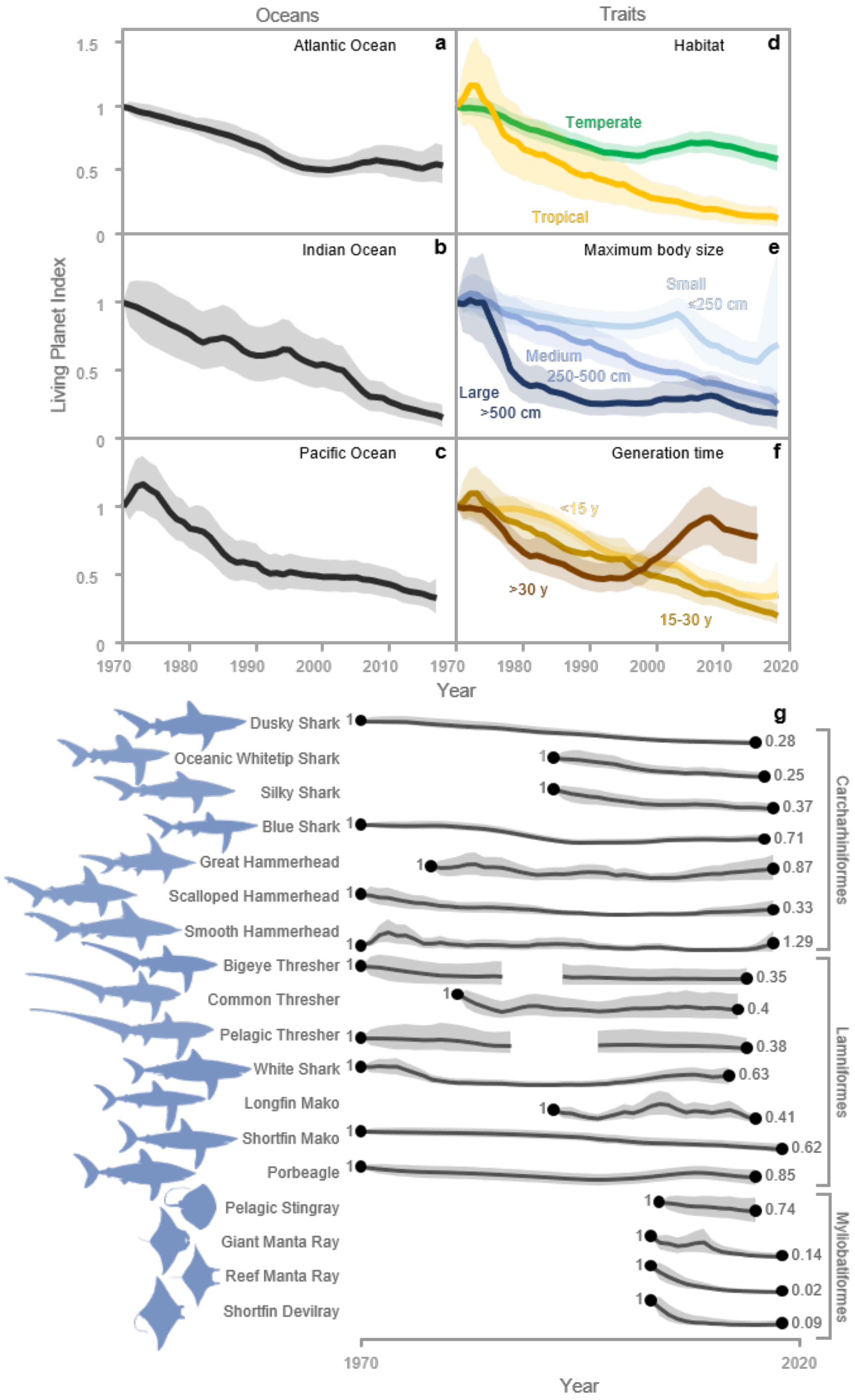


Figure 2 | Living Planet Index for 18 oceanic sharks from 1970 to 2018 disaggregated by Oceans (a, b, c), and the traits (d) geographical zone, (e) body size (maximum total length), (f) generation time (GT), and (g) species (species' time-series are in Extended Data Figure 4 to 9). Lines denote the mean and shaded regions the 95% credible intervals.

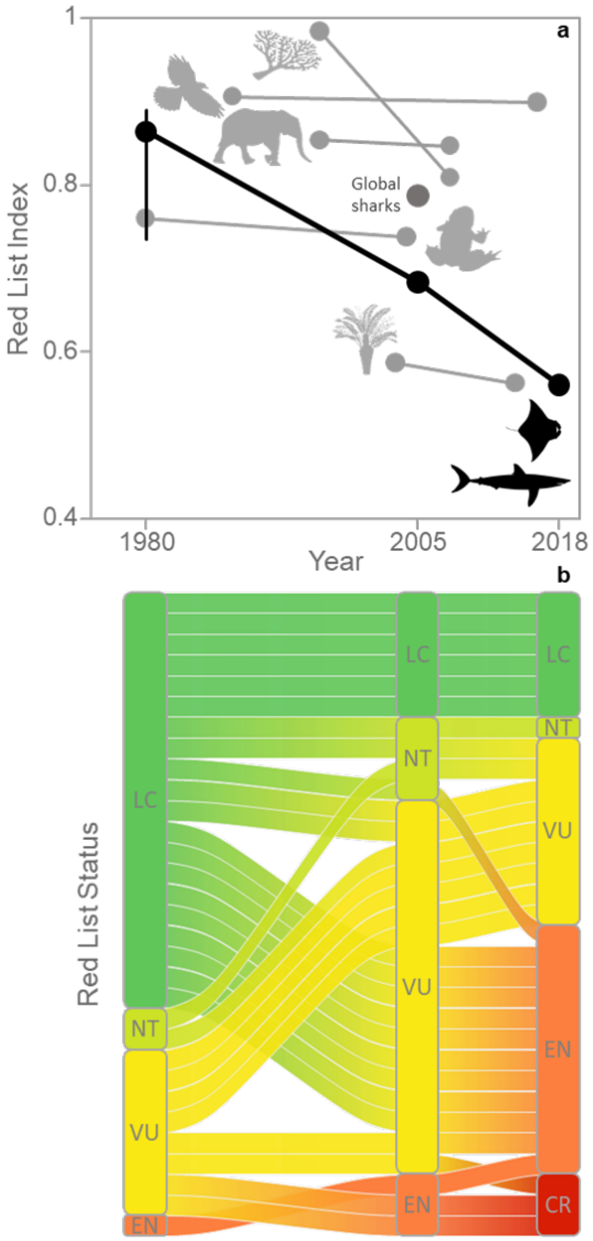
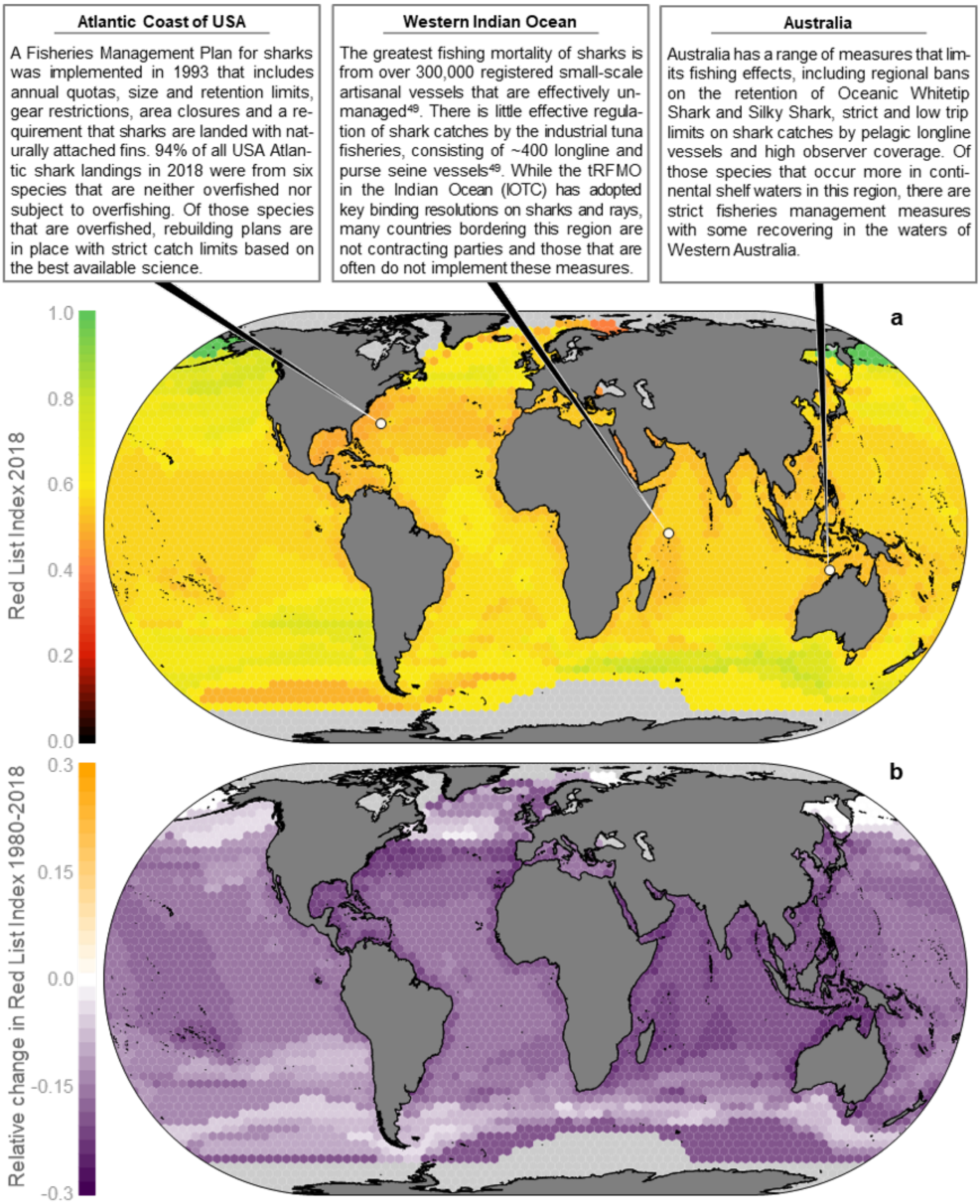


Figure 3 | (a) Global Red List Index (RLI) for the 31 oceanic shark species (black line) estimated in 1980, 2005, and 2018, and for mammals, birds, amphibians, reef-forming corals, and cycads (in grey), and global Chondrichthyans (sharks, rays, and chimaeras; stand-alone point in dark grey labelled ‘Global sharks’)[14] between 1980 and 2014. The error bar denotes the uncertainty around the retrospective 1980 IUCN status (see Methods). A RLI value of 1.0 equates to all species qualifying as Least Concern (i.e., not expected to become Extinct in the near future), while a RLI value of 0 equates to all species having gone Extinct. (b) Change in Red List status of oceanic sharks from 1980 to 2018.



Atlantic Coast of USA

A Fisheries Management Plan for sharks was implemented in 1993 that includes annual quotas, size and retention limits, gear restrictions, area closures and a requirement that sharks are landed with naturally attached fins. 94% of all USA Atlantic shark landings in 2018 were from six species that are neither overfished nor subject to overfishing. Of those species that are overfished, rebuilding plans are in place with strict catch limits based on the best available science.

Western Indian Ocean

The greatest fishing mortality of sharks is from over 300,000 registered small-scale artisanal vessels that are effectively unmanaged[49]. There is little effective regulation of shark catches by the industrial tuna fisheries, consisting of ~400 longline and purse seine vessels[49]. While the tRFMO in the Indian Ocean (IOTC) has adopted key binding resolutions on sharks and rays, many countries bordering this region are not contracting parties and those that are often do not implement these measures.

Australia

Australia has a range of measures that limits fishing effects, including regional bans on the retention of Oceanic Whitetip Shark and Silky Shark, strict and low trip limits on shark catches by pelagic longline vessels and high observer coverage. Of those species that occur more in continental shelf waters in this region, there are strict fisheries management measures with some recovering in the waters of Western Australia.

Figure 4 | World map of the 31 oceanic sharks current Red List Index (RLI) (a) and difference in Red List Index between 1980 and 2018 (b). Each hexagon is 100,000km^2. A RLI value of 1.0 equates to all species qualifying as Least Concern (i.e., not expected to become Extinct in the near future), while a RLI value of 0 equates to all species having gone Extinct. The text boxes address variation in fishing pressure and management progress in situations with apparent similarly high extinction risk on the map (a).

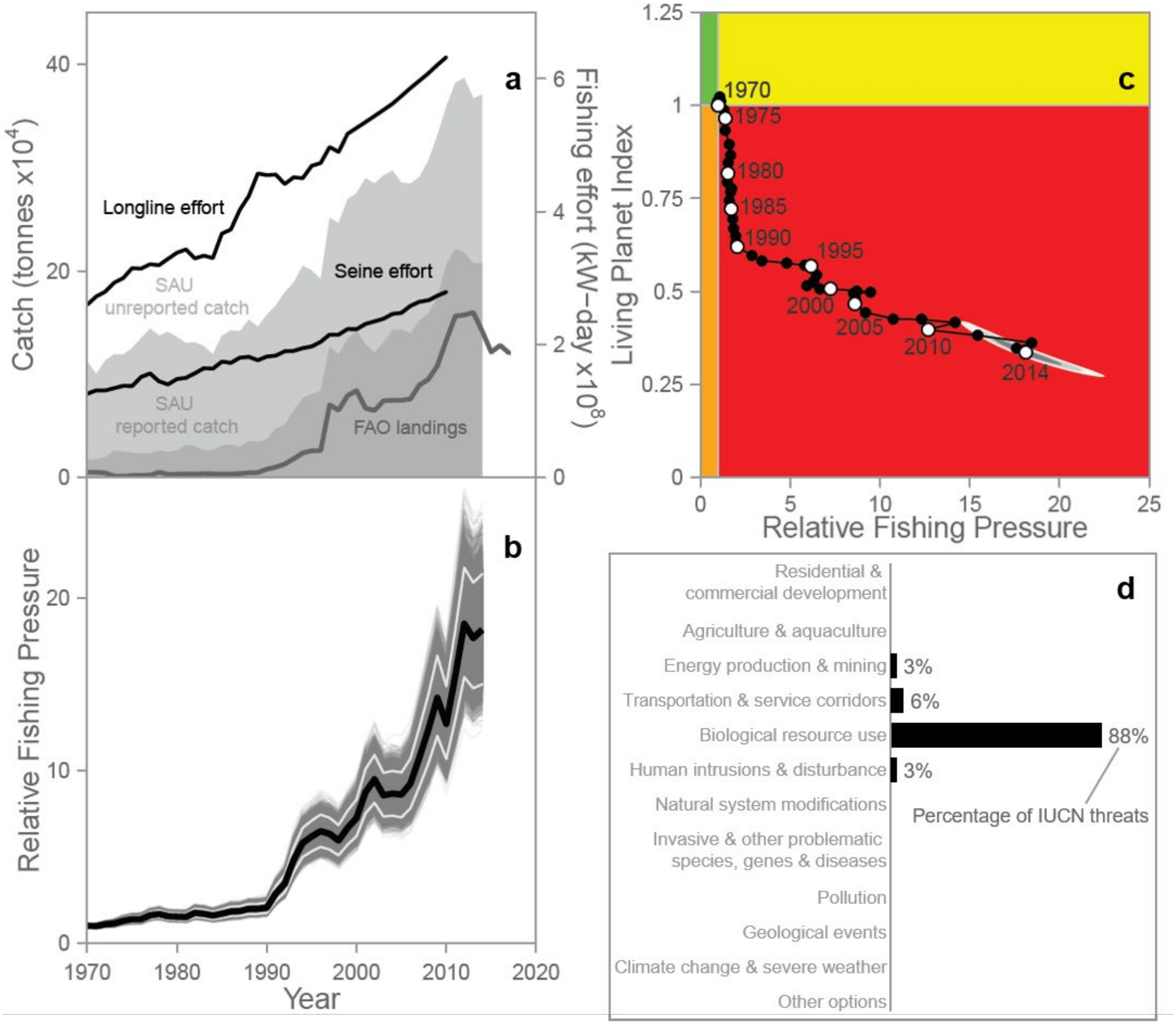


Figure 5 | (a) Global catch data of 14 oceanic sharks and fishing effort of longline and seine gears. SAU reported catch: Sea Around Us project reported catch data. SAU unreported catch data: Sea Around Us reconstructed unreported catch data. FAO landings: Food and Agriculture Organization of the United Nations reported landings data. Longline effort and Seine effort are effective fishing effort[37] (data corrected for technological creep, see Supplementary Information Methods 1). (b) Fishing pressure (catch) encountered by oceanic sharks relative to the fishing pressure (catch) in 1970 and to their abundance from 1970 to 2014.

The black line denotes the mean, the white lines the 95% credible intervals and the grey lines each iteration. (c) Living Planet Index as a function of Relative Fishing Pressure (RFP, *n*=14 species) from 1970 (the initial state where LPI and RFP = 1) to 2014 for oceanic sharks (*n*=18 species). The plot is divided into four panels: green panel (upper left) corresponds to a higher abundance than 1970 and a low RFP; red panel (bottom right) corresponds to a lower abundance than in 1970 and also a high RFP; the yellow panel (upper right) and orange panel (bottom left) corresponds to intermediate situations, respectively to a higher abundance than 1970 but a higher RFP, and to a lower abundance than in 1970 but also a lower RFP. Black line and points represent the annual trajectory over time. Light-grey, grey, and dark-grey polygons denote the 50%, 80%, and 95% 2D kernel density estimate of the iterations of LPI vs RFP for the last year (2014). (d) Percentage of reported threat categories in the 31 oceanic shark Red List assessments.

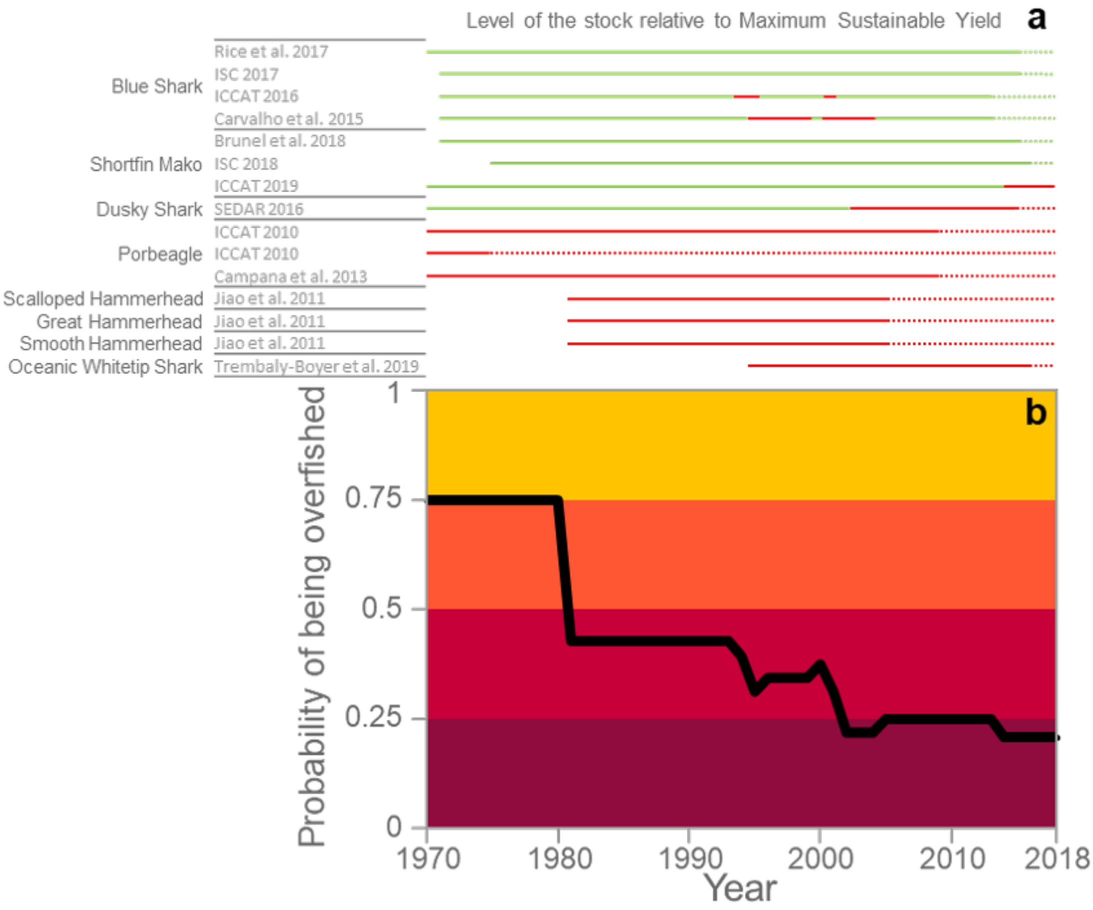


Figure 6 | (a) Oceanic shark stock status — over time — being at level (biomass, abundance) above Maximum Sustainable Yield (MSY) (green lines) or below MSY (red lines). Dotted lines indicate that a stock is above or below MSY following the last stock assessment value. (b) Probability over time that species are at levels of biomass or abundance equal or greater than that would achieve Maximum Sustainable Yield.

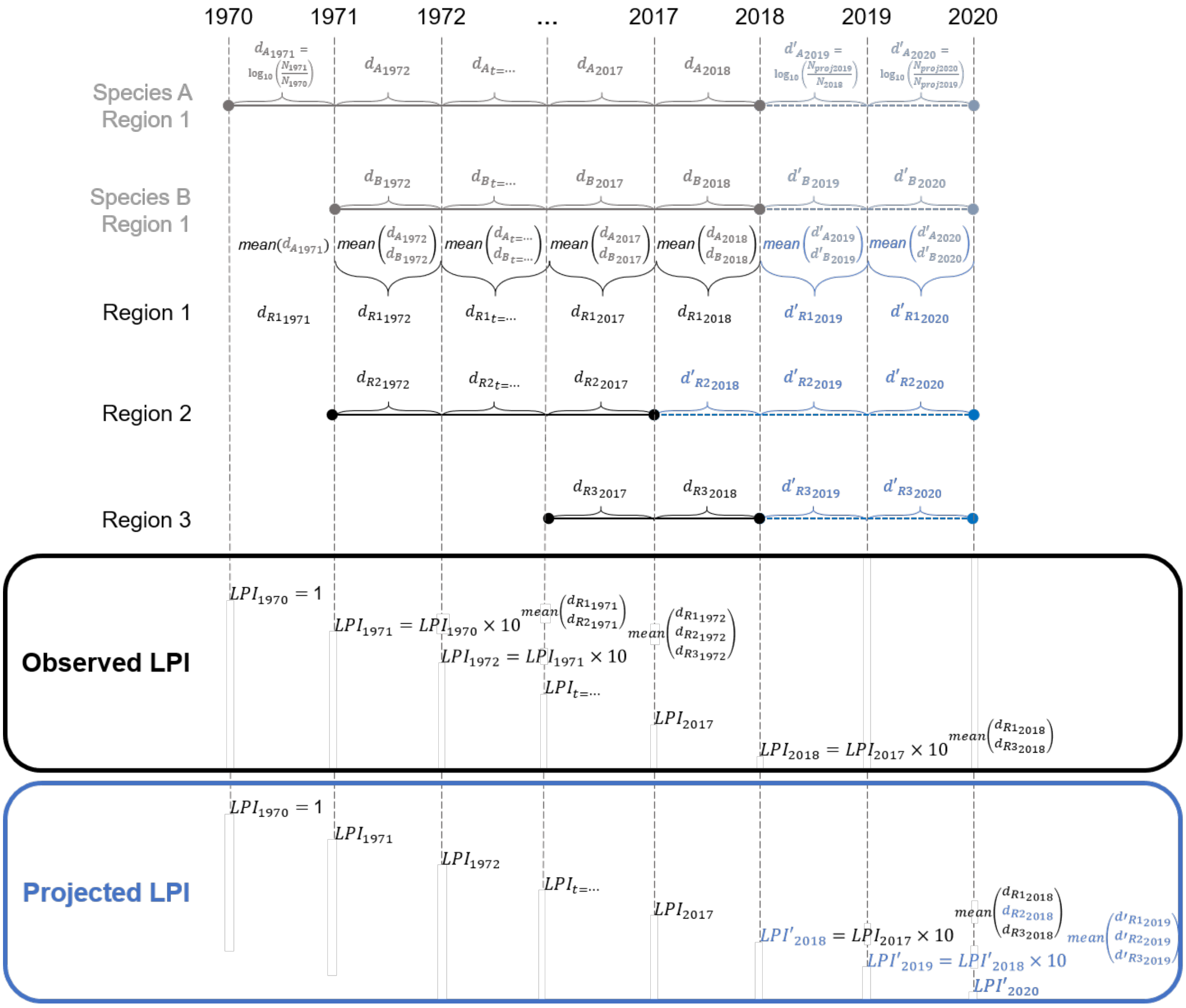
Text box 1. Hierarchical building of the global LPI and RLI

- **Global Living Planet Index** (track changes in abundance)
  Average year-to-year rates of change for all Oceans then convert rate of change to index scale
  - **For each Ocean** (North/South: only for Atlantic and Pacific)
    Average year-to-year rates of change of sub-Oceans
    - **For each sub-Ocean**
      Average year-to-year rates of change for all species
      - **For each species**
        Estimate year-to-year rates of change
        - **For each time-series**
          Average year-to-year rates of change for all Oceans then convert rate of

- **Global Red List Index** (track changes in extinction risk)
  Sum all numbers and divide by score of worst scenario possible (all EX) then convert to 0-1 scale (by removing 1 from the total)
  - **For each species**
    Collate existing assessment criteria + retrospective + modify non-genuine change
    Transform status into number (LC=0; NT=1; VU=2; EN=3; CR=4; EX=5)

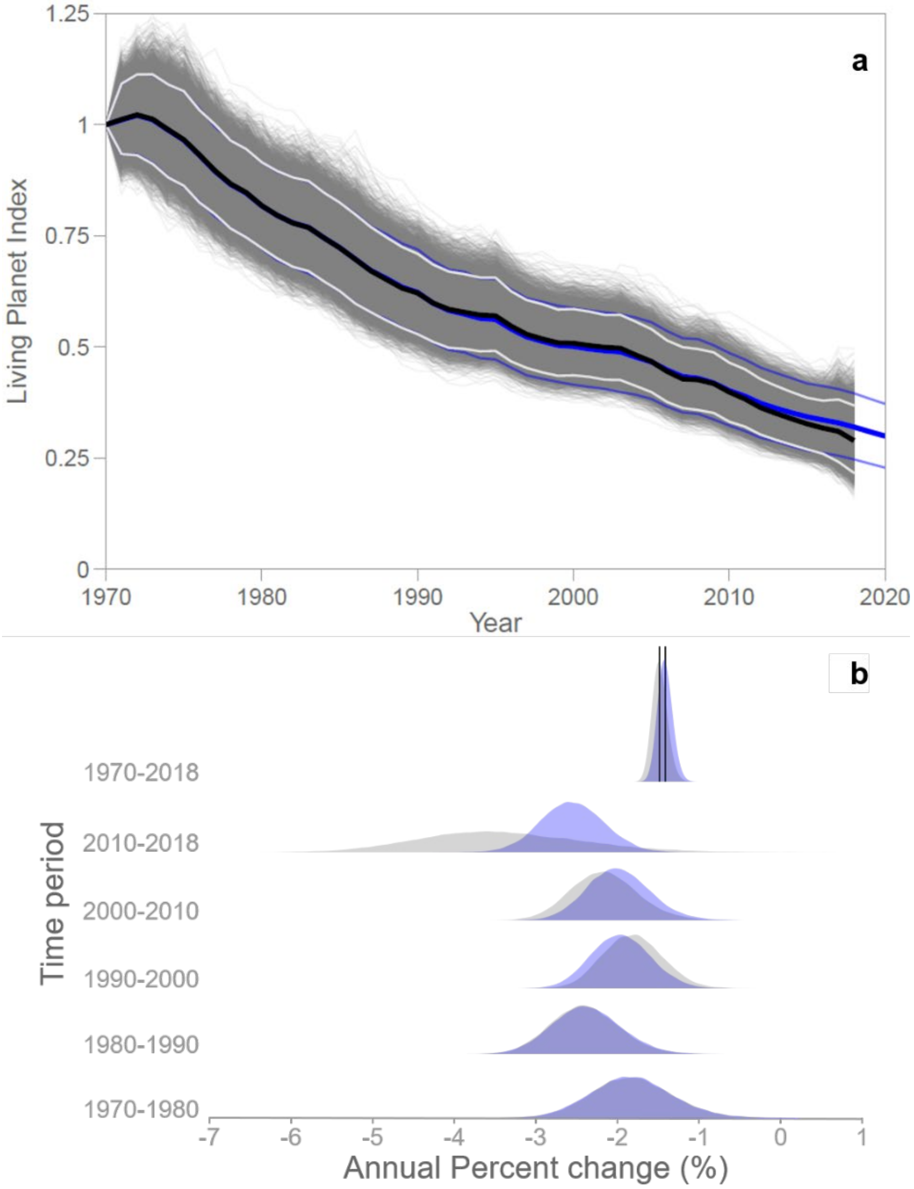
Extended Data Figure 1 | Schematic example of constructing the observed (black) and projected (blue) Living Planet Index. First, year-to-year rates of change, abbreviated yyrc thereafter, (d_t) are averaged between species in the same region (e.g., in *Region 1*, species *A* with d_{A_t} and species *B* with d_{B_t} averaged in d_{R1_t}). In a second step, yyrc are averaged between regions *Region 1, 2* and *3* to give the global yyrc.

The observed LPI builds on yyrc calculated from the estimated abundance index from the state-space population model. The projected LPI builds on yyrc calculated from the estimated and projected, after the last data point to 2020, abundance index from the state-space population model.

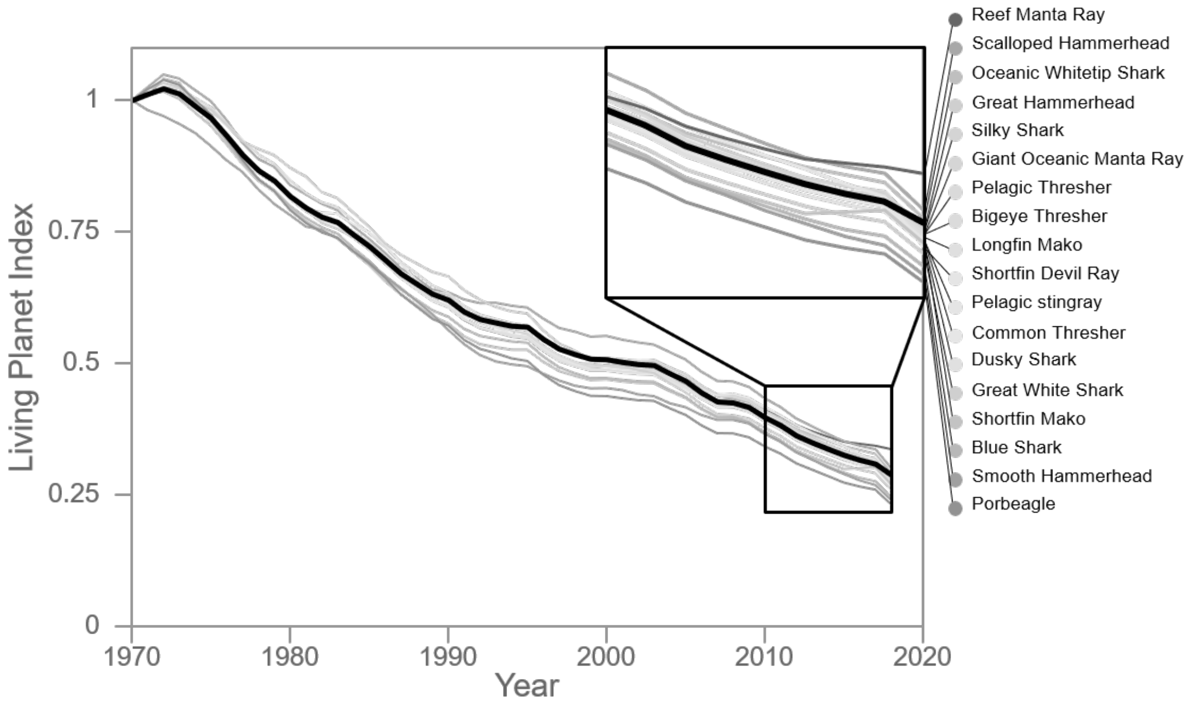


Extended Data Figure 2 | (a) Global Living Planet Index for oceanic sharks and rays estimated from 1970 to 2018 in black and extrapolated to 2020 in blue. The black and the thick blue lines denote respectively the mean of the estimated and extrapolated LPI. The white and thin blues lines denote respectively, the 95% credible intervals of the estimated and extrapolated LPI and the grey lines each iteration of the estimated LPI.

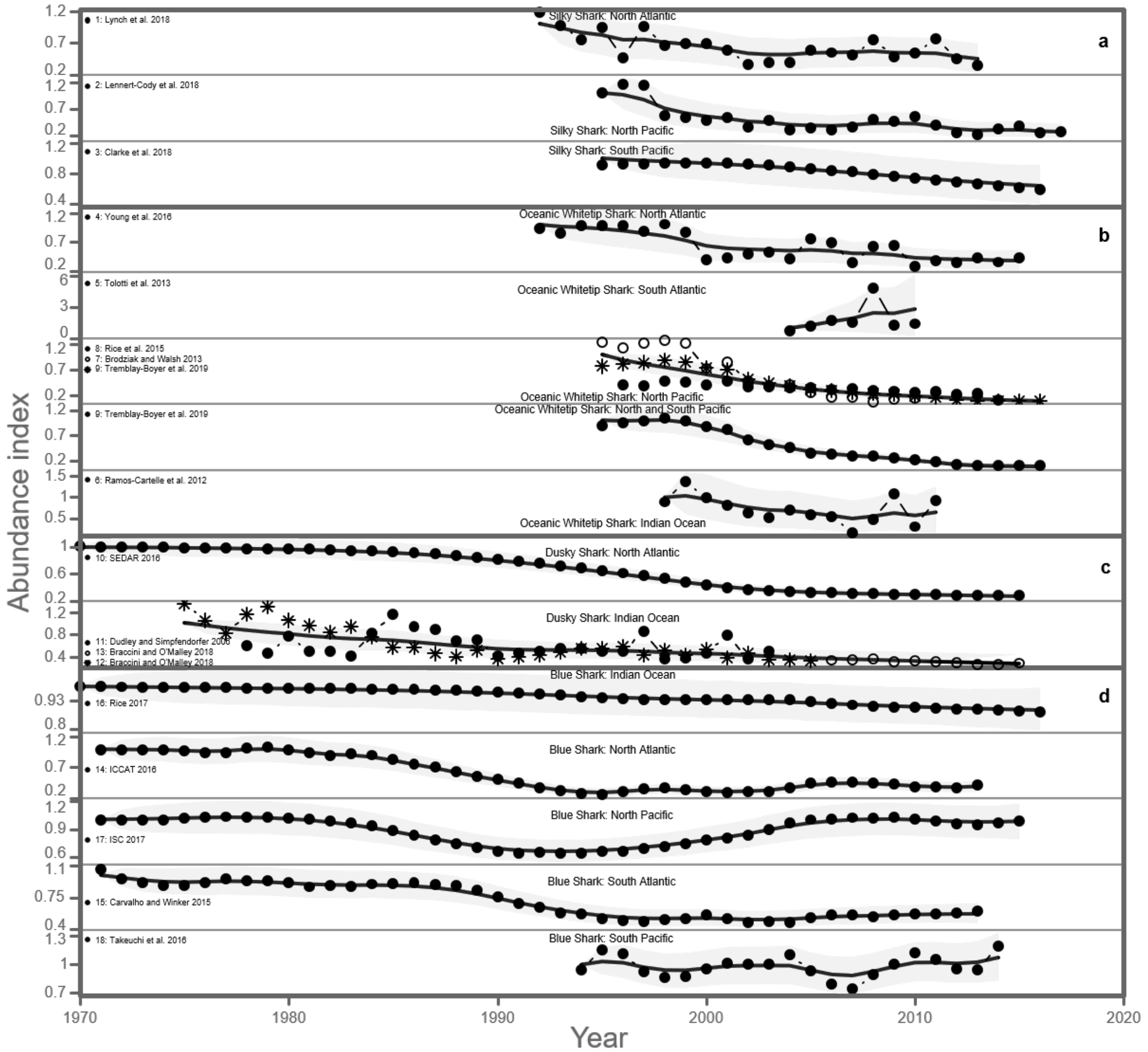
(b) The annual percentage change was calculated from the posteriors of the estimated LPI (in grey) and extrapolated LPI (in blue) around the final assessment year relative to the posteriors for 1970. Vertical bars on the 1970-2018 period denote the median of the estimated and extrapolated LPI.



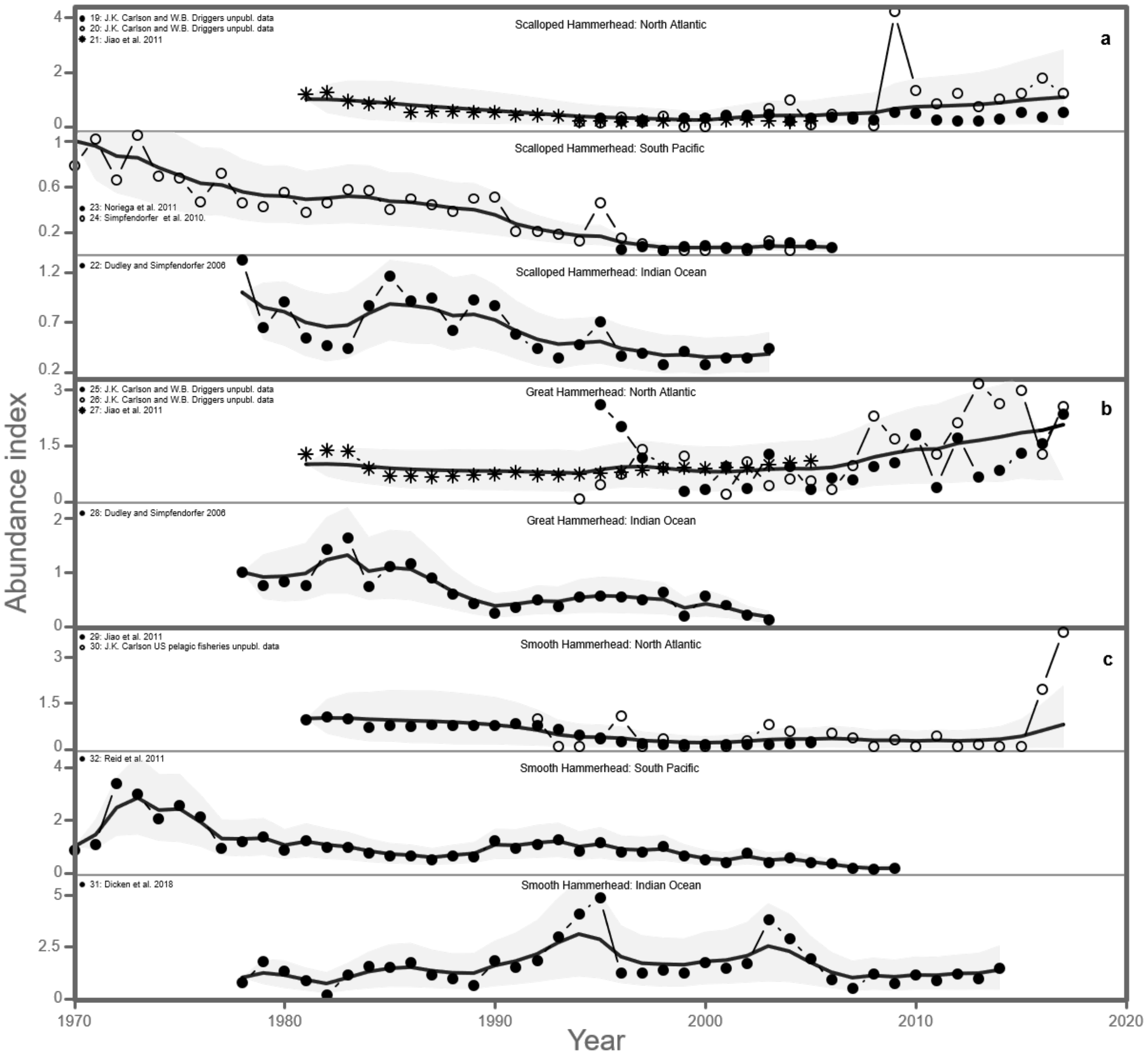
Extended Data Figure 3 | Mean global Living Planet Index for oceanic sharks and rays from 1970 to 2018 (black line). Faint gray lines show the effect of excluding all data for a single species at a time and recalculating the mean global LPI for all other species. No means from jackknife species trends fall outside the 95% Credible Interval from the run with all the datasets included, suggesting our selection of species did not unduly influence the overall LPI result.



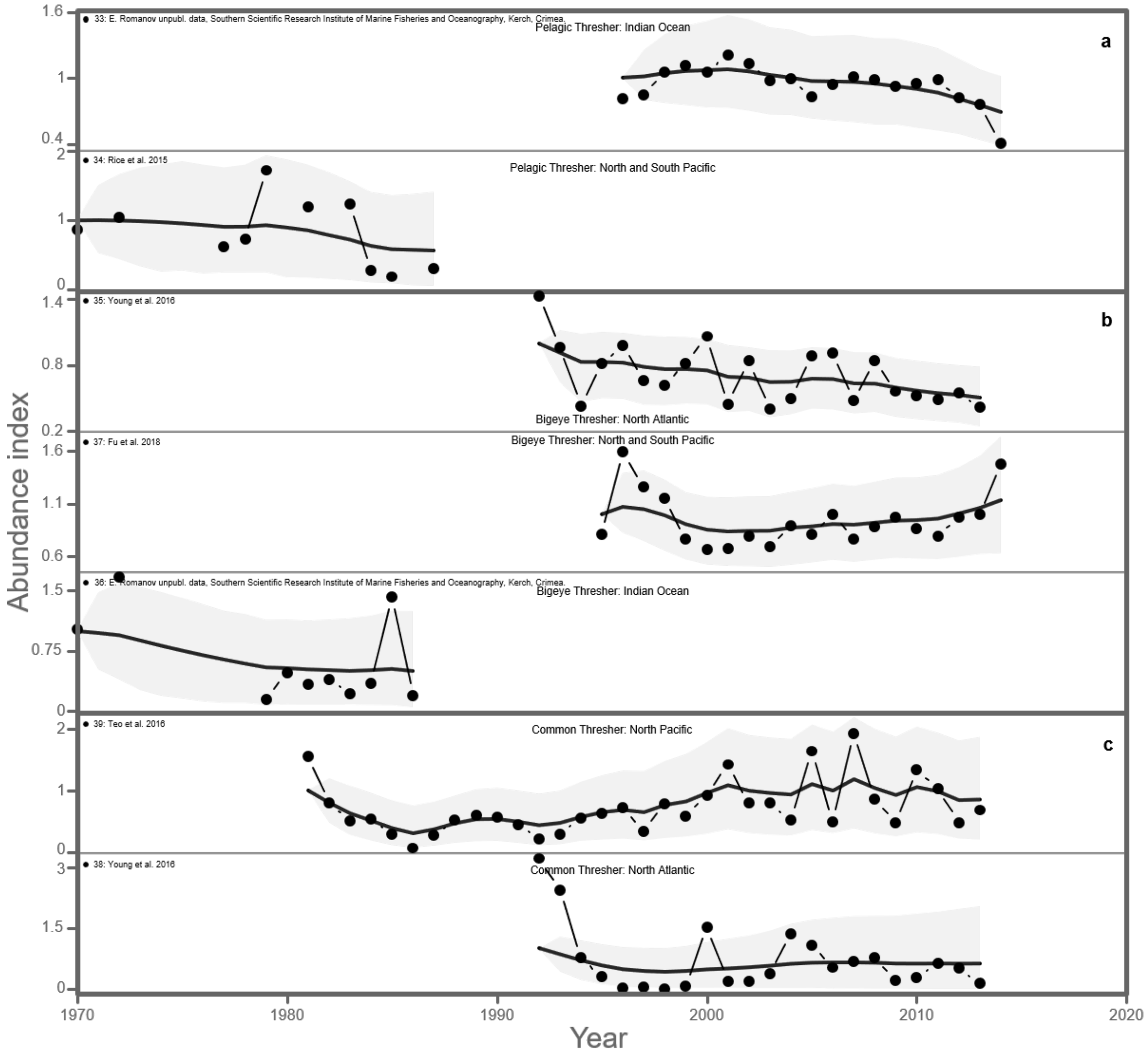
Extended Data Figure 4 | Observed (black or empty points, and stars indicate different time-series) and modeled (black line) abundance index for (a) Silky Shark (*Carcharhinus falciformis*), (b) Oceanic Whitetip Shark (*Carcharhinus longimanus*), (c) Dusky Shark (*Carcharhinus obscurus*) and (d) Blue Shark (*Prionace glauca*) obtained from the state-space population model. Shaded regions denote 95% credible intervals.



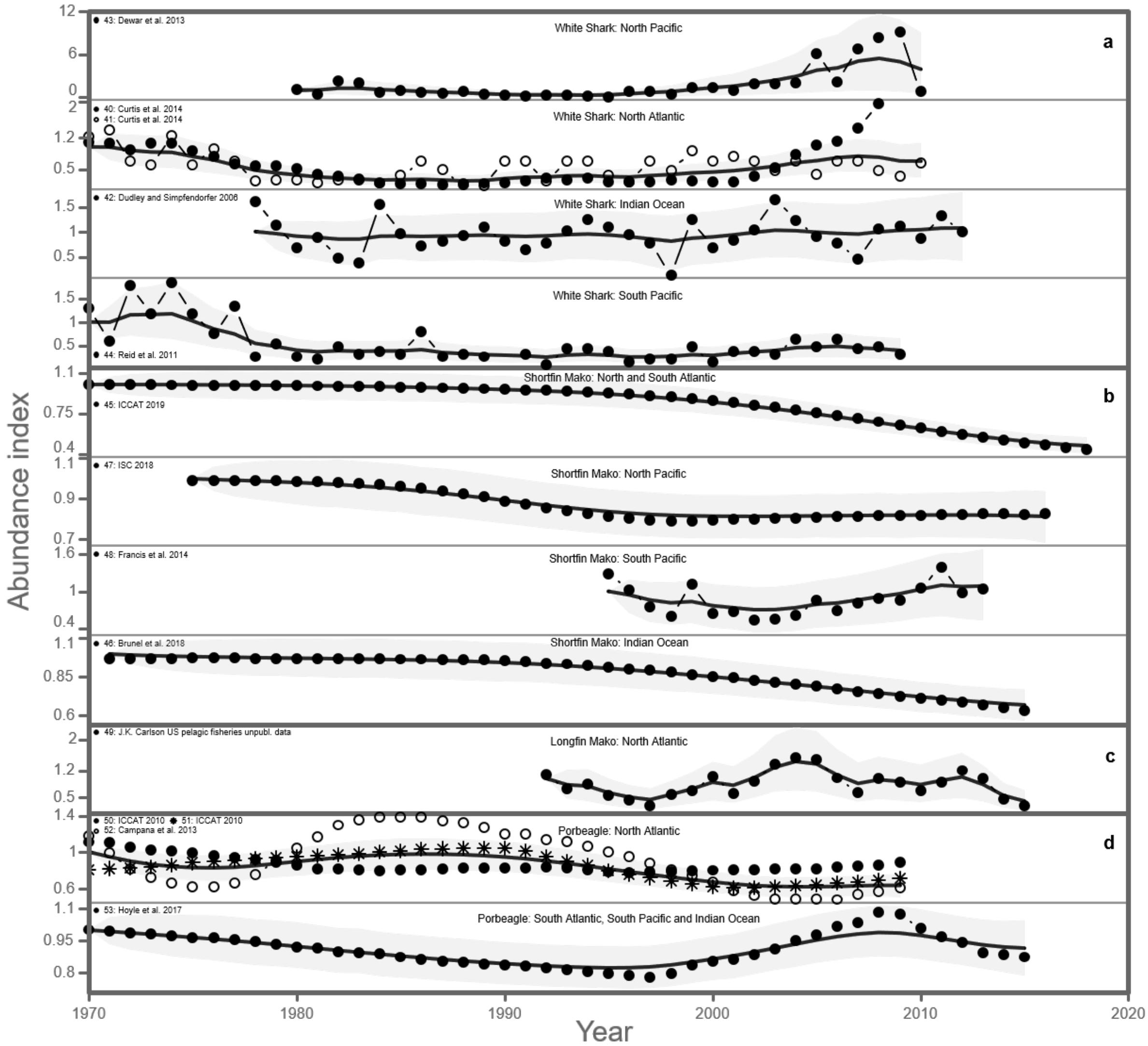
Extended Data Figure 5 | Observed (black or empty points, and stars indicate different time-series) and modeled (black line) abundance index for (a) Scalloped Hammerhead (*Sphyrna lewini*), (b) Great Hammerhead (*Sphyrna mokarran*) and (c) Smooth Hammerhead (*Sphyrna zygaena*) obtained from the state-space population model. Shaded regions denote 95% credible intervals.



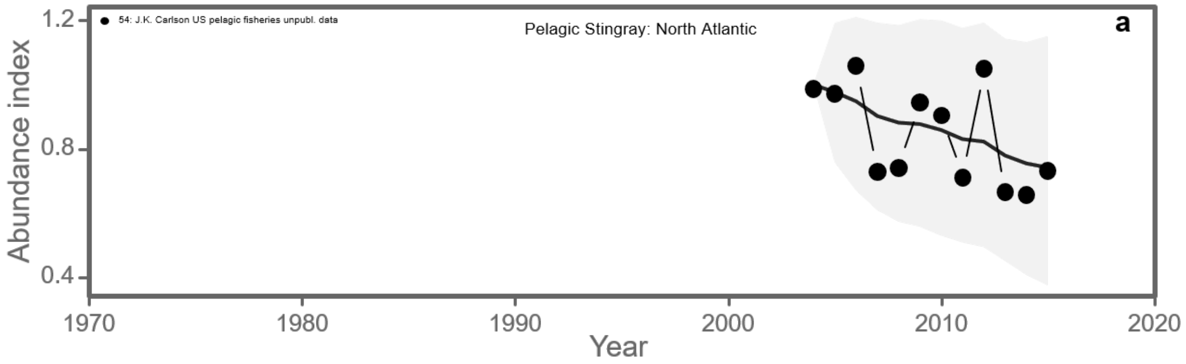
Extended Data Figure 6 | Observed (points) and modeled (black line) abundance index for (a) Pelagic Thresher (*Alopias pelagicus*), (b) Bigeye Thresher Shark (*Alopias superciliosus*) and (c) Common Thresher Shark (*Alopias vulpinus*) obtained from the state-space population model. Shaded regions denote 95% credible intervals.



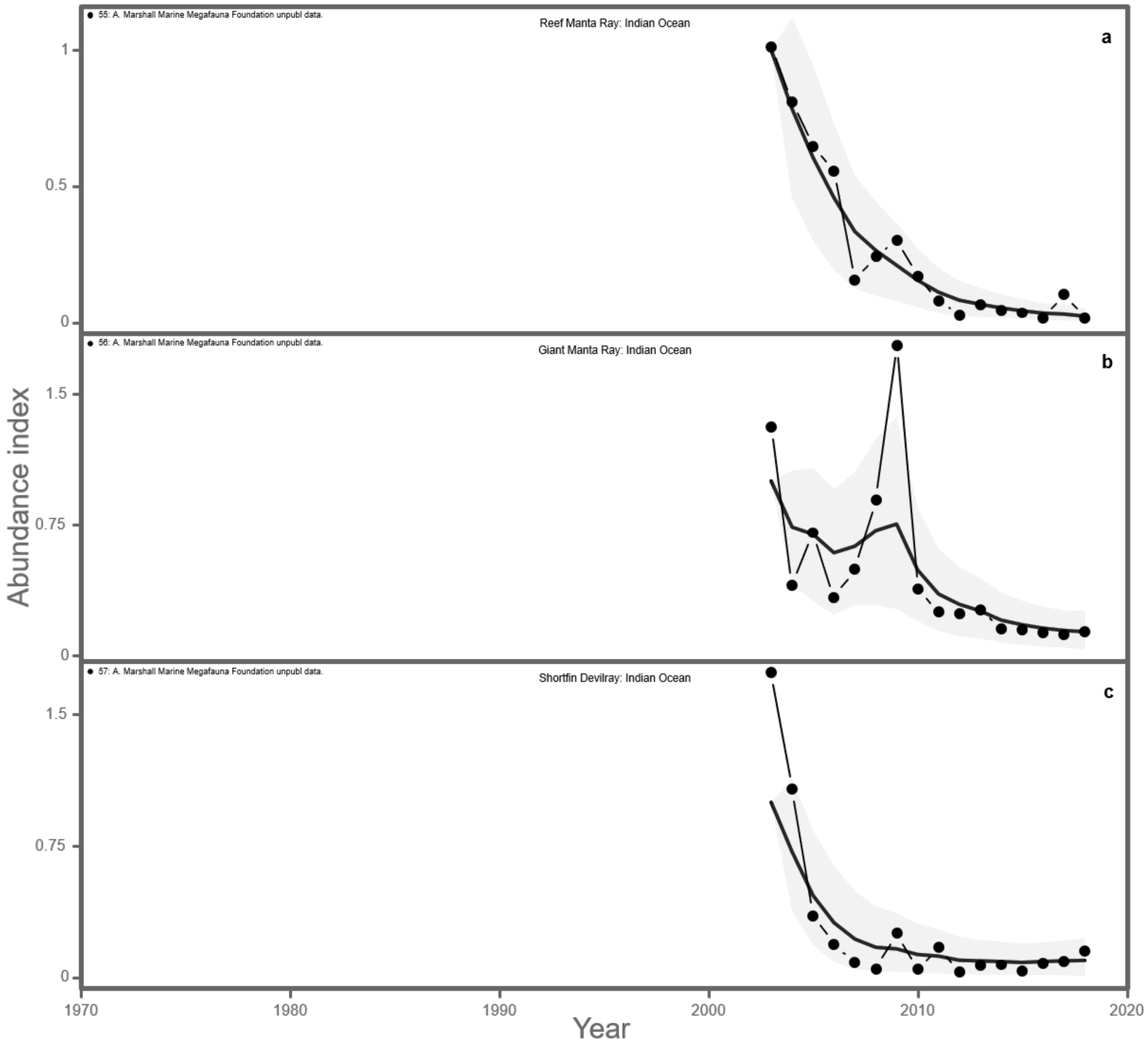
Extended Data Figure 7 | Observed (black or empty points, and stars indicate different time-series) and modeled (black line) abundance index for (a) White Shark (*Carcharodon carcharias*), (b) Shortfin Mako (*Isurus oxyrinchus*), (c) Longfin Mako (*Isurus paucus*) and (d) Porbeagle (*Lamna nasus*) obtained from the state-space population model. Shaded regions denote 95% credible intervals.



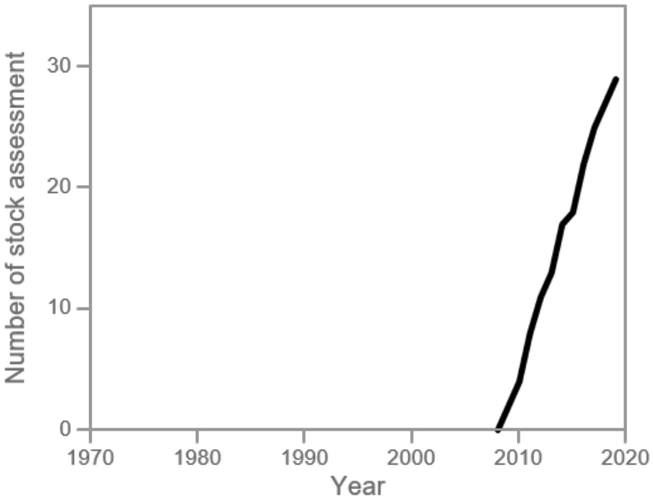
Extended Data Figure 8 | Observed (points) and modeled (black line) abundance index for Pelagic Stingray (*Pteroplatytrygon violacea*) obtained from the state-space population model. Shaded regions denote 95% credible intervals.



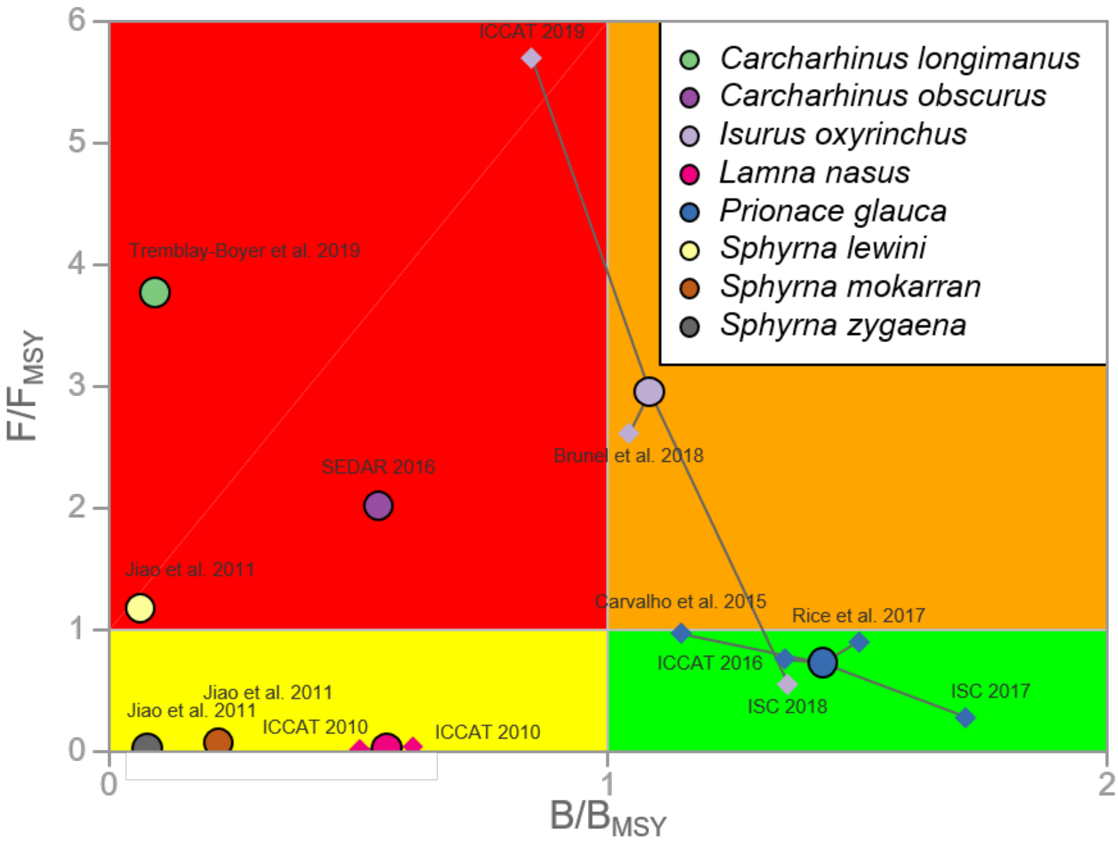
Extended Data Figure 9 | Observed (points) and modeled (black line) abundance index for (a) Reef Manta Ray (*Mobula alfredi*), (b) Giant Manta Ray (*Mobula birostris*) and (c) Shortfin Devilray (*Mobula kuhlii*) obtained from the state-space population model. Shaded regions denote 95% credible intervals.



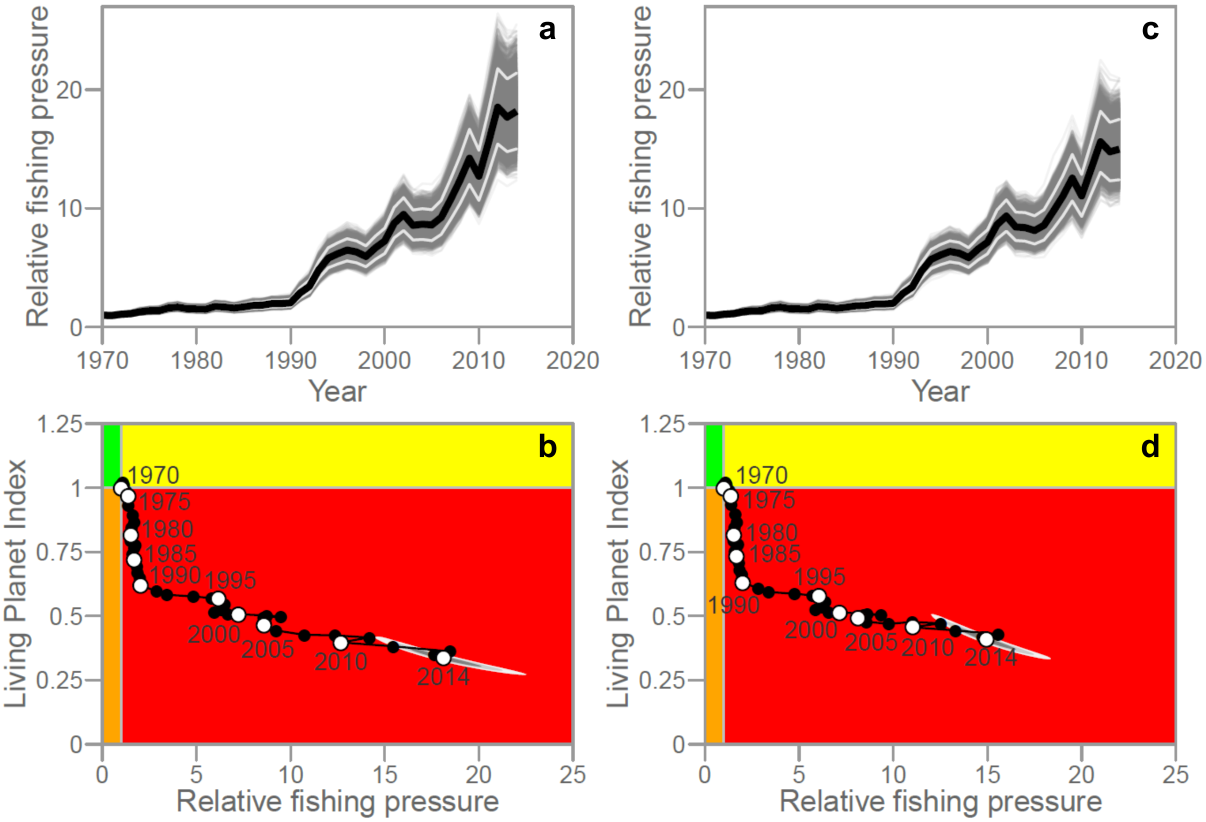
Extended Data Figure 10 | Number of published stock assessments for oceanic sharks and rays over time.



Extended Data Figure 11 | Presentation of 14 stocks of oceanic sharks (no available stock assessments for oceanic rays) in a pressure (F/F_{MSY}) status (biomass or abundance over value at MSY) plot, for the last year with available data. Circles represent the species' unique values if only one stock exists, and diamonds represent the mean of the different stocks when the species has multiple stocks. The plot is divided into four panels: red panel (upperleft) with 4 stocks and 3 species, corresponds to stocks that are being overfished and where overfishing is occurring; orange panel (upperright) with 1 stock and 1 species, corresponds to stocks that are not overfished but where overfishing is occurring; yellow panel (bottomleft) with 4 stocks and 3 species, corresponds to stocks that are overfished but where overfishing is not occurring; and green panel (bottomright) with 5 stocks and 1 species, corresponds to stocks that are not overfished and where overfishing is not occurring.



Extended Data Figure 12 | Fishing pressure (catch) encountered by oceanic sharks and rays relative to the fishing pressure (catch) in 1970 and to their abundance from 1970 to 2014 (a and c) and Living Planet Index as a function of Relative Fishing Pressure from 1970 (initial state where the LPI and the RFP were equal to 1) to 2014 (b and d). Panels on the left (a and c) are for the 18 oceanic sharks and rays (same as Figure 5) and panels on the right (b and d) are for the 14 oceanic sharks and rays for which catch data were available. The black line denotes the mean, the white lines the 95% credible intervals and the grey lines each iteration. The b and d plots are divided into four panels: green panel (upper left) corresponds to a higher abundance than 1970 and a low relative fishing pressure; red panel (bottom right) corresponds to a lower abundance than in 1970 and also a high relative fishing pressure; the yellow panel (upper right) and orange panel (bottom left) corresponds to intermediate situations, respectively to a higher abundance than 1970 but a high relative fishing pressure, and to a lower abundance than in 1970 but also a low relative fishing pressure. Black line and points represent the annual trajectory over time. Light-grey, grey and dark-grey areas denotes the 50%, 80% and 95% 2D kernel density estimate of the iterations of LPI vs RFP for the last years (2014).


a
Relative fishing pressure
0
10
20
1970
1980
1990
2000
2010
2020
Year
c
Relative fishing pressure
0
10
20
1970
1980
1990
2000
2010
2020
Year
b
Living Planet Index
0
0.25
0.5
0.75
1
1.25
1970
1975
1980
1985
1990
1995
2000
2005
2010
2014
0
5
10
15
20
25
Relative fishing pressure
d
Living Planet Index
0
0.25
0.5
0.75
1
1.25
1970
1975
1980
1985
1990
1995
2000
2005
2010
2014
0
5
10
15
20
25
Relative fishing pressure

Supplementary Methods 1

Correction of nominal longline and seine fishing effort to effective fishing effort

We used the technological efficiency, or 'creep factor', following eqn. 2 and 3 from [71], to adjust the fishing effort of longline and seine gears, the two industrial gears that catch most oceanic sharks, from [37] to adjust for the progressive increase in the effectiveness of fishing gear due to vessel and gear technological improvements.

Supplementary Methods 2

The details of generation time (GT) were presented to the workshop for review and the final choices were used in the published IUCN Red List assessments and associated supplementary material for each species. We encountered nine situations and describe the quality of data in order of increasing confidence.

1. No suitable age and GT estimates were available, even from related species, for the Megamouth Shark.
2. Age and GT were borrowed from a nearby species, e.g. we assumed the Longfin Mako GT was the same as the Shortfin Mako, the Smooth hammerhead GT was the same as the Scalloped Hammerhead, the Giant Manta Ray is similar to the Reef Manta Ray, the Shortfin, Atlantic, Pigmy, Sicklefin, and Bentfin Devilray are based on the Giant Devilray and hence are overestimates.
3. For many species there were no or few choices as there was only a single, unvalidated, age and growth estimate, e.g. Crocodile Shark, Whale Shark, Basking Shark, and Pelagic Stingray.
4. Female median age at maturity and maximum age are estimated from aquarium-held specimens and mark-recapture data, e.g. Reef Manta Ray.

5. Female median age at maturity and maximum age varies slightly between regions and it was not clear which study was 'better' or more representative and neither study is validated, e.g. Pelagic Thresher and Blue Shark. Pelagic Thresher shark GT is 16.5 years in Taiwan and 20.6 years in Indonesia and the average of both was used in the Red List assessment was 18.5 years.
6. Female median age at maturity and maximum age varies between regions and the more conservative, precautionary observed age estimate was chosen, e.g. Silky Shark, Oceanic Whitetip Shark, and Blue Shark.
7. Female median age at maturity and maximum age varies between regions and different regional estimates were used in the estimation of population reduction for the red List Assessment, e.g. Salmon Shark, Great Hammerhead, and Dusky Shark.
8. The growth curve available encompassed a narrow range of sizes than that observed elsewhere in the geographic distribution, and the growth curve was extrapolated to yield a more plausible maximum age (A_{max}). In the Bigeye Thresher the observed female age-at-maturity is 12–13 years and maximum age 20 years in Taiwan, Northwest Pacific[72]. These Taiwanese age data were used to generate growth curves that encompass a wider age and size range than the observed data, and thus were used to estimate female A_{mat} of 9 years and A_{max} of 28 years resulting in GT of 18.5 years[73].
9. There was a bomb radiocarbon validated estimate for one region and this was assumed to be valid for the species range, e.g. Common Thresher and White Shark.

Supplementary Table

Table S1. Description of the 57 time-series of the 18 oceanic sharks and rays.

Max. size: maximum size as total length, or *disc width in centimeters

CPUE: Catch-Per-Unit-Effort

SPUE: Sightings-Per-Unit-Effort

GT: Generation time in years

† *Alopias* species-complex was used to represent catches from the Pacific for *Alopias pelagicus* in this species Red List assessment and in this analysis. The three thresher shark species A. pelagicus, A. *superciliosus*, and *A. vulpinus*, were combined by [74]due to a lack of species-specific data. These data are most likely to comprise the two first species[75,76, E. Romanov unpubl. data], however the proportion of the two species in this data is not defined[74], and these data are used only as a possible indication of *Alopias pelagicus* trends.

Latin name **Common name**	**N°**	**Start**	**End**	**Region of dataset**	**Data type**	**Geographical zone**	**Max. size**	**GT**	**References**
A. Carcharhiniformes: Carcharhinidae									
Carcharhinus falciformis Silky Shark	1.	1992	2013	North Atlantic	Standardized CPUE	Tropical	371	15	Lynch et al. 2018[77]
	2.	1995	2017	North Pacific	Standardized CPUE	Tropical	371	15	Lennert-Cody et al. 2018[78]
	3.	1995	2016	South Pacific	Standardized CPUE	Tropical	371	15	Clarke et al. 2018[79]
Carcharhinus longimanus Oceanic Whitetip Shark	4.	1992	2015	North Atlantic	Standardized CPUE	Tropical	395	20.4	Young et al. 2016[80]
	5.	2004	2010	South Atlantic	Standardized CPUE	Tropical	395	20.4	Tolotti et al. 2013[81]
	6.	1998	2011	Indian Ocean	Standardized CPUE	Tropical	395	20.4	Ramos-Cartelle et al. 2012[82]
	7.	1995	2010	North Pacific	Standardized CPUE	Tropical	395	20.4	Brodziak and Walsh 2013[83]
	8.	1996	2014	North Pacific	Updated standardized CPUE	Tropical	395	20.4	Rice et al. 2015[74]
	9.	1995	2009	North and South Pacific	Stock assessment	Tropical	395	20.4	Tremblay-Boyer et al. 2019[55]
Carcharhinus obscurus Dusky Shark	10.	1960	2015	North Atlantic	Stock assessment	Temperate	420	29.8	SEDAR 2016[26]
	11.	1978	2003	Indian Ocean	Nominal CPUE	Temperate	420	38	Dudley and Simpfendorfer 2006[84]

Latin name Common name	N°	Start	End	Region of dataset	Data type	Geographical zone	Max. size	GT	References
	12.	1975	2005	Indian Ocean	Standardized CPUE	Temperate	420	38	Braccini and O'Malley 2018[85]
	13.	2006	2015	Indian Ocean	Standardized CPUE	Temperate	420	38	Braccini and O'Malley 2018[85]
Prionace glauca Blue Shark	14.	1971	2013	North Atlantic	Stock assessment	Temperate	380	10	ICCAT 2016[86]
	15.	1971	2013	South Atlantic	Stock assessment	Temperate	380	10	Carvalho and Winker 2015[87]
	16.	1949	2016	Indian Ocean	Stock assessment	Temperate	380	10.5	Rice 2017[88]
	17.	1971	2015	North Pacific	Stock assessment	Temperate	380	10.5	ISC 2017[89]
	18.	1994	2014	South Pacific	Stock assessment	Temperate	380	10.5	Takeuchi et al. 2016[70]
B. Carcharhiniformes: Sphyrnidae									
Sphyrna lewini Scalloped Hammerhead	19.	1995	2017	North Atlantic	Nominal CPUE	Tropical	420	24.1	J.K. Carlson and W.B. Driggers unpubl. data
	20.	1994	2017	North Atlantic	Standardized CPUE	Tropical	420	24.1	J.K. Carlson and W.B. Driggers unpubl. data
	21.	1981	2005	North Atlantic	Stock assessment	Tropical	420	24.1	Jiao et al. 2011[30]
	22.	1978	2003	Indian Ocean	Standardized CPUE	Tropical	420	24.1	Dudley and Simpfendorfer 2006[28]
	23.	1996	2006	South Pacific	Catch	Tropical	420	24.1	Noriega et al. 2011[90]
	24.	1964	2004	South Pacific	Standardized CPUE	Tropical	420	24.1	Simpfendorfer et al. 2010[91]
Sphyrna mokarran Great Hammerhead	25.	1995	2017	North Atlantic	Nominal CPUE	Tropical	610	24.75	J.K. Carlson and W.B. Driggers unpubl. data
	26.	1994	2017	North Atlantic	Standardized CPUE	Tropical	610	24.75	J.K. Carlson and W.B. Driggers unpubl. data
	27.	1981	2005	North Atlantic	Stock assessment	Tropical	610	24.75	Jiao et al. 2011[30]
	28.	1978	2003	Indian Ocean	Standardized CPUE	Tropical	610	23.7	Dudley and Simpfendorfer 2006[28]
Sphyrna zygaena Smooth Hammerhead	29.	1981	2005	North Atlantic	Stock assessment	Tropical	400	24.1	Jiao et al. 2011[30]
	30.	1992	2017	North Atlantic	Standardized CPUE	Tropical	400	24.1	J.K. Carlson US pelagic fisheries unpubl. data
	31.	1978	2014	Indian Ocean	Nominal CPUE	Tropical	400	24.1	Dicken et al. 2018[92]
	32.	1950	2009	South Pacific	Standardized CPUE	Tropical	400	24.1	Reid et al. 2011[93]
C. Lamniformes: Alopiidae									
Alopias pelagicus Pelagic Thresher	33.	1967	1987	Indian Ocean	Nominal CPUE	Tropical	365	18.5	E. Romanov unpubl. data, Southern Scientific Research Institute of Marine Fisheries and Oceanography, Kerch, Crimea.
	34.	1996	2014	North and South Pacific	Standardized CPUE	Tropical	365	18.5	Rice et al. 2015[74,†]
Alopias superciliosus Bigeye Thresher	35.	1992	2013	North Atlantic	Standardized CPUE	Tropical	484	18.5	Young et al. 2016[94]
	36.	1966	1986	Indian Ocean	Nominal CPUE	Tropical	484	18.5	E. Romanov unpubl. data, Southern Scientific Research Institute of Marine Fisheries and Oceanography, Kerch, Crimea.
	37.	1995	2014	North and South Pacific	Standardized CPUE	Tropical	484	18.5	Fu et al. 2018[95]

Latin name **Common name**	**N°**	**Start**	**End**	**Region of dataset**	**Data type**	**Geographical zone**	**Max. size**	**GT**	**References**
Alopias vulpinus Common Thresher	38.	1992	2013	North Atlantic	Standardized CPUE	Temperate	573	25.5	Young et al. 2016[94]
	39.	1981	2013	North Pacific	Nominal CPUE	Temperate	573	25.5	Teo et al. 2016[96]
D. Lamniformes: Lamnidae									
Carcharodon carcharias White Shark	40.	1961	2008	North Atlantic	Standardized relative abundance	Temperate	640	53	Curtis et al. 2014[48]
	41.	1961	2010	North Atlantic	Standardized relative abundance	Temperate	640	53	Curtis et al. 2014[48]
	42.	1978	2012	Indian Ocean	Standardized CPUE	Temperate	640	53	Dudley and Simpfendorfer 2006[28]
	43.	1980	2010	North Pacific	Nominal CPUE	Temperate	640	53	Dewar et al. 2013[97]
	44.	1950	2009	South Pacific	Standardized CPUE	Temperate	640	53	Reid et al. 2011[93]
Isurus oxyrinchus Shortfin Mako	45.	1950	2017	North and South Atlantic	Stock assessment	Temperate	445	25	ICCAT 2019[27]
	46.	1971	2015	Indian Ocean	Preliminary stock assessment	Temperate	445	24	Brunel et al. 2018[98]
	47.	1975	2016	North Pacific	Stock assessment	Temperate	445	24	ISC 2018[99]
	48.	1995	2013	South Pacific	Standardized CPUE	Temperate	445	24	Francis et al. 2014[100]
Isurus paucus Longfin Mako	49.	1992	2015	North Atlantic	Standardized CPUE	Tropical	427	25	J.K. Carlson US pelagic fisheries unpubl. data
Lamna nasus Porbeagle	50.	1926	2009	North Atlantic	Stock assessment	Temperate	357	19.5	ICCAT 2010[101]
	51.	1961	2009	North Atlantic	Stock assessment	Temperate	357	19.5	ICCAT 2010[101]
	52.	1962	2009	North Atlantic	Stock assessment	Temperate	357	19.5	Campana et al. 2013[102]
	53.	1962	2015	South Atlantic, South Pacific and Indian Ocean	Stock assessment	Temperate	233	38.25	Hoyle et al. 2017[103]
D. Myliobatiformes: Dasyatidae									
Pteroplatytrygon violacea Pelagic Stingray	54.	2004	2015	North Atlantic	Standardized CPUE	Temperate	90*	6.5	J.K. Carlson US pelagic fisheries unpubl. data
E. Myliobatiformes: Mobulidae									
Mobula alfredi Reef Manta Ray	55.	2003	2018	Indian Ocean	Nominal SPUE	Tropical	500*	29	A. Marshall Marine Megafauna Foundation unpubl data.
Mobula birostris Giant Manta Ray	56.	2003	2018	Indian Ocean	Nominal SPUE	Tropical	700*	29	A. Marshall Marine Megafauna Foundation unpubl data.
Mobula kuhlii Shortfin Devilray	57.	2003	2018	Indian Ocean	Nominal SPUE	Tropical	135*	12.8	A. Marshall Marine Megafauna Foundation unpubl data.

Table S2. IUCN Red List Status of the 18 oceanic sharks and rays.

CR, Critically Endangered; EN, Endangered; VU, Vulnerable; NT, Near Threatened; LC, Least Concern.

*Retrospective Red List assessment based on 2018 IUCN Species Survival Commission Shark Specialist Group workshop participants' expert judgement (blue when no assessment was available and green when assessment(s) was available).

[1] Previous assessment(s) refers to a different species concept.

Latin name **Common name**	**IUCN Red List Status**			**Red List Status for RLI**		
	Pre2000s	**2000s**	**2010s**	**1980***	**2005**	**2018**
A. Carcharhiniformes: Carcharhinidae						
Carcharhinus falciformis Silky Shark		LC$_{2000}$; NT$_{2007}$	NT$_{2015}$; VU$_{2017}$	NT	NT	VU
Carcharhinus galapagensis Galapagos Shark		NT$_{2003}$	LC$_{2018}$	LC	LC*	LC
Carcharhinus longimanus Oceanic Whitetip Shark		NT$_{2000}$; VU$_{2006}$	CR$_{2018}$	VU	VU	CR
Carcharhinus obscurus Dusky Shark	EN$_{1996}$	NT$_{2000}$; VU$_{2007}$	EN$_{2018}$	LC	VU	EN
Prionace glauca Blue Shark		NT$_{2000}$; NT$_{2005}$	NT$_{2018}$	LC	NT	NT
B. Carcharhiniformes: Sphyrnidae						
Sphyrna lewini Scalloped Hammerhead		NT$_{2000}$; EN$_{2007}$	CR$_{2018}$	VU	EN	CR
Sphyrna mokarran Great Hammerhead		DD$_{2000}$; EN$_{2007}$	CR$_{2018}$	VU	EN	CR
Sphyrna zygaena Smooth Hammerhead		NT$_{2000}$; VU$_{2005}$	VU$_{2018}$	NT	VU	VU
C. Lamniformes: Alopiidae						
Alopias pelagicus Pelagic Thresher		VU$_{2004}$	EN$_{2018}$	VU	VU	EN
Alopias superciliosus Bigeye Thresher		VU$_{2007}$	VU$_{2018}$	VU	VU	VU
Alopias vulpinus Common Thresher		DD$_{2000}$; DD$_{2002}$; VU$_{2007}$	VU$_{2018}$	VU	VU	VU
D. Lamniformes: Cetorhinidae						
Cetorhinus maximus Basking Shark	VU$_{1996}$	VU$_{2000}$; VU$_{2005}$	EN$_{2018}$	EN	EN*	EN
E. Lamniformes: Lamnidae						
Carcharodon carcharias White Shark	VU$_{1996}$	VU$_{2000}$; VU$_{2005}$	VU$_{2018}$	VU	VU	VU
Isurus oxyrinchus Shortfin Mako		NT$_{2000}$; VU$_{2004}$	EN$_{2018}$	LC	VU	EN
Isurus paucus Longfin Mako		VU$_{2006}$	EN$_{2018}$	LC	VU	EN

Latin name Common name	IUCN Red List Status			Red List Status for RLI		
	Pre2000s	2000s	2010s	1980*	2005	2018
Lamna ditropis Salmon Shark		DD$_{2000}$; LC$_{2008}$	LC$_{2018}$	LC	LC	LC
Lamna nasus Porbeagle	VU$_{1996}$	NT$_{2000}$; VU$_{2006}$	VU$_{2018}$	VU	VU	VU
F. Lamniformes: Megachasmidae						
Megachasma pelagios Megamouth Shark		DD$_{2000}$; DD$_{2005}$	LC$_{2015}$	LC	LC*	LC
G. Lamniformes: Odontaspididae						
Odontaspis noronhai Bigeye Sand Tiger		DD$_{2000}$; DD$_{2005}$	LC$_{2018}$	LC	LC*	LC
H. Lamniformes: Pseudocarchariidae						
Pseudocarcharias kamoharai Crocodile Shark		NT$_{2000}$; NT$_{2005}$	LC$_{2018}$	LC	LC*	LC
I. Orectolobiformes: Rhincodontidae						
Rhincodon typus Whale Shark	DD$_{1996}$	VU$_{2000}$; VU$_{2005}$	EN$_{2016}$	LC	VU	EN
J. Myliobatiformes: Dasyatidae						
Pteroplatytrygon violacea Pelagic Stingray		LC$_{2007}$	LC$_{2018}$	LC	LC	LC
K. Myliobatiformes: Mobulidae						
Mobula alfredi Reef Manta Ray		VU$_{2010}$	VU$_{2018}$	LC	VU	VU
Mobula birostris Giant Manta Ray		VU$_{2000}$	EN$_{2018}$	LC	VU	EN
Mobula eregoodoo Longhorned Pygmy Devilray			EN$_{2018}$	LC	VU^{*,1}	EN
Mobula hypostoma Atlantic Devilray		DD$_{2008}$	EN$_{2018}$	LC	VU*	VU
Mobula kuhlii Shortfin Devilray		DD$_{2007}$	EN$_{2018}$	LC	VU*	EN
Mobula mobular Giant Devilray			EN$_{2018}$	LC	VU^{*,1}	EN
Mobula munkiana Pygmy Devilray		NT$_{2006}$		LC	NT	VU
Mobula tarapacana Sicklefin Devilray		DD$_{2006}$	VU$_{2016}$; EN$_{2018}$	LC	NT*	EN
Mobula thurstoni Bentfin Devilray		NT$_{2006}$	NT$_{2016}$; EN$_{2018}$	LC	VU*	EN

Table S3. Description of the 15 stock assessment outputs of 8 species used in the Figure 6 and Extended Figure 11.

MSY: Maximum Sustainable Yield

SSB: Stock Spawning Biomass

B: Biomass

N: Abundance

*no global fishing mortality trajectory was available for this stock assessment.

The Blue Shark stock assessment[70] couldn't be included because no estimates of MSY-related quantities were possible.

Genus	species	Type	References	Source
Carcharhinus	*longimanus*	SSB/SSB_{MSY}	Tremblay-Boyer et al. 2019[55]; Mean weighted run between all models	Given by Tremblay-Boyer
Carcharhinus	*obscurus*	$SSFec/SSFec_{MSY}$	SEDAR 2016[26]; Base run page 42 table 3.7	From report
Isurus	*oxyrinchus*	B/B_{MSY}	Brunel et al. 2018[98]; page 14 figure 6 (panel B and C)	From report
Isurus	*oxyrinchus*	$SSFec/SSFec_{MSY}$	ICCAT 2019[27]; base 3; run 3	From report
Isurus	*oxyrinchus*	SSB/SSB_{MSY}	ISC 2018[99]; page 82 figure 15 (black line/blue line); modeling period (1975-2016)	From report
Lamna	*nasus*	SSN/SSN_{MSY}	Campana et al. 2013[102]*; page 38 table 12 and page 35 table 9; model 1	From report
Lamna	*nasus*	B/B_{MSY}	ICCAT 2010[101]; page 1996 figure 23; C; NeastEAtl	From report
Lamna	*nasus*	B/B_{MSY}	ICCAT 2010[101]; page 1992 figure 17; D; NWestAtl	From report
Prionace	*glauca*	B/B_{MSY}	Carvalho et al. 2015[87]; Run 2	Given by Winker
Prionace	*glauca*	SSF/SSF_{MSY}	ICCAT 2016[86]; page 35 figure 13 and figure 14; Run 6	From report
Prionace	*glauca*	SSB/SSB_{MSY}	ISC 2017[89]; Reference case model	Given by Winker
Prionace	*glauca*	SB/SB_{MSY}	Rice et al. 2017[88]	Given by Winker
Sphyrna	*lewini*	N/N_{MSY}	Jiao et al. 2011[30]; Average between all 7 models	Given by Jiao
Sphyrna	*mokarran*	N/N_{MSY}	Jiao et al. 2011[30]; Average between all 7 models	Given by Jiao
Sphyrna	*zygaena*	N/N_{MSY}	Jiao et al. 2011[30]; Average between all 7 models	Given by Jiao

Supplementary Discussion 1

Are steep declines of devil rays in Mozambique the exception or a window on the history of exploitation?

Over the past decade or so, steep declines in devilrays have been recorded by scientists in many countries[104]. A key discussion point at the IUCN Red List workshop was whether these declines are unique, one-off occurrences or whether they are the synecdoche — the part that reflects the whole. Mozambique and Sri Lanka both recently came out of longstanding civil wars — Mozambique (spanning 1977 to 1992), Sri Lanka (1983 to 2009). Fishing and international trade was limited during these conflicts but rapidly resumed and expanded once the conflicts ceased[105]. Hence, both places have only relatively recently seen improved access to fishing gears that allow incidental capture of these large oceanic rays and, to some degree, exposure to industrialized fisheries and to the growing Chinese market demand for highly valued gill plates. Consequently, a range of devil ray species were subject to target and by-catch fisheries in both countries[106,107]. The participants felt that a valid working hypothesis was that steep declines in these two countries occurred at a time sufficiently recent to have been observed and tracked by local scientists. The rapidity of decline in Mozambique given limited fishing effort, coupled with ongoing declines in Sri Lanka as catching intensity grows, suggests that similar steep declines may have occurred in other Indian Ocean countries a decade or two previously, prior to scientific observation of these species and their fisheries[108,109]. These declines also match declines reported in other areas with intense fishing pressure, like Indonesia[106,110]. There are plenty of anecdotal clues from other regions that suggest that populations of devil rays have declined in similar ways in other areas as well, but these most recently studies have been documented more comprehensively. One way to test this hypothesis would be to undertake traditional ecological knowledge surveys of the occurrence of species aggregations, the timing of appearance of gillnets, and the start of gill plate exports resulting in the onset of fisheries targeting and retaining bycatch of these species around the Indian Ocean[106,107].

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