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Available at: https://doi.org/10.1038/s41586-019-1444-4

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Industrialised fishing of the high seas (areas beyond national jurisdiction) is a major source of mortality to marine megafauna\textsuperscript{1-3}. Effective management and conservation of highly migratory species in the high seas depends on resolving overlap between animal movements and distributions and fishing effort across far-reaching population ranges\textsuperscript{4,5}. Yet, this information at a global scale is lacking\textsuperscript{1,5,6}. Here we show, based on a unique big-data approach combining satellite-tracked movements of 1,681 pelagic sharks (23 species) and global fishing fleets, that 45\% of space used by sharks in an average year falls under the footprint of pelagic longline fisheries, the gear type catching most pelagic sharks\textsuperscript{5,6}. Strikingly, monthly shark-longline overlap remained high at 40\%, indicating significant overlap in both space and time. Space use hotspots of commercially valuable species had the highest overlap with longlines (80–94\%) and were also associated with significant increases in fishing effort and capture-induced shark mortality compared to other species\textsuperscript{7,8}, either because fisheries directly target sharks or sharks occupy habitats of targeted fish stocks. Protected species within some national jurisdictions and on the high seas overlapped longline fisheries by >80\%, emphasising the continued need for management measures that minimise bycatch of the most threatened species. Only a few large-scale hotspots of shark distribution occurred in areas generally free from industrial fishing, with some typically associated with effective local management. We conclude that pelagic sharks have limited spatial refuges from current levels of fishing effort on the high seas. These results demonstrate an urgent need for conservation measures at high-seas shark hotspots and highlight the potential of simultaneous satellite surveillance of megafauna and fishers as a tool for near–real time, dynamic management of marine megafauna.

Humans have hunted large marine animals (marine megafauna) in open oceans for at least 42,000 years\textsuperscript{9}, however only since the 1950s have the international fishing fleets that target
large, epipelagic fishes spread into the high seas\textsuperscript{10}. Prior to this, highly mobile fishes occupying this environment inhabited a spatial refuge largely free from exploitation, since fishing mostly concentrated on continental shelves\textsuperscript{3,10}. Of the fishes occupying the high seas, pelagic sharks’ movements will likely have a strong impact on their vulnerability to fishing pressure: they are among the widest-ranging of vertebrates, with some species exhibiting annual ocean-basin-scale migrations\textsuperscript{11}, long term trans-ocean movements\textsuperscript{12}, and/or fine-scale site fidelity to preferred shelf and open ocean areas\textsuperscript{5,11,13}. These species account for ~50% of all identified shark catch worldwide in target fisheries or as bycatch\textsuperscript{14}. Regional declines in abundance of pelagic sharks have been reported\textsuperscript{15,16}, but it is unclear whether exposure to high fishing effort extends across ocean-wide population ranges and overlaps areas in the high seas where sharks are most abundant\textsuperscript{5,15}. Conservation of pelagic sharks – which currently have limited high seas management\textsuperscript{14,17,18} – would benefit greatly from a clearer understanding of the spatial relationships between sharks’ preferred habitats and active fishing zones. However, obtaining unbiased estimates of shark and fisher distributions is complicated by the fact that most data on pelagic sharks comes from catch records and other fisheries-dependent sources\textsuperscript{17,18}.

Here, we provide the first global estimate of the extent of space use overlap of marine vertebrates with industrial fisheries. This is based on the analysis of the movements of pelagic sharks tagged with satellite transmitters in the Atlantic, Indian and Pacific oceans, together with fishing vessels monitored globally by the automatic identification system (AIS), developed as a vessel safety and anti-collision system (see Methods). Our study focused on 23 species of large pelagic sharks (median maximum total body length = 3.7 m) that occupy oceanic and/or neritic habitats spanning broad distributions from temperate to tropical waters (Supplementary Table 1). All these species face some level of fishing pressure in coastal, shelf and/or high-seas fisheries, with the International Union for the Conservation of Nature
(IUCN) Red List assessing 26% of the 23 species globally as having ‘near threatened’ status,
48% as ‘vulnerable’ and 17% ‘endangered’ (Supplementary Table 2). Regional fisheries
management organizations (RFMOs) are tasked with management of sharks in high seas
areas, yet little or no management is in place for the majority of species \(^3,5,14-20\)
(Supplementary Table 2).

From 2002–2017 we tagged 1,804 pelagic sharks with satellite transmitters, with 60% of
deployments occurring between 2010 and 2017 (Methods; Extended Data Fig. 1,
Supplementary Tables 3, 4). Eleven of the largest species/taxa groups accounted for 96% of
all tags deployed (blue Prionace glauca; shortfin mako Isurus oxyrinchus; tiger Galeocerdo
cuvier; salmon Lamna ditropis; whale Rhincodon typus; white Carcharodon carcharias;
oceanic whitetip Carcharhinus longimanus; porbeagle Lamna nasus; silky Carcharhinus
falciformis; bull Carcharhinus leucas; and hammerhead Sphyrna spp. sharks)
(Supplementary Table 3). Tracks with daily locations were reconstructed for 1,681
individuals totalling 281,724 tracking days (Methods).

Movement patterns indicated that multiple species aggregated within the same large-scale
areas within an ocean (Fig. 1). Species co-occurred in major oceanographic features, such as
the Gulf Stream (blue, shortfin mako, tiger, white and porbeagle sharks), the California
Current (blue, shortfin mako, white and salmon sharks), and in the East Australian Current
(blue, shortfin mako, tiger, white and porbeagle sharks) (Fig. 1, Extended Data Fig. 2;
Supplementary Results and Discussion 2.1). The global density map reveals distribution
patterns of pelagic sharks and locations of space use hotspots (defined here as those areas
with ≥75\(^{th}\) percentile of weighted daily location density). Implementation of a weighted
spatial density meant individual location estimates closer to a tagging location received a
lower weight than later locations because more sharks had locations earlier in their tracks\(^{13}\),
thus reducing bias (Fig. 2a) (see Methods). Major hotspots of tracked pelagic sharks in the
Atlantic Ocean were in the Gulf Stream and its western approaches, Caribbean Sea, Gulf of Mexico and around oceanic islands such as the Azores (Fig. 2a). In the Indian Ocean, hotspots were evident in the Agulhas Current, Mozambique Channel, the South Australian Basin and northwest Australia, while Pacific hotspots were in the California Current, Galapagos Islands, eastern Equatorial Counter Current, and around New Zealand (Supplementary Table 5). Although tagging sites occurred as expected in some shark space use hotspots – as tagging rates are inherently higher in hotspots – we also identified numerous hotspots where no tagging sites occurred: in the North Atlantic (outer Gulf Stream, Charlie Gibbs Fracture Zone, western European shelf edge and Bay of Biscay); Indian Ocean (Somali Basin, Chagos Archipelago, South Australian Basin); and the Pacific (Alaska Current, outer California Current, white shark ‘Café’ area13, North Equatorial Current, northern East Pacific Rise, Isakov/Makarov Seamounts, Chatham Rise) (Extended Data Fig. 1).

To determine the extent to which shark space use hotspots fall under the footprint of global industrialised fisheries we mapped the movements of fishing vessels carrying AIS transmitters, estimated to be fitted on 50–75% of active vessels >24 m length21. In the context of monitoring fishing activity, there are known disadvantages of using AIS data22 compared to vessel monitoring system (VMS) data; for example, longer gaps in data coverage in space and time23 and the potential for misidentification of fishing activity by different gears21. However, given that VMS data is not widely available, the principal advantage of AIS is as a freely available global dataset of fishing activity that provides a useful and valid starting point for investigating the overlap of shark space use by global fisheries. As a first step we mapped the mean annual fishing effort (days) of 83,628 AIS-equipped fishing vessels using various gear types21 during 2012–2016 (Extended Data Fig. 3; Methods). In addition to using all fishing vessels within the dataset, the estimated global fishing effort of drifting pelagic
longline \((n = 5,565)\) and purse seine vessels \((n = 6,941)\) were mapped separately as these two gears catch the majority of pelagic sharks\(^{14,17}\) (Fig. 2b; Extended Data Fig. 4).

The global distribution map of all vessels’ fishing effort identifies several large-scale, high use areas such as the western European Shelf in the northeast Atlantic, Mediterranean Sea, Patagonian Shelf off Argentina, Peru Current, the Equatorial Pacific region and off China (Extended Data Fig. 3, Supplementary Table 6). There were also areas where industrial fishing activity appeared sparse, for example the central and southwest North Atlantic, northeast Pacific, and northern Indian oceans. To explore the spatial heterogeneities of sharks and vessels we used generalised additive models to determine how shark relative density and fishing effort were affected by environmental covariates (see Methods; Supplementary Table 7). Distributions of pelagic shark density and fishing effort of all vessels, and for pelagic longline vessels separately, were best explained by the same drivers, with all demonstrating strong relationships with habitat types characterised by surface and subsurface temperature gradients (fronts\(^{24}\); thermoclines) and/or high primary productivity (Extended Data Table 1, Extended Data Fig. 5). Relative densities of sharks were higher around ocean areas with specific surface (fronts, ~1.0°C/100 km; and mesoscale eddy edges) and subsurface (thermocline, ~40 m) boundary conditions and moderate chlorophyll-\(a\) concentrations (~0.3 mmol m\(^{-3}\)), a proxy for primary productivity. The same set of environmental covariates best explained distributions of shark densities and fishing effort of all vessels and of longlines only (Supplementary Results and Discussion 2.2). This predicts high spatial overlap because sharks are known to aggregate in biologically productive features like fronts to enhance foraging opportunities\(^{5,6,24}\), a behaviour that fishers exploit to increase their chances of making higher catches of commercially valuable sharks and other epipelagic fishes\(^{5,6}\). For pelagic longliners, national fleets that target sharks for fins and meat (or as targeted bycatch) include China, Taiwan, Spain and Portugal\(^{5,14}\), which comprise 67% of all AIS-tracked
longlining vessels analysed in this study (Extended Data Table 2). Other large national fleets such as the U.S.A., Canada and Japan potentially take shark as unintentional bycatch\(^7\). Hence, two potential explanations for spatial overlap of sharks and fishing vessels include: (i) fishers track sharks (shark habitats) as target species for valuable fins and, for some species, meat, or (ii) sharks occur in similar habitats as fishers because, for example, they have the same target prey (e.g. tunas, billfishes) or prey on the same species that targeted fish also feed upon (e.g. small-bodied schooling fish).

To quantify the actual shark space use occupied by fishing vessels, as indicated by the modelling, we calculated the mean spatial overlap of tracked sharks with fisheries for a mean year within the datasets (Methods). Overlap was defined as shark and vessel spatial co-occurrence within a \(1 \times 1^\circ\) grid cell in an average year, where \(1^\circ\) latitude at the equator (110.6 km) matches the approximate length of high seas longlines, i.e. 100 km long with an average of 1,200 baited hooks\(^5\). Globally, the distribution of industrial fishing activity of all vessels in the dataset overlapped 81% of the space use of tracked sharks at the \(1 \times 1^\circ\) scale (mean overlap = 80.8\% ± 29.9 S.D.; median = 96.2\%, \(n = 1,681\) tracks). Decreasing grid cell size can reduce percentage spatial overlap estimates\(^21\), however although we found the mean overlap at \(0.5 \times 0.5^\circ\) and \(0.25 \times 0.25^\circ\) grid cell sizes decreased as expected, it remained relatively high at 67 and 56\%, respectively (Extended Data Table 3). However, there were large regions of oceans where no or very few sharks were satellite tracked despite high fishing activity, for example the Patagonian Shelf and in the northwest and southeast Pacific Ocean (Extended Data Fig. 3). The northwest Pacific Ocean supports major global fishing-effort hotspots off China and Japan, yet there were very limited shark tracking data in this region. This suggests that either sharks are already in low abundance such that tagging studies are less viable, or, more likely, that transmitters are not available or data cannot be
accessed. This study highlights an urgent need for fishery-independent shark occurrence data, such as from tracking, to underpin spatial risk assessments in global fishing hotspots.

We focused our detailed analysis of shark overlap with that of longline fishing effort, as this gear catches most pelagic sharks globally\(^\text{17}\) and since most AIS fishing vessel gear types represented in the dataset do not target or bycatch sharks\(^\text{21}\). Where we were able to determine shark space use directly using tags, coverage by fisheries was dominated by pelagic longline gear (Fig. 2a, b). The mean spatial overlap between sharks and longline fishing effort was 45% (mean = 44.8% ± 41.4 S.D.; median = 33.7%) at the 1 × 1° grid size (Extended Data Table 2), with the spatial pattern being very similar to that for sharks and all mapped AIS fishing vessels (compare Fig. 2b with Extended Data Fig. 3a). Across four regions where the majority of sharks were tracked, mean spatial overlap of all 11 most frequently tracked species/taxa groups with longline fishing effort ranged from 24% (east Pacific; \(n = 585\) tracks) to 55% (north Atlantic; \(n = 656\) tracks) and 66% (Oceania: Australia, New Zealand, southeast Asia; \(n = 151\) tracks), up to 82% for the southwest Indian ocean (\(n = 114\) tracks) (Extended Data Table 4).

Hotspots of spatial overlap intensity (see Methods) of sharks and longlines were evident in the Gulf Stream and stretching eastward to the Azores, western European shelf edge, west African upwelling, California Current, east of the Galapagos, Agulhas Current, Seychelles archipelago, the southern Great Barrier Reef, and New Zealand shelf waters (Fig. 2c, Supplementary Table 8). Overlap intensity varied across species and among oceans, reflecting the heterogeneous distributions of space use by sharks and longline fishing activity (Extended Data Fig. 6). For example, spatial overlap of sharks and longline fishing effort, averaged across all oceans, ranged from 92% for the porbeagle, down to 11% for the oceanic whitetip shark. Among oceans, the overlap of space use by blue sharks – the pelagic shark
most commonly caught by open-ocean longline fleets\textsuperscript{17} – was 94\% in the North Atlantic, decreasing to 34\% in the east Pacific.

An important question is whether significant areas of the high seas used by pelagic sharks exist that are largely free from AIS-monitored fishing activity of longline and purse seine vessels as these could be targeted for shark conservation measures. Identifying such areas can only be addressed with the fishery-independent distributions presented here. We found some large–scale areas with low overlap between shark space use and fishing effort, e.g. the central and south-western North Atlantic (Fig. 2a, b; Extended Data Fig. 4). Similarly, the high seas in the northeast Pacific, the South Australian Basin, and some waters between Australia and New Zealand supported space use by sharks but sparse AIS fishing vessel activity. Although it is possible longliners and purse seiners were present but not using AIS, low fishing activity also occurred in many of the territorial waters around oceanic islands in the Atlantic, Indian Ocean and Pacific (Fig. 2b), indicating these zones, some of which are marine protected areas (MPAs), may offer some refuge to sharks from AIS-monitored fishing vessels. For example, the Chagos Archipelago (Indian Ocean) was identified as a shark hotspot even though no sharks were tagged there, with this archipelago lying within one of the world’s largest MPAs that has maintained a ban on commercial fishing since 2010. Furthermore, the shark hotspot in the south-western North Atlantic centred in the Caribbean showed very low overlap with AIS vessels, possibly due to the presence of a large MPA (Bahamas) that prohibits pelagic longline fishing\textsuperscript{25} or due to few vessels there using AIS. However, a general characteristic of large areas with low longline fishing activity was also one of lower shark densities (<75\% percentile of relative density; Fig. 2a), indicating sharks were not remaining in these areas but moving through them, potentially as part of foraging excursions or migrations for reproduction\textsuperscript{11,13}. The lower relative density of sharks suggests lower productivity – confirmed by our modelling results (model 1; Extended Data Fig. 5) – and consequently
poorer fishing opportunities, which may explain the low fishing effort. The results also show that very few large hotspots of space use by pelagic sharks occurred in areas free from AIS fishing vessels, particularly longline and purse seine gears (Fig. 2c; Extended Data Fig. 4).

To estimate the potential risk of exposure of sharks in different ocean regions to longline fishing effort, we calculated the fishing effort individual sharks were subjected to on each track day, standardised to account for variations in individual track durations (hereafter termed fishing effort per shark space use) (see Methods). As expected across all oceans and species, longline fishing effort per shark space use was highly variable (mean = 34.7 d ± 125.4 S.D.; median = 8.7 d) (Extended Data Table 3). Given this, we tested whether the mean annual longline fishing effort (2012–2016) overlap with mean annual shark space use (2002–2017) was indicative of actual sharks captured and landed by fisheries. We compared the mean annual longline fishing effort for North Atlantic shark species (the ocean for which we had the most species and tracks) with Food and Agriculture Organization of the United Nations (FAO) officially recorded mean annual North Atlantic landings of those species (2012–2016) (Methods). We found a significant positive relationship between landings and AIS longline effort (linear regression, $r^2 = 0.51$, $n = 9$ species or taxa group, $F = 7.14$, $F_{0.05(1,7)} = 5.59$, $p = 0.032$) (Extended Data Fig. 7), confirming longline fishing effort in shark space use areas reflects major trends in fishing-induced shark mortality.

The extent of spatial overlap between shark distribution and longline fishing effort indicates which species are more exposed to fishing and how this exposure is distributed (Fig. 3). Since actual shark mortality (landings) is related to longline fishing effort in shark space use areas, it follows that sharks exposed to high fishing overlap and effort (greater susceptibility) will be at greater risk of capture than those exposed to low overlap and effort (Fig. 3; Extended Data Table 4). We found the main commercially valuable pelagic sharks were grouped within
the highest potential risk zone in the North Atlantic and east Pacific (blue and shortfin mako
sharks), and in the Oceania region (blue shark) (Fig. 3a,b) (see Supplementary Results and
Discussion 2.3, 2.4 for significance tests and results for other species). In the North Atlantic,
between 79 and 94% of tracked space used by shortfin mako and blue sharks, respectively,
overlapped with longline fisheries, but fishing effort within this overlap was also significantly
greater (means: mako = 12.2 d ± 9.0 S.D.; blue = 14.0 d ± 9.7 S.D.) compared to other
tracked sharks (range, 0.12 – 6.7 d) (Fig. 3a; Extended Data Table 4b; Extended Data Fig. 6).
However, exposure risk varied between oceans because although spatial overlap of shortfin
mako and blue sharks remained relatively high in the east Pacific (~40%), and at 55.7% for
blue shark in Oceania, longline fishing effort was lower there (means: ~1 d in Pacific; 6.6 d
in Oceania) (Fig. 3a,b,d; Extended Data Fig. 6).

Among sharks generally considered less commercially valuable, including tiger and bull
sharks, we found exposure risk to longlines was high in some but not all regions. Bull sharks
used spatially limited areas within southwest Indian Ocean shelf and oceanic island habitats,
and in those areas they were at increased risk due to high average overlap (100%) and fishing
effort (45.6 d) (Extended Data Table 4d; Extended Data Figure 6j). This greater susceptibility
could lead to high localised catches, which, if replicated elsewhere, could explain why bull
sharks are one of the ten most commonly traded species in the Hong Kong fin market26. In
contrast, tiger sharks were exposed to higher than average overlap in the Indian Ocean
(87.3%) and Oceania (63%), but fishing effort overlapping this species was lower than
average in all oceans (Fig. 3a-d; Extended Data Tables 4d, e).

High risk was evident for internationally protected sharks under CITES (Convention on
International Trade in Endangered Species) Appendix II and RFMO regulations. The
porbeagle shark (IUCN Red List ‘endangered’ globally) and the white shark (‘vulnerable’
globally) have low population sizes compared to historic levels (Supplementary Table 2). In the North Atlantic we found an average 97% overlap of porbeagle space use and higher than average fishing effort (6.7 d) (Fig. 3a), indicating high potential for incidental bycatch mortality. We found white sharks in the highest risk zone in all oceans where it was tracked, with mean spatial overlap with longline fisheries ranging from 55% (east Pacific) to 96% (southwest Indian Ocean) and fishing effort in those areas being between 2.7 d (east Pacific) and 17.0 d (southwest Indian Ocean) (Fig. 3a-d; Extended Data Table 4). Our results showing high fishing overlap and effort for porbeagle and white sharks highlight the need for continued protection – including sufficient scientific observer coverage on vessels to underpin accurate data reporting – in the regions we identify where risk is greatest so that stock rebuilding can continue, which for porbeagle is estimated to take a further 30 years.

The highest levels of exposure risk of sharks to longline fisheries were not constant but varied seasonally as shark and fishing vessel space use shifted in relation to each other (Fig. 4; Extended Data Fig. 8). Overall for species with sufficient data (plotted in Fig. 4), the mean monthly overlap of shark space use with longline fishing effort was 40.5% (± 26.9 S.D.; median = 24.2%), similar to the mean annual overlap of 45%. This indicates shark-longline overlap remained relatively high in both space and time. Generally, sharks spent 5–6 months per year in the lowest risk zone and 2–6 months in the highest, with differing patterns of changing exposure to fishing evident across species (Fig. 4). For example, overlap and longline fishing effort for North Atlantic blue and southwest Indian Ocean white sharks both remained relatively high (~60% overlap, ~40 d effort), but with highest risk occurring at discrete times in the year (Extended Data Fig. 9). For Indian Ocean white sharks, this pattern arises from long-range seasonal movements (Feb, Jun/Jul, Oct) into annually persistent areas of high longline fishing effort (>60% overlap, >40 d effort) (Extended Data Fig. 9d). For blue sharks, the discrete pattern appears driven by sharks and longline vessels co-occurring...
maximally in boreal winter and summer, with lower exposure risk occurring in boreal spring
and autumn as sharks migrate north before returning south\(^5\). Longline fisheries also made this
seasonal south-north-south movement, but lagging behind movements of blue sharks, thus
lower overlap and effort during those times (Extended Data Fig. 9a). Similarly, annual risk
patterns of east Pacific white and Australian tiger sharks were driven by migratory behaviour,
with highest risk (~20% overlap, ~10 d effort) occurring for three consecutive months in
boreal (white) and austral (tiger) spring as sharks arrive in areas with higher longline fishing
effort (Extended Data Fig. 9c,e). In contrast, shortfin mako sharks in the North Atlantic were
exposed to high overlap (>55%) and effort (>32 d) continually through the boreal summer
and autumn (Jun–Nov), principally due to occupation of a space use hotspot located where
the Gulf Stream and Labrador Current converge that results in persistent high overlap with
high longline fishing effort (Fig. 4b; Extended Data Fig. 9b). Shortfin mako and vessel
tracking indicates that fishery-induced mortality within this hotspot is therefore likely to be
high. This was confirmed by the high return rate of satellite tags (19.3%) attached to Atlantic
shortfin makos \((n = 119 \text{ tags}; \text{ tracking duration: mean } \pm \text{ SD} = 161.5 \text{ d } \pm 156.9; \text{ median } = 109\)
d) that were returned to us after sharks were captured by Atlantic longline fishing vessels. To
our knowledge, this is the highest species-specific return rate yet recorded in an ocean scale,
as opposed to regional scale, study\(^7,8\) (Fig. 2c; Extended Data Table 5; Supplementary Results
and Discussion 2.4).

High fishing effort focused on extensive shark hotspots of commercially valuable species
raises particular concern. There is limited high seas management for commercial species,
including blue and shortfin mako sharks\(^5,20\). The results from AIS indicate a high probability
of overexploitation of commercial species as high seas space use hotspots are exposed to high
fisheries overlap across their ranges for significant periods of a year (Extended Data Figs. 6,
Overall, this pattern suggests a future with limited spatial refuge from industrial longline fishing effort that is currently centred on ecologically important shark hotspots.

The patterns of high overlap and fishing effort observed for sharks suggest different mechanisms driving shark fishing hotspots. The high overlap and fishing effort observed in commercially important shark hotspots, together with high catches (landings), support the explanation that fishers track sharks. For example, North Atlantic blue and shortfin mako sharks are known target species of Chinese, Spanish and Portuguese longlining fleets (Extended Data Table 2). However, this is not necessarily the case for all global hotspots. Internationally protected species such as the white shark was subject to high overlap and effort in the North Atlantic, southwest Indian, and northeast and southwest Pacific oceans despite no target fisheries. This indicates that high overlap is due to white sharks co-occurring in habitats of target fish species (e.g. tunas) that fishers track.

Our results show that globally important habitat areas for threatened pelagic sharks overlap significantly with industrial fishing activity in both space and time. Given the high fishing effort in hotspots of many species for significant portions of the year, and the very few tracked hotspots free from exploitation, our study reveals exposure risk of sharks to fisheries in the high seas is spatially extensive – stretching across entire ocean-scale population ranges for some species. The distribution maps reported here are, therefore, a first but essential underpinning for a conservation blueprint for pelagic sharks in this high seas habitat. Our study highlights the scale of fishing overlap with shark hotspots and argues for more effective and timely monitoring, reporting and management of pelagic sharks as a result. To enhance the recovery of vulnerable species, one solution is designation of large-scale MPAs around ecologically important space use hotspots of pelagic sharks, notwithstanding the need for more complete reporting of catch data to support stricter conventional management by catch
prohibitions or quotas. This study outlines shark hotspot locations where fishing effort is currently relatively low, which is where shark conservation could be maximized, while minimizing impact on fishing activity not directed at sharks. Although the legal framework remains challenging to develop a legally binding treaty for managing high seas fauna, burgeoning technology for global surveillance and enforcement now offers valuable additional options for a step change in ocean management.

Satellite monitoring of ocean-scale movements by marine megafauna, oceanographic features (eddies, fronts) and global fishing vessel distributions could provide signals of shifting space use by megafauna due to environmental changes that, in turn, could inform designation of new temporary time-area closures to industrial fishing and tracking of fishers’ displacement activities. The potential of AIS as a global fisheries and conservation management tool suggests that, given the remoteness and vast extent of the high seas, if we are to reverse the observed declines and so rebuild populations of iconic ocean predators such as pelagic sharks, technology-led conservation measures – conservation technology – will be crucial in addition to conventional management methods. Conservation technology could evolve in the future toward incorporation of adaptive management strategies that are actionable in real time. The rapid development of autonomous vehicles has created a need to develop machine-learning real-time assessments of risks, developments that can be readily transposed to assess risks in the overlap between fishing vessels and sharks across the global ocean.


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**Acknowledgements.** We thank all involved with the many aspects of fieldwork and data collection; full details are given in the *Supplementary Information*. Data analysis was funded by the Marine Biological Association (MBA) and the UK Natural Environment Research Council (NERC) (NE/R00997X/1) (to D.W.S.), with additional research support from the Save Our Seas Foundation and the NERC Oceans 2025 Strategic Research Programme in which D.W.S. was a principal investigator. D.W.S. was supported by an MBA Senior Research Fellowship, N.Q. by European Regional Development Fund (FEDER) via the Programa Operacional Competitividade e Internacionalização (COMPETE), National Funds via Fundação para a Ciência e a Tecnologia (FCT) under PTDC/MAR/100345/2008 and COMPETE FCOMP-01-0124-FEDER-010580 (to N.Q. and D.W.S.), Norte Portugal Regional Operational Programme (NORTE 2020) under the PORTUGAL 2020 Partnership Agreement through the European Regional Development Fund (ERDF) under project MarInfo (NORTE-01-0145-FEDER-000031), an FCT Investigator Fellowship IF/01611/2013 (N.Q.), FCT Doctoral Fellowship PD/BD/52603/2014 (M.V.), and A.M.M.S. was supported by ARC grant DE170100841 and operational funds from the Australian Institute for Marine Science (AIMS). The Tagging of Pacific Predators programme and Global Fishing Watch are thanked for making their data freely available. We thank Marc Dando for creating the shark images. This research contributes to the Global Shark Movement Project (GSMP) and the Marine Megafauna Movement Analytical Program.
**Author Contributions.** GSMP was coordinated by D.W.S. N.Q. and D.W.S. conceived the study, N.Q., N.E. Humphries and D.W.S. designed the study, and all authors contributed to animal tagging, fieldwork, data collection and/or contribution of tools; full details given in *Supplementary Information*. N.Q., N.E. Humphries, A.C., M.V., I.C., A.M.M.S., L.L.S., S.J.S. and D.W.S. analysed collated data. D.W.S. drafted the paper with contributions from N.Q., N.E. Humphries and A.M.M.S. All authors contributed to subsequent drafts.
Fig. 1. Movements of oceanic and neritic pelagic sharks. (a) Daily state-space model locations estimates from raw locations relayed by satellites from transmitters deployed on 1,681 sharks from 23 species between 2002–2017. Extent of individual shark species space-use areas are illustrated for blue *Prionace glauca* (b), shortfin mako *Isurus oxyrinchus* (c), tiger *Galeocerdo cuvier* (d), white *Carcharodon carcharias* (e) and whale *Rhincodon typus* sharks (f). Shark images created by M. Dando.
Fig. 2. Spatial distributions and overlap intensity of sharks and longline fishing vessels.

(a) Distribution of the weighted, normalized location density of ≥75th percentile (relative density) of tracked sharks in 1 × 1° grid cells. (b) Mean annual distribution of fishing effort (mean days per grid cell) of AIS tracked longlining vessels in 2012–2016 (see Methods). (c) Distribution of the overlap intensity between shark density and longline fishing effort (spatial co-occurrence within 1 × 1° grid cells). Spatial overlap intensity hotspots were defined as 1 ×
1° grid cells with ≥75% overlap. Blue circles denote locations where tagged sharks were caught by commercial fishers.
**Fig. 3. Estimated exposure risk of sharks to capture by longline fishing activity.** Plots (left) showing shark-longline vessel spatial overlap against longline fishing effort per shark space use indicate species subject to high overlap and fishing effort (higher than average overlap and effort; higher risk red zone on plot) and those with lower overlap and effort (lower than average overlap and effort; lower risk green zone) for (a) North Atlantic, (b)
eastern Pacific and (c) southern Indian oceans, and (d) for the Oceania region. Lines separating the coloured zones are fixed at the average values of spatial overlap (y axis) and fishing effort per shark space use (x axis) for all species combined. For each ocean, relative density distributions of selected shark species (middle map panels) are shown in comparison to where overlap intensity hotspots of shark-longline vessels occur (map panels on right; see Methods for details). Shark species identification codes (e.g. PGL) used on panels are given in Fig. 1. Error bars denote ± one standard deviation of the mean. Shark images created by M. Dando.
Fig. 4. Temporal changes in shark exposure risk to longline fishing. Mean annual shark-longline vessel spatial overlap versus longline fishing effort for the four most data-rich species: (a) blue, (b) shortfin mako, (c, d) white, and (e) tiger sharks. Lines separating the coloured zones are fixed at the respective species average values of spatial overlap (y axis) and fishing effort per shark space use (x axis). Horizontal bars denote months in different
fishing exposure risk zones (red, highest risk; green, lowest). Error bars denote ± one standard deviation of the mean. Shark images created by M. Dando.
Methods

Study animals and tagging. Satellite transmitter tags were attached to 1,804 large pelagic sharks at multiple tagging sites in the Atlantic, Indian and Pacific oceans (Extended Data Fig. 1). The number of tagged individuals varied among species and ranged from one to 280. Two satellite-transmitter tag types (ARGOS, advanced research and global observation satellite transmitter; and PSAT, pop-off satellite-linked archival transmitter) were used. Sharks were either captured with baited hooks (longlines, rod-and-line angling, or with handlines), in purse seine during commercial fishing operations, or tagged free-swimming in the water. Tags were attached to the first dorsal fin or in the dorsal musculature. All animal handling procedures were approved by institutional ethical review committees and completed by trained personnel. Data were provided by the 37 data owners to the senior author and quality checked prior to archiving in a database. Poor quality data were reported for 123 tags (72 ARGOS and 51 PSAT) due to, for example, early tag failure, premature tag pop-off, and/or a high percentage of locations estimated with high spatial error, e.g. raw computed geolocations over land, all of which resulted in poor state-space model fits leading to short or unreliable track reconstructions. Hence, analyses were restricted to the remaining 1,681 tracks from 1,066 ARGOS and 615 PSAT tags on sharks from 23 species ranging in duration per species from 20 to 57,037 days with a median of 4.1 years total track time per species (Supplementary Table 3). The number of sharks tracked within each region is given in Supplementary Table 9.

Track processing. Movements of PSAT-tagged sharks were estimated using either satellite-relayed data from each tag or from archival data after the tags were physically recovered. Data were provided as: (i) raw shark positions that were previously reconstructed using software provided by the tag manufacturers (e.g. Wildlife Computers, Redmond, USA; Microwave Telemetry, USA), where daily maximal rate-of-change in light intensity was used
to estimate local time of midnight or midday for longitude calculations, and day-length estimation for determining latitude\textsuperscript{31,32}; or (ii) filtered positions where a state-space model (SSM) (unscented Kalman filter with sea surface temperature, UKFSST)\textsuperscript{33} had been applied to correct the raw geolocation estimates and obtain the most probable track. In the first case, raw positions were corrected using the UKFSST SSM (UKFSST R package) in addition to a bathymetric correction applied to the initial Kalman position estimates (analyzepsat R add-on). A daily time-series of locations was estimated using a continuous-time correlated random walk (CTCRW) Kalman filter\textsuperscript{34} (crawl R package). UKFSST geolocations were parameterised with standard deviation (SD) constants (K) which produces the smallest mean deviation from concurrent Argos positions\textsuperscript{35}. In the latter case, the CTCRW filter was applied to produce regular time-series.

For ARGOS transmitter tags, data were provided as raw ARGOS (Doppler frequency shift) position estimates. Location class (LC) Z data – assigned for a failed attempt at obtaining a position – were discarded from the dataset. The remaining raw position estimates (LC 3, 2, 1, 0, A and B) were analysed point-to-point with a 3 m s\textsuperscript{-1} speed filter to remove outlier locations. Subsequently, the CTCRW SSM was applied to each individual track, producing a single position estimate per day. ARGOS positions were parameterised with the K error model parameters for longitude and latitude implemented in the crawl R package\textsuperscript{34}.

Shark tracking data from the Tagging of Pacific Predators (TOPP) program were downloaded from the Animal Tracking Network (ATN) hosted by the Integrated Ocean Observing System (<https://ioos.noaa.gov/project/atan/>; downloaded September 2017). Both ARGOS and light-based geolocation data in ATN had already been filtered with a Bayesian based SSM\textsuperscript{36}. Briefly, the SSM was fitted to each track individually, using the WinBUGS software that conducts Bayesian statistical analyses using Markov chain Monte Carlo (MCMC) sampling\textsuperscript{37}. For each track, two MCMC chains each of length 10,000 were run and a sample of 2,000
from the joint posterior probability distribution was obtained by discarding the first 5,000
iterations and retaining every 5\textsuperscript{th} of the remaining iterations. SSM fits were posteriorly
inspected for obvious problems (e.g. unrealistic movements\textsuperscript{13}). Because two different SSMs
were applied to data used in this study, we tested for possible biases in the spatial density
analysis (see below) by comparing $1 \times 1^\circ$ density grid maps obtained with both UKFSST and
Bayesian-based filtered tracks using a subset of 83 ARGOS-linked tracks in the North
Atlantic (blue shark, $n = 27$; mako, $n = 42$; white, $n = 3$; oceanic whitetip, $n = 11$).
Differences in spatial grid density between the two methods were negligible (Supplementary
Fig. 1).

**Spatial density analysis.** To obtain unbiased estimates of shark spatial density, gaps between
consecutive dates in the raw tracking data were interpolated to one position per day. The
frequency of long temporal gaps in a reconstructed track can result in extensive interpolated
movements driven by the underlying random walk model rather than a shark’s movement
pattern\textsuperscript{13}. Although the frequency of long temporal gaps (>20 days) in our dataset was low
(Supplementary Table 10), nonetheless, any tracks with gaps exceeding 20 d were split into
segments prior to interpolation, thus avoiding the inclusion of unrepresentative interpolated
location estimates\textsuperscript{5}. Similarly, location estimates derived for periods exceeding 20 d were
also discarded from TOPP data\textsuperscript{13}.

To account for biases in spatial density associated with (i) variable track lengths and (ii)
shorter tracks near the tagging location, a weighting procedure was applied\textsuperscript{13} and data were
normalised to account for unequal sample sizes across species. Briefly, each daily location
estimate was weighted by the inverse number of individuals of a given species with location
estimates for the same relative day. Periods with gaps >20 d were not included when
weighting the locations. After the 85\textsuperscript{th} percentile of the track length, daily weights were fixed.
Under this weighting scheme, individual location estimates closer to the tagging location
received a lower weight than later locations because more sharks had locations earlier in their tracks. Also, longer tracks received a higher total weight than shorter tracks because of the higher number of locations received. Therefore, calculated spatial densities were more representative of the actual distributions and less affected by tag loss, failure or a spatial bias towards deployment location. Total weights for each species were normalised to one so that within the study area each species contributed equally to the density patterns. Species with comparatively very low numbers of tracks were grouped and treated as one (these were: *C. galapagensis, C. limbatus, A. vulpinus, A. pelagicus, O. ferox, C. brachyurus, C. obscurus, N. cepedianus* and *C. plumbeus*). Hammerhead (3 species) and mako (2 species) shark species were also clustered and analysed as taxa groups, *Sphyrna* spp. and *Isurus* spp., respectively. Spatial densities (overall averages) were calculated for all species together (Fig. 2a) and per species at a 1 × 1° grid cell resolution (Extended Data Fig. 6).

**Fishing vessel geolocation data.** The automatic identification system (AIS) was developed as a vessel safety and anti-collision system with global coverage, rather than to track fishing vessels for fishery management purposes\(^\text{21-23}\). However, its global coverage of locations of many thousands of ships through time enables fishing effort distribution to be analysed\(^\text{21,22}\). Here, fishing effort (hours of fishing) data gridded at 0.01° by flag state and gear type were obtained from Global Fishing Watch (GFW) (available at <http://globalfishingwatch.org/datasets-and-code/fishing-effort/>). GFW used raw AIS vessel tracking data obtained from ORBCOMM via their AIS-enabled satellite constellation (<https://www.orbcomm.com/eu/networks/satellite-ais>) to calculate fishing effort and derive the gridded data, described in detail in Kroodsma *et al.*\(^\text{21}\). Briefly, GFW uses two neural network algorithms to categorize different types of fishing gear, e.g. drifting longlines, purse seines, in addition to estimating the spatio-temporally resolved locations where fishing gears were most likely deployed by individual vessels\(^\text{21,38}\). We used the GFW gridded fishing effort
data in the years 2012 to 2016 for all gear types, and for drifting pelagic longlines and purse
seines. For each type, we summed the number of days fishing in a year within each 1 × 1°
grid cell and averaged across years. For the seasonal analysis, we summed the number of
days fishing in each month within each 1 × 1° grid cell and averaged across years. Global
distributions of fishing effort for all gear types, longlines and purse seines were mapped
separately and overlaid by shark relative spatial density to determine spatial overlap intensity
at the global and ocean scale, and for each species per ocean. AIS data coverage increased
from 2012 to 2016 as more satellite AIS receivers were launched and commenced
operation21. However, the global spatial distribution of longline vessel fishing effort was
broadly similar across years (Extended Data Fig. 10) and variation in annual maximum
fishing effort displayed no increasing trend over time, indicating our calculated mean annual
fishing effort for 2012–2016 did not overestimate spatial overlap or fishing effort but can be
considered conservative (Extended Data Fig. 10).

**Shark and fishing effort environment modelling.** To model shark and fishing vessel
distributions in relation to environmental variables, data were extracted from online databases
(Supplementary Fig. 2). The environmental variables were selected based upon their
demonstrated importance in affecting shark occurrence and included: (i) sea water
temperature (°C) (abbreviation used in models: sea surface temperature, SST; temperature at
100 m, TEM_100) known to influence the presence of many pelagic shark species5,13; (ii)
maximum thermal gradient (°C/100 km) (TGR) influences shark spatial density5, and was
calculated here based on the SST data and using maximum gradient maps by calculating
where for each pixel a geodetic–distance-corrected maximum thermal gradient was
calculated; (iii) sea water salinity (psu) (SAL), an important determinant of habitat use in
some sharks1,38; (iv) sea surface height above geoid (m) (SSH) that influences shark
presence5 and catches by fisheries6; (v) ocean mixed layer depth thickness or thermocline


depth (m) (MLD) that affects pelagic shark foraging behaviour\textsuperscript{39}; (vi) mass concentration chlorophyll \textit{a} in sea water (mmol m\textsuperscript{-3}) (CHL) as a proxy for productivity that often characterises preferred habitats of sharks\textsuperscript{5,39}; (vii) mole concentration of phytoplankton expressed as carbon in sea water concentration (mmol m\textsuperscript{-3}) (PHY) as a direct measure of productivity; (viii) net primary production of biomass expressed as carbon per unit volume in sea water (g m\textsuperscript{-3}/day) (NPP) quantifying productivity; and (ix) mole concentration of dissolved molecular oxygen in sea water (mmol m\textsuperscript{-3}) (DO) that can strongly influence shark space use\textsuperscript{1}. Environmental datasets \textit{i} to \textit{v} were downloaded from Copernicus Marine Environment Monitoring Service (CMEMS) Global Ocean Physics Reanalysis product (goo.gl/E4eXDM; downloaded November 2017) and datasets \textit{vi} to \textit{ix} from CMEMS Global Ocean Biochemistry Hindcast product (goo.gl/5hpBs2; downloaded November 2017). CMEMS data were available for 2002 to 2014 from the surface to 5,500 m as monthly datasets. Using custom-written software overall averages (2002-2014) were calculated at a 1 \times 1\degree grid cell resolution for surface and 100 m depth layers (with the exception of SSH and MLD; Supplementary Fig. 2). Most of these variables and interactions are also considered important for explaining fishing patterns\textsuperscript{5,6}.

We developed and compared a set of generalised additive models (GAMs) with a gaussian family and an identity link using the log-transformed relative density of sharks (\(D_r\))\textsuperscript{13} as response variable. Because we were interested in understanding the general environmental preferences of sharks, we considered the relative density for all 23 shark species combined without considering random effects per species. All environmental variables were standardised and colinearity checked prior to inclusion in the models. Highly skewed environmental variables were logged before standardisation, this included most predictors at the surface (except for SAL and SSH) and also NPP (for sharks only) and TGR at 100 m (TGR\textsubscript{100}). The selection of variables to include in each model was made to avoid inclusion...
of colinear variables in the same model and to specifically address key hypotheses. All
possible combinations of 16 variables were not undertaken because many of them are
colinear and could not be included in the same model. Rather, we focused on testing
ecologically relevant hypotheses. A description of the general hypothesis tested with each
model included in the model set is given in Supplementary Table 7. Including models with a
reduced number of variables was also necessary, as some variables were colinear with
variables included in other models. Because sharks respond to surface and subsurface thermal
gradients which often support higher biological productivity\textsuperscript{5,6,13,39}, we tested for interactions
between MLD and SST, CHL and MLD at 100 m (MLD\textsubscript{100}), CHL at 100 m (CHL\textsubscript{100})
and TEM at 100 m (TEM\textsubscript{100}), MLD and TGR at the surface, MLD and CHL\textsubscript{100},
CHL\textsubscript{100} and TEM\textsubscript{100}, and between SAL and TEM\textsubscript{100}.

GAM with a Tweedie distribution and log link function provided the best modelling approach
for the fishing effort, as this distribution includes a family of probability distributions
including normal, gamma, Poisson and compound Poisson-gamma. We considered two
response variables separately: fishing effort of all vessels, and fishing effort of longline
vessels only. In our model set we included different combinations of a total of the same 16
explanatory environmental variables used for shark density modelling (see previous section;
Supplementary Table 7), and also a null (all terms equal to zero), intercept-only model. The
dimension basis for all terms was limited to 5 (i.e., \( k = 5 \)) to assist controlling for
overfitting\textsuperscript{40}. We then used the Akaike’s information criterion (AIC)\textsuperscript{41} to compare the models
in the model set for all sharks and fishing vessels. We assessed the relative strength of
evidence for each model using the weights of AIC, and the goodness of fit of each model by
calculating the percentage of deviance explained (\%DE). All models were implemented in R
using the mgcv package\textsuperscript{42}. 
Shark/vessel spatial overlap and effort. The spatial overlap (%) between an individual tracked shark and fishing effort was calculated as the number of days that sharks and fishing effort (days) occurred in the same $1 \times 1^\circ$ grid cells in an average year, as a function of all shark grid cells occupied and standardised for shark track length, and summarised as:

Spatial overlap (%) = (number of days with overlap) / (total number of track days) $\times$ 100

A fixed $1 \times 1^\circ$ geographic grid cell (where $1^\circ$ latitude at the equator = 110.6 km) was chosen because it encompassed the maximum length of fishing gear deployed by a single vessel, i.e. the length of drifting longlines are typically 100 km in total length$^5$. We examined the effect of grid cell size$^{43}$ on spatial overlap estimates by calculating the overlap of all sharks tracked with ARGOS transmitters ($\sim$0.5 – 11 km spatial accuracy$^{44}$) with all fishing vessels, then with longliners separately, at $0.5 \times 0.5^\circ$ and $0.25 \times 0.25^\circ$ grid cell sizes. An estimate of fishing effort that an individual shark was exposed to within the space each occupied was termed fishing effort per shark space use and calculated as:

Individual shark exposure to fishing effort (d) = (total number of fishing days) / (total number of track days)

Spatial overlap and fishing effort were also calculated for each of the most data-rich species per month to assess changes within an average year. To determine the spatial variation in overlap and fishing effort within the space used by sharks for mapping purposes, we calculated the overlap intensity in each $1 \times 1^\circ$ grid cell as the product of shark density (number of daily locations) and the number of fishing days.

To test for differences in exposure risk of sharks to fishing activity between different species within the general fishing areas designated by the Food and Agriculture Organization of the United Nations (FAO) (Supplementary Fig. 3), we undertook statistical analysis of exposure risk calculated for each shark as the product of the mean spatial overlap and mean fishing
Since data were not normal (Shapiro-Wilk normality test, \( p < 0.05 \)), a Kruskal–Wallis (KW) test was performed (with pairwise Wilcoxon rank sum tests as a post-hoc test). Because of differences in the number of tagged individuals per species, groups of >25 sharks per species were randomly selected and the KW test performed. This procedure was repeated 1,000 times and the percentage of times that significant differences were observed were recorded. Species with fewer than 25 individuals tracked were removed from the analysis. Given the relatively low number of sharks tracked in the southwest Indian Ocean and Oceania regions (Supplementary Table 10), statistical tests were restricted to the North Atlantic and eastern Pacific regions. In the Atlantic selected species were: \( P. \) glauca \((n = 152)\), \( I. \) serratus \((n = 120)\), \( G. \) cuvier \((n = 131)\), \( C. \) carcharias \((n = 26)\), \( C. \) longimanus \((n = 99)\), \( L. \) nasus \((n = 46)\), \( C. \) leucas \((n = 38)\) and Sphyrna spp. \((n = 40)\); Pacific, species were: \( P. \) glauca \((n = 112)\), \( I. \) oxyrinchus \((n = 113)\), \( L. \) ditropis \((n = 172)\), \( R. \) typus \((n = 77)\) and \( C. \) carcharias \((n = 59)\).

**Shark landings.** Annual pelagic shark landings by species/taxa groups were obtained from the FAO database (<FAO.org/fishery/statistics/global-capture-production/query/en>; downloaded September 2018) and related to fishing effort per shark space use of each species/taxa group. Landings reported for the North Atlantic (northwest, northeast, western central and eastern central Atlantic) between 2012 and 2016 were used in the analysis since it spanned the period that longline fishing effort was monitored (2012–2016). Data were extracted for nine species or taxa groups that are regularly caught by shelf and/or high-seas fisheries in the North Atlantic, the region in which most tags were deployed. The species/taxa groups were: \( P. \) glauca, \( I. \) oxyrinchus, \( C. \) longimanus, \( C. \) leucas, \( C. \) falciformis, \( L. \) nasus, \( G. \) cuvier, \( C. \) carcharias, and hammerheads (Sphyrna spp.) comprising \( S. \) lewini, \( S. \) mokarran and \( S. \) zygaena. Mean annual landings (t) per species/taxa group were calculated and related to AIS longline fishing effort per shark space use.
Additional references


Extended Data Table 1. Summary of fitted generalised additive models (GAM) relating the log-transformed weighted relative density of all sharks ($D_t$) and the fishing effort of all vessels and of longlines only to environmental variables. Environmental variables included in each model are detailed in Supplementary Table 7. $wAIC$ indicates the weight of the Akaike’s information criteria for each model in the model set with bold highlighting the highest ranked model. The percentage of deviance explained ($%DE$) by each model is given and the highest and second highest values for each response variable are highlighted in bold.

<table>
<thead>
<tr>
<th>Model</th>
<th>$D_t$</th>
<th>Fishing effort (all vessels)</th>
<th>Longline fishing effort</th>
</tr>
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<td>$wAIC$</td>
<td>%DE</td>
<td>$wAIC$</td>
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</tr>
<tr>
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<td>9.42</td>
<td>0.000</td>
</tr>
<tr>
<td>4</td>
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<td>8.21</td>
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</tr>
<tr>
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</tr>
<tr>
<td>6</td>
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<td>8</td>
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</table>
**Extended Data Table 2.** The number (a) and total hours fished (b) by flag state of the 5,565 AIS longline fishing vessels analysed in this study arranged by the largest twenty values (totals for 2012 – 2016). In (a) the number of vessels per flag state is the total number of unique Maritime Mobile Safety Identity (MMSI) codes present in the dataset in 2012 – 2016. In (b), the total longline hours fished is the total during 2012 – 2016.

(a)

<table>
<thead>
<tr>
<th>Flag state</th>
<th>No. AIS longline vessels</th>
<th>% total</th>
</tr>
</thead>
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<td>China</td>
<td>2,646</td>
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</tr>
<tr>
<td>Taiwan</td>
<td>791</td>
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</tr>
<tr>
<td>Japan</td>
<td>460</td>
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</tr>
<tr>
<td>Korea</td>
<td>248</td>
<td>4.46</td>
</tr>
<tr>
<td>Spain</td>
<td>227</td>
<td>4.08</td>
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<tr>
<td>USA</td>
<td>187</td>
<td>3.36</td>
</tr>
<tr>
<td>Portugal</td>
<td>67</td>
<td>1.20</td>
</tr>
<tr>
<td>Canada</td>
<td>65</td>
<td>1.17</td>
</tr>
<tr>
<td>Vanuatu</td>
<td>63</td>
<td>1.13</td>
</tr>
<tr>
<td>Fiji</td>
<td>46</td>
<td>0.83</td>
</tr>
<tr>
<td>Australia</td>
<td>43</td>
<td>0.77</td>
</tr>
<tr>
<td>India</td>
<td>39</td>
<td>0.70</td>
</tr>
<tr>
<td>Russia</td>
<td>35</td>
<td>0.63</td>
</tr>
<tr>
<td>South Africa</td>
<td>33</td>
<td>0.59</td>
</tr>
<tr>
<td>Seychelles</td>
<td>28</td>
<td>0.50</td>
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<tr>
<td>Argentina</td>
<td>27</td>
<td>0.49</td>
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<tr>
<td>Greece</td>
<td>22</td>
<td>0.40</td>
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<tr>
<td>Italy</td>
<td>22</td>
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<td>New Caledonia</td>
<td>21</td>
<td>0.38</td>
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<tr>
<td>France</td>
<td>20</td>
<td>0.36</td>
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<tr>
<td>Flag state</td>
<td>Total longline hours fished</td>
<td>% total</td>
</tr>
<tr>
<td>----------------</td>
<td>----------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>China</td>
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</tr>
<tr>
<td>Taiwan</td>
<td>4,476,896</td>
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<td>Korea</td>
<td>4,292,482</td>
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<tr>
<td>Japan</td>
<td>3,996,883</td>
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</tr>
<tr>
<td>Spain</td>
<td>2,972,677</td>
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</tr>
<tr>
<td>Portugal</td>
<td>630,843</td>
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<tr>
<td>Vanuatu</td>
<td>425,445</td>
<td>1.69</td>
</tr>
<tr>
<td>Fiji</td>
<td>284,558</td>
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<tr>
<td>USA</td>
<td>278,485</td>
<td>1.11</td>
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<tr>
<td>Australia</td>
<td>191,313</td>
<td>0.76</td>
</tr>
<tr>
<td>New Caledonia</td>
<td>187,137</td>
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</tr>
<tr>
<td>Russia</td>
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<td>0.67</td>
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<tr>
<td>Reunion Islands</td>
<td>164,682</td>
<td>0.66</td>
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<tr>
<td>Chile</td>
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<td>0.65</td>
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<tr>
<td>Argentina</td>
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<tr>
<td>South Africa</td>
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<tr>
<td>Seychelles</td>
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<tr>
<td>France</td>
<td>129,678</td>
<td>0.52</td>
</tr>
<tr>
<td>Malaysia</td>
<td>104,742</td>
<td>0.42</td>
</tr>
<tr>
<td>Canada</td>
<td>86,943</td>
<td>0.35</td>
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</table>
Extended Data Table 3. Effect of different grid cell size on the global mean spatial overlap of sharks and fishing vessels calculated for all ARGOS transmitter tracked sharks \((n = 1066)\) and all fishing vessels (including longline), and sharks and all longline vessels separately. ARGOS tracked sharks were used in the analysis because the spatial accuracy of locations was <11 km (see Methods for explanation).

<table>
<thead>
<tr>
<th></th>
<th>Grid cell size</th>
<th>Mean spatial overlap (%)</th>
<th>One standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sharks and all fishing vessels (incl. longline)</td>
<td>1 × 1°</td>
<td>81.77</td>
<td>28.48</td>
</tr>
<tr>
<td></td>
<td>0.5 × 0.5°</td>
<td>67.17</td>
<td>35.39</td>
</tr>
<tr>
<td></td>
<td>0.25 × 0.25°</td>
<td>56.47</td>
<td>36.31</td>
</tr>
<tr>
<td>Sharks and all longline vessels</td>
<td>1 × 1°</td>
<td>39.21</td>
<td>40.91</td>
</tr>
<tr>
<td></td>
<td>0.5 × 0.5°</td>
<td>30.26</td>
<td>37.63</td>
</tr>
<tr>
<td></td>
<td>0.25 × 0.25°</td>
<td>24.00</td>
<td>33.62</td>
</tr>
</tbody>
</table>
**Extended Data Table 4.** Calculated mean spatial overlap and fishing effort for ocean regions and species. S.D., ± one standard deviation of the mean; S.E., ± one standard error of the mean. Ocean regions were selected based upon FAO fishing regions (see Supplementary Figure 3). There were 70 individual sharks that did not fall into FAO regions and these were not included in this analysis.

(a) **All ocean regions.** Calculated spatial overlap and longline fishing effort for the 11 most data-rich species/taxa groups.

<table>
<thead>
<tr>
<th>Species</th>
<th>N tags</th>
<th>Mean spatial overlap (%)</th>
<th>Median</th>
<th>S.D.</th>
<th>S.E.</th>
<th>Mean fishing effort (days)</th>
<th>Median</th>
<th>S.D.</th>
<th>S.E.</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Prionace glauca</em></td>
<td>280</td>
<td>68.5</td>
<td>90.5</td>
<td>37.3</td>
<td>2.2</td>
<td>8.4</td>
<td>5.4</td>
<td>9.7</td>
<td>0.6</td>
</tr>
<tr>
<td><em>Carcharhinus leucas</em></td>
<td>41</td>
<td>21.2</td>
<td>0.0</td>
<td>36.5</td>
<td>5.7</td>
<td>3.4</td>
<td>0.0</td>
<td>13.1</td>
<td>2.0</td>
</tr>
<tr>
<td><em>Isurus oxyrinchus</em></td>
<td>262</td>
<td>57.9</td>
<td>61.3</td>
<td>36.9</td>
<td>2.3</td>
<td>6.4</td>
<td>1.9</td>
<td>8.2</td>
<td>0.5</td>
</tr>
<tr>
<td><em>Carcharhinus longimanus</em></td>
<td>105</td>
<td>10.9</td>
<td>1.3</td>
<td>20.8</td>
<td>2.0</td>
<td>0.2</td>
<td>0.0</td>
<td>0.4</td>
<td>0.0</td>
</tr>
<tr>
<td><em>Lamna nasus</em></td>
<td>56</td>
<td>92.1</td>
<td>100.0</td>
<td>17.2</td>
<td>2.3</td>
<td>6.4</td>
<td>5.7</td>
<td>4.1</td>
<td>0.5</td>
</tr>
<tr>
<td><em>Lamna ditropis</em></td>
<td>172</td>
<td>8.8</td>
<td>2.8</td>
<td>13.1</td>
<td>1.0</td>
<td>0.2</td>
<td>0.0</td>
<td>0.3</td>
<td>0.0</td>
</tr>
<tr>
<td><em>Carcharhinus falciformis</em></td>
<td>51</td>
<td>52.2</td>
<td>69.5</td>
<td>45.2</td>
<td>6.3</td>
<td>8.0</td>
<td>1.0</td>
<td>11.6</td>
<td>1.6</td>
</tr>
<tr>
<td><em>Sphyra spp.</em></td>
<td>66</td>
<td>29.3</td>
<td>10.5</td>
<td>37.7</td>
<td>4.6</td>
<td>0.7</td>
<td>0.0</td>
<td>1.9</td>
<td>0.2</td>
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<tr>
<td><em>Galeocerdo cuvier</em></td>
<td>254</td>
<td>40.8</td>
<td>27.3</td>
<td>41.0</td>
<td>2.6</td>
<td>2.0</td>
<td>0.4</td>
<td>3.7</td>
<td>0.2</td>
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<tr>
<td><em>Rhincodon typus</em></td>
<td>164</td>
<td>27.7</td>
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<td>39.6</td>
<td>3.1</td>
<td>2.8</td>
<td>0.0</td>
<td>8.0</td>
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<tr>
<td><em>Carcharodon carcharias</em></td>
<td>160</td>
<td>72.2</td>
<td>78.2</td>
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<td>2.1</td>
<td>7.1</td>
<td>3.8</td>
<td>11.2</td>
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<tr>
<td><strong>Total tags or Mean</strong></td>
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<td><strong>43.8</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
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</table>
(b) **North Atlantic.** Calculated spatial overlap and longline fishing effort for the 11 most data-rich species/taxa groups.

<table>
<thead>
<tr>
<th>Species</th>
<th>N tags</th>
<th>Mean spatial overlap (%)</th>
<th>Median</th>
<th>S.D.</th>
<th>S.E.</th>
<th>Mean fishing effort (days)</th>
<th>Median</th>
<th>S.D.</th>
<th>S.E.</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Prionace glauca</em></td>
<td>152</td>
<td>93.7</td>
<td>100.0</td>
<td>14.2</td>
<td>1.2</td>
<td>14.0</td>
<td>11.5</td>
<td>9.7</td>
<td>0.8</td>
</tr>
<tr>
<td><em>Carcharhinus leucas</em></td>
<td>38</td>
<td>15.0</td>
<td>0.0</td>
<td>29.9</td>
<td>4.9</td>
<td>0.1</td>
<td>0.0</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
<td><em>Isurus oxyrinchus</em></td>
<td>120</td>
<td>79.4</td>
<td>99.6</td>
<td>33.8</td>
<td>3.1</td>
<td>12.2</td>
<td>11.3</td>
<td>9.0</td>
<td>0.8</td>
</tr>
<tr>
<td><em>Carcharhinus longimanus</em></td>
<td>99</td>
<td>8.0</td>
<td>0.5</td>
<td>17.4</td>
<td>1.7</td>
<td>0.1</td>
<td>0.0</td>
<td>0.4</td>
<td>0.0</td>
</tr>
<tr>
<td><em>Lamna nasus</em></td>
<td>46</td>
<td>96.8</td>
<td>100.0</td>
<td>9.3</td>
<td>1.4</td>
<td>6.7</td>
<td>6.0</td>
<td>4.2</td>
<td>0.6</td>
</tr>
<tr>
<td><em>Lamna ditropis</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Carcharhinus falciformis</em></td>
<td>1*</td>
<td>100.0</td>
<td>100.0</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
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</tr>
<tr>
<td>Sphyra spp.</td>
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<td>15.0</td>
<td>40.1</td>
<td>6.3</td>
<td>0.7</td>
<td>0.1</td>
<td>1.7</td>
<td>0.3</td>
</tr>
<tr>
<td><em>Galeocerdo cuvier</em></td>
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<td>23.9</td>
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<td>2.6</td>
<td>1.3</td>
<td>0.1</td>
<td>2.9</td>
<td>0.3</td>
</tr>
<tr>
<td><em>Rhincodon typus</em></td>
<td>3</td>
<td>60.2</td>
<td>56.3</td>
<td>25.6</td>
<td>14.8</td>
<td>6.2</td>
<td>0.9</td>
<td>9.7</td>
<td>5.6</td>
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<tr>
<td><em>Carcharodon carcharias</em></td>
<td>26</td>
<td>83.3</td>
<td>90.9</td>
<td>21.3</td>
<td>4.2</td>
<td>5.7</td>
<td>4.5</td>
<td>4.8</td>
<td>0.9</td>
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<tr>
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<td></td>
<td></td>
<td><strong>4.8</strong></td>
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</tbody>
</table>

*The single tag was not included in the mean overlap or effort values shown.*
(c) **East Pacific.** Calculated spatial overlap and longline fishing effort for the 11 most data-rich species/taxa groups.

<table>
<thead>
<tr>
<th>Species</th>
<th>N tags</th>
<th>Mean spatial overlap (%)</th>
<th>Median</th>
<th>S.D.</th>
<th>S.E.</th>
<th>Mean fishing effort (days)</th>
<th>Median</th>
<th>S.D.</th>
<th>S.E.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prionace glauca</td>
<td>112</td>
<td>34.5</td>
<td>24.7</td>
<td>31.3</td>
<td>3.0</td>
<td>1.0</td>
<td>0.3</td>
<td>1.8</td>
<td>0.2</td>
</tr>
<tr>
<td>Carcharhinus leucas</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Isurus oxyrinchus</td>
<td>113</td>
<td>36.1</td>
<td>34.3</td>
<td>26.4</td>
<td>2.5</td>
<td>1.1</td>
<td>0.8</td>
<td>1.8</td>
<td>0.2</td>
</tr>
<tr>
<td>Carcharhinus longimanus</td>
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<td>62.1</td>
<td>3.0</td>
<td>2.1</td>
<td>0.4</td>
<td>0.4</td>
<td>0.2</td>
<td>0.1</td>
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<tr>
<td>Lamna nasus</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lamna ditropis</td>
<td>172</td>
<td>8.8</td>
<td>2.8</td>
<td>13.1</td>
<td>1.0</td>
<td>0.2</td>
<td>0.0</td>
<td>0.3</td>
<td>0.0</td>
</tr>
<tr>
<td>Carcharhinus falciformis</td>
<td>17</td>
<td>4.2</td>
<td>0.0</td>
<td>11.9</td>
<td>2.9</td>
<td>0.1</td>
<td>0.0</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Sphyra spp.</td>
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<td>0.0</td>
<td>10.7</td>
<td>2.3</td>
<td>0.0</td>
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<td>Galeocerdo cuvier</td>
<td>12</td>
<td>0.6</td>
<td>0.0</td>
<td>1.6</td>
<td>0.5</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
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<tr>
<td>Rhincodon typus</td>
<td>77</td>
<td>12.2</td>
<td>0.0</td>
<td>20.9</td>
<td>2.4</td>
<td>0.4</td>
<td>0.0</td>
<td>1.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Carcharodon carcharias</td>
<td>59</td>
<td>55.0</td>
<td>58.2</td>
<td>24.4</td>
<td>3.2</td>
<td>2.7</td>
<td>2.8</td>
<td>2.0</td>
<td>0.3</td>
</tr>
<tr>
<td>Total tags or Mean</td>
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</tr>
</tbody>
</table>
(d) **Indian Ocean.** Calculated spatial overlap and longline fishing effort for the 11 most data-rich species/taxa groups.

<table>
<thead>
<tr>
<th>Species</th>
<th>N tags</th>
<th>Mean spatial overlap (%)</th>
<th>Median</th>
<th>S.D.</th>
<th>S.E.</th>
<th>Mean fishing effort (days)</th>
<th>Median</th>
<th>S.D.</th>
<th>S.E.</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Prionace glauca</em></td>
<td>5</td>
<td>91.9</td>
<td>100.0</td>
<td>11.4</td>
<td>5.1</td>
<td>5.4</td>
<td>4.4</td>
<td>4.9</td>
<td>2.2</td>
</tr>
<tr>
<td><em>Carcharhinus leucas</em></td>
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<td>47.2</td>
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<tr>
<td><em>Isurus oxyrinchus</em></td>
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</tr>
<tr>
<td><em>Carcharhinus longimanus</em></td>
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<td></td>
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<tr>
<td><em>Lamna nasus</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Lamna ditropis</em></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td><em>Carcharhinus falciformis</em></td>
<td>33</td>
<td>75.5</td>
<td>93.6</td>
<td>35.7</td>
<td>6.2</td>
<td>12.4</td>
<td>8.4</td>
<td>12.5</td>
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<tr>
<td>Sphyra spp.</td>
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<tr>
<td><em>Galeocerdo cuvier</em></td>
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<td>87.3</td>
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<td>31.0</td>
<td>6.1</td>
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<tr>
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<td>48.2</td>
<td>7.0</td>
<td>8.0</td>
<td>0.0</td>
<td>13.1</td>
<td>1.9</td>
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<tr>
<td><em>Carcharodon carcharias</em></td>
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<td>98.6</td>
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<td>0.9</td>
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<td>19.8</td>
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</table>
(e) **Oceania.** Calculated spatial overlap and longline fishing effort for the 11 most data-rich species/taxa groups.

<table>
<thead>
<tr>
<th>Species</th>
<th>N tags</th>
<th>Mean spatial overlap (%)</th>
<th>Median</th>
<th>S.D.</th>
<th>S.E.</th>
<th>Mean fishing effort (days)</th>
<th>Median</th>
<th>S.D.</th>
<th>S.E.</th>
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<td>71.4</td>
<td>42.3</td>
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<td>6.6</td>
<td>1.6</td>
<td>9.3</td>
<td>2.8</td>
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<tr>
<td><em>Carcharhinus leucas</em></td>
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<td></td>
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<tr>
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<td>9.0</td>
<td>3.2</td>
<td>1.0</td>
<td>3.6</td>
<td>0.9</td>
</tr>
<tr>
<td><em>Carcharhinus longimanus</em></td>
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<tr>
<td><em>Lamna nasus</em></td>
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<td>78.0</td>
<td>27.2</td>
<td>8.6</td>
<td>4.7</td>
<td>4.0</td>
<td>3.4</td>
<td>1.1</td>
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<tr>
<td><em>Lamna ditropis</em></td>
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<tr>
<td><em>Carcharhinus falciformis</em></td>
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<tr>
<td>Sphyra spp.</td>
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<tr>
<td><em>Galeocerdo cuvier</em></td>
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<td><em>Carcharodon carcharias</em></td>
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</table>
**Extended Data Table 5.** Tag recapture data for the most data-rich species studied.

<table>
<thead>
<tr>
<th>Shark species</th>
<th>Total tagged</th>
<th>No. recaught</th>
<th>Total tagged</th>
<th>No. recaught</th>
<th>Total tagged</th>
<th>No. recaught</th>
<th>Total tagged</th>
<th>No. recaught</th>
<th>Total tagged</th>
<th>No. recaught</th>
<th>Total tagged</th>
<th>No. recaught</th>
<th>Total tagged</th>
<th>No. recaught</th>
</tr>
</thead>
<tbody>
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<td>Silky</td>
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<td>0</td>
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<td>2</td>
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<td>2</td>
<td>58</td>
<td>0</td>
<td>1398</td>
<td>65</td>
<td>4.65</td>
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<td>Tiger</td>
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<td>131</td>
<td>5</td>
<td>12</td>
<td>0</td>
<td>26</td>
<td>0</td>
<td>58</td>
<td>0</td>
<td>1398</td>
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<tr>
<td>Mako</td>
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<td>5</td>
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<td>Salmon</td>
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<td>1398</td>
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</tbody>
</table>

Total: 1398
Extended Data Fig. 1. The location of shark tag deployment sites in relation to shark space use hotspots. Red circles denote the locations where satellite transmitters were attached and sharks released, and blue squares in the eastern Pacific denote annual median deployment locations of tags by the Tagging of Pacific Predators (TOPP) program (ref. 13). Shark space use hotspots are shown as the 75th (blue dotted lines) and 90th percentiles (red dotted lines) of the relative density of estimated shark positions within $1 \times 1^\circ$ grid cells given in Fig. 2a.
Extended Data Fig. 2. Schematic maps of oceanographic and physical features. Major ocean currents (a) and physical features (b) referred to in this paper. Coloured arrows in a denote thermal regime of currents, with warmer colours indicating greater water temperature. Abbreviations in b denote: CGFZ, Charlie Gibbs Fracture Zone; GBR, Great Barrier Reef; PNG, Papua New Guinea; IMS, Isakov and Makarov Seamounts.
Extended Data Fig. 3. Spatial distribution of fishing vessels and overlap intensity with sharks. (a) Distribution of 83,628 AIS tracked fishing vessels’ effort (mean annual days spent per grid cell) between 2012 and 2016 (see Methods). (b) Distribution of the overlap intensity between shark density and fishing effort (spatial co-occurrence within 1 × 1° grid cells). Spatial overlap intensity hotspots were defined as 1 × 1° grid cells with ≥75% overlap. Note the similar overlap intensity pattern of sharks and all mapped AIS fishing vessels as that determined for sharks and longline vessels in Fig. 2c.
Extended Data Fig. 4. Spatial distribution of purse seine fishing vessels and overlap intensity with sharks. (a) Distribution of 6,941 AIS purse seine vessels’ fishing effort (mean annual days spent per grid cell) between 2012 and 2016 (see Methods). (b) Distribution of the overlap intensity between shark density and fishing effort (spatial co-occurrence within 1 × 1° grid cells). Spatial overlap intensity hotspots were defined as 1 × 1° grid cells with ≥75% overlap.
<table>
<thead>
<tr>
<th>Shark spatial density</th>
<th>MLD_0m</th>
<th>TGR_0m</th>
<th>Interaction</th>
<th>SSH_0m</th>
<th>CHL-a_0m</th>
<th>SAL_100m</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MODEL 1</strong></td>
<td>![Graph]</td>
<td>![Graph]</td>
<td>![Graph]</td>
<td>![Graph]</td>
<td>![Graph]</td>
<td>![Graph]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fishing effort (all vessels)</th>
<th>mgl_0m</th>
<th>Temperature/Slope_0m</th>
<th>Interaction</th>
<th>ssh_0m</th>
<th>chl_0m</th>
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<tr>
<td><strong>MODEL 1</strong></td>
<td>![Graph]</td>
<td>![Graph]</td>
<td>![Graph]</td>
<td>![Graph]</td>
<td>![Graph]</td>
<td>![Graph]</td>
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</tbody>
</table>
Extended Data Fig. 5. Estimated relationships between relative density of all sharks (top panel) and AIS fishing effort of all vessels (middle panels) and longlines only (bottom panels) with all environmental variables in the highest ranked (Model 1) of the generalised additive models (GAM) tested. Third column shows the interaction results between the two variables described in the first and second columns. Asterisks indicate significance level for each smooth term included in the GAM, representing $p < 0.001$ (***) , $< 0.01$ (**).
Figure 1: Distribution maps of different species of sharks.

(a) PGL: Relative density and overlap intensity (%).
(b) JOLX: Relative density and overlap intensity (%).
(c) GCU: Relative density and overlap intensity (%).
(d) LDI: Relative density and overlap intensity (%).
(e) RTY: Relative density and overlap intensity (%).
(f) CCA: Relative density and overlap intensity (%).
Extended Data Fig. 6. Relative density and spatial overlap intensity distributions for individual shark species. Relative density of sharks (left panels) tracked in 2002–2017 in comparison with shark-vessel spatial overlap intensity with AIS longline fishing vessels.
(2012–2016) (right panels) for the 11 most data-rich species/taxa groups: (a) blue, *Prionace glauca*; (b) shortfin mako, *Isurus oxyrinchus*; (c) tiger, *Galeocerdo cuvier*; (d) salmon shark, *Lamna ditropis*; (e) whale shark, *Rhincodon typus*; (f) white, *Carcharodon carcharias*; (g) oceanic whitetip, *Carcharhinus longimanus*; (h) porbeagle, *Lamna nasus*; (i) silky, *Carcharhinus falciformis*; (j) bull, *Carcharhinus leucas*; and (k) hammerhead sharks, *Sphyrna* spp. (comprising: scalloped, *S. lewini*; great, *S. mokarran*; and smooth, *S. zygaena*). Shark images created by M. Dando.
Extended Data Fig. 7. Relationship between North Atlantic fisheries’ shark landings and AIS longline fishing effort in shark-vessel overlap areas. Plot showing shark landings from the North Atlantic (mean, 2012–2016) extracted from the Food and Agriculture Organization of the United Nations (FAO) total capture production database (see Methods) is dependent upon fishing effort of AIS longline vessels (2012–2016) in shark species space use areas in the North Atlantic (2002-2017). For linear regression analysis, we tested the null hypothesis ($H_0$) that $\beta = 0$ after normalising landings by log transformation and fishing effort by square-root transformation. We computed $r^2 = 0.51$, $F = 7.14$ and $F_{0.05(1, 1.7)} = 5.59$, therefore rejecting $H_0$ at the 5% level of significance with $p = 0.032$. Species identification codes are given in Fig. 1.
Extended Data Fig. 8. Example of temporal changes in spatial overlap and fishing effort. (a) Annual variation in shark-longline vessel spatial overlap and (b) longline fishing effort per shark space use. Shark species identification codes are given in Fig. 1. Error bars are ± 1 S.D. Shark images created by M. Dando.
Extended Data Fig. 9. Seasonal shifts in sharks, longline vessels and shark-vessel overlap intensity. Relative spatial density of sharks (left panels), longline fishing effort (middle), and percentage spatial overlap intensity (right panels) in each seasonal quarter for (a) North Atlantic blue and (b) shortfin mako sharks, (c) east Pacific and (d) southwest Indian Ocean white sharks, and for (e) tiger sharks in the Oceania region. Shark species identification codes at bottom right of each panel are given in Fig. 1.
Extended Data Fig. 10. Annual spatial distribution of AIS longline fishing effort, 2012–2016. The global distribution of AIS monitored fishing effort varied across years as new AIS satellite receivers became operational which increases global coverage (for details see ref. 21). However, we calculated the mean annual fishing effort distribution across the 5 year period since the global spatial extent was broadly similar between years but also overlapped temporally with more years for which we had shark track data (2002–2017). The maximum fishing effort value observed per grid cell showed no increasing trend through time (max. value: 2012 = 291 fishing effort days; 2013 = 2337 d; 2014 = 1860 d; 2015 = 1749 d; 2016 = 3908 d) indicating a mean value taken across the 5 years was conservative and unlikely to lead to overestimates of fishing effort per shark space use (see Methods).