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Global catches, exploitation rates, and rebuilding options for sharks

Boris Worm [a,*], Brendal Davis [a], Lisa Kettemer [a], Christine A. Ward-Paige [a], Demian Chapman [b], Michael R. Heithaus [c], Steven T. Kessel [d], Samuel H. Gruber [e]

[a] Biology Department, Dalhousie University, Halifax, NS, Canada B3H 4R2
[b] Institute for Ocean Conservation Science, School of Marine and Atmospheric Sciences, Stony Brook University, Stony Brook, NY 11794-5000, USA
[c] Department of Biological Sciences, Florida International University, North Miami, FL 33181, USA
[d] Great Lakes Institute for Environmental Research, University of Windsor, Windsor, ON, Canada N9B 3P4
[e] Bimini Biological Field Station, University of Miami, Miami, FL 33176-2050, USA

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A B S T R A C T

Adequate conservation and management of shark populations is becoming increasingly important on a global scale, especially because many species are exceptionally vulnerable to overfishing. Yet, reported catch statistics for sharks are incomplete, and mortality estimates have not been available for sharks as a group. Here, the global catch and mortality of sharks from reported and unreported landings, discards, and shark finning are being estimated at 1.44 million metric tons for the year 2000, and at only slightly less in 2010 (1.41 million tons). Based on an analysis of average shark weights, this translates into a total annual mortality estimate of about 100 million sharks in 2000, and about 97 million sharks in 2010, with a total range of possible values between 63 and 273 million sharks per year. Further, the exploitation rate for sharks as a group was calculated by dividing two independent mortality estimates by an estimate of total global biomass. As an alternative approach, exploitation rates for individual shark populations were compiled and averaged from stock assessments and other published sources. The resulting three independent estimates of the average exploitation rate ranged between 6.4% and 7.9% of sharks killed per year. This exceeds the average rebound rate for many shark populations, estimated from the life history information on 62 shark species (rebound rates averaged 4.9% per year), and explains the ongoing declines in most populations for which data exist. The consequences of these unsustainable catch and mortality rates for marine ecosystems could be substantial. Global total shark mortality, therefore, needs to be reduced drastically in order to rebuild depleted populations and restore marine ecosystems with functional top predators.

1. Introduction

Sharks, skates, rays and chimaeras together comprise the chondrichthyan fishes (Class *Chondrichthyes*), a group of about 1000 species that has persisted for at least 400 million years, rendering them one of the oldest extant vertebrate groups on the planet. Recently, however, the global growth of fishing, coupled with *Chondrichthyes*' relatively slow growth and reproductive rates, have resulted in the progressive depletion of populations around the world. This trend has been particularly pronounced for sharks, largely due to their inherent vulnerability, and an increasing demand, particularly for their fins, in the Asian market [1–4]. As such, many shark species are comparable to great whales, which also have late maturity, slow growth and low reproductive rates, and experienced escalating global fishing pressure until a global whaling moratorium came into effect in 1986 [5]. Similar to whales, quantifying the precise extent of sharks' decline, the risk of species extinction, and the consequences for marine ecosystems have been challenging and controversial, mostly due to data limitations [4,6–8].

A key problem is the incomplete reporting of shark catches to the United Nations Food and Agriculture Organization (FAO), which tracks the status of fisheries worldwide. Caught sharks are often not landed and are instead discarded at sea [7,9], with such discards not usually reported to national or international management agencies unless there are trained observers on board. Compounding this problem is the practice of shark finning, where the animal's fins are removed prior to the body being discarded at sea [9]. Due to the high value of the fins in Asian markets this practice is globally widespread. Some jurisdictions, such as Canada, the United States, Australia, and Europe have gradually introduced anti-finning legislation over the last 10 years, yet the practice continues in most other parts of the world [2]. Therefore it is very likely that reported catches represent only a fraction of total shark mortality. For example, Clarke et al. [9] used

* Corresponding author. Tel.: +1 902 494 2146.
E-mail address: bworm@dal.ca (B. Worm).

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trade auction records from Hong Kong to estimate that the total mass of sharks caught for the fin trade. Estimates ranged between 1.21 and 2.29 Mt (million metric tons) yr^{-1} with a median estimate of 1.70 Mt yr^{-1} in the year 2000. This amounted to more than four times the reported shark catch from FAO at that time [9].

Notwithstanding these problems, the FAO, among other management bodies, has long recognized the conservation challenges associated with sharks and their relatives, and it launched an International Plan of Action for Sharks in 1999 (IPOA-Sharks, which also includes skates, rays, and chimaeras). This plan aims to enhance the conservation and management of sharks and their sustainable use, while improving data collection and the monitoring and management of shark fisheries [10]. The IPOA-Sharks further recommends that all states contributing to fishing mortality on sharks should participate in its management, and should have developed a National Shark Plan by 2001. However, progress remains disappointing so far, with limited adoption and implementation of IPOA goals at the national level [2,11].

The objective of this paper is to provide an up-to-date assessment of the current status of shark populations including estimated global catches, current exploitation rates (herein defined as the total catch divided by the estimated biomass), and potential extinction risks at current levels of exploitation. Based on this review, possible management solutions for conserving and rebuilding shark populations are discussed. The authors intend to provide critical baseline information for the further development of national and international action plans that help ensure the conservation of sharks and their relatives.

2. Methods

Available information to estimate total shark fishing mortality, including reported landings, dead discards, and illegal, unregulated and unreported (IUU) landings were compiled for this paper. Caught sharks are either landed (reported or IUU) or discarded (alive or dead). Discarded sharks that are finned suffer 100% mortality, and those that are not finned suffer a lower post-release mortality [12]. These components (reported and IUU landings, dead discards) are estimated here from published data. In some cases it was necessary to convert shark numbers to weights or vice versa. To this end published estimates of average shark weights for species belonging to four major species groups were extracted from the available peer-reviewed literature: pelagic (e.g. *Prionace glauca*, *Isurus oxyrinchus*), large coastal (e.g. *Galeocerdo cuvier, Carcharhinus leucas*), small coastal (e.g. *Squalidae, Squatina spp.*), and deep water sharks (e.g. *Centrophorus granulosus, Apristurus profundorum*). Published weights from each study were averaged by species group in each study (e.g. all pelagic species weights were combined into one estimate), and then the median weight was computed across studies.

Reported catches were derived from the 'Fishstat' FAO online landings database [13]. FAO results were also compared with the 'Sea Around Us Project' (SAUP) database at the University of British Columbia, which is based on the FAO data and additional sources [14]. Since results were similar ($<10\%$ difference in catches), and temporal coverage was more complete (1950–2010) for the FAO data, the latter was used for analysis. Chondrichthyan catches included the following categories: large coastal and pelagic sharks, small coastal sharks, deep-water sharks, undifferentiated sharks, rays and chimaeras (mixed group), rays, skates, chimaeras (separate groups) and undifferentiated skates and rays. To estimate the total take of sharks, the proportion of sharks relative to other chondrichthyan catch from the differentiated groups was determined, and it was assumed that it was the same as in the undifferentiated (mixed species) group. Global trade data for shark fins were extracted and summarized from the same data base. For regional comparison, we also analyzed trade data from the Government of Hong Kong Department of Aquaculture and Fisheries Census and Statistics Reports.

The extent of illegal, unregulated and unreported (IUU) catch was estimated from the peer-reviewed literature [15] by taking the average of the low (11 Mt yr^{-1}) and high estimates (26 Mt yr^{-1}) for global IUU fishing, equivalent to 18.5 Mt yr^{-1}. Since the proportion of chondrichthyans in the IUU catches is unknown, it was assumed that chondrichthyans comprise the same proportion in the IUU catch as they do in the reported catch (1.2% on average). This is likely conservative because shark catches are often unreported, for example in artisanal or bycatch fisheries. When converting IUU catches to numbers of individuals it was also assumed that the proportional representation of major species groups was similar to the reported catch.

The amount of discarded sharks was estimated from published data, where scientifically trained observers had determined the overall catch rates for sharks in commercial fisheries. This analysis was performed comprehensively for the global longline fleet, a major fishery that operates worldwide and is well-known for its high proportion of shark bycatch and discards [3]. First the rate of shark catch was estimated from published sources for each major ocean basin, then this was scaled up by using the reported global longline effort, estimated at 1.4 billion hooks for the year 2000 [16]. Global effort and catch rate data were not available for other fishing gears that catch sharks (e.g. gillnet, purse-seine, troll, and trawl). Hence it was assumed that the proportion of longline shark catch in the total global shark catch would be the same as the proportion of large pelagic sharks in the total reported catch, which averaged at 52%. This assumption is based on the rationale that more than 80% of pelagic sharks caught every year are estimated to be caught on longlines [17]. Furthermore, the proportion of sharks that are finned before being discarded was estimated, along with the proportion of sharks that die post-release from other injuries, by compiling and averaging estimates of shark finning and post-release mortality from peer-reviewed published sources.

Furthermore, an average global exploitation rate for sharks was estimated. The exploitation rate is commonly defined as the total catch divided by the total biomass. Only one published estimate of total biomass was available, which amounts to 86.3 Mt for all elasmobranchs (sharks, rays, skates) combined [18]. It was assumed that half of this biomass (43.2 Mt) is comprised of sharks. The rationale for this assumption is that about half of all elasmobranch species are sharks and about half of the reported elasmobranch landings by weight are sharks. The overall biomass estimate was derived by macro-ecological scaling laws, and as such represents unexploited biomass which does not account for the effects of fishing (methodological details can be found in [18]). Here, it was assumed that half of the original biomass has been depleted due to fishing (21.6 Mt). The rationale for this number is that exploited fish stocks globally are estimated to be at $\sim$30%–45% of their original biomass [19], and 50% is therefore a conservative assumption for a highly exploited group, where many populations have declined 80% or more [20]. The resulting estimate of global shark biomass (21.6 Mt) was used as a basis for estimating global exploitation rate.

Two more independent estimates of exploitation rate were computed here. Published estimates of instantaneous fishing mortality (F) for assessed shark populations were extracted from the global RAM Legacy database of stock assessments [21] and other peer-reviewed sources. These estimates were converted to exploitation rates (U) as follows:

$$U = 1 - \exp(-F), \quad (1)$$

and then averaged across all populations. The second independent estimate of exploitation rate was derived by using the published median estimate of total shark catches for the fin trade, or 1.7 Mt [9], and dividing this by the total biomass estimate derived above. Note that this procedure is again conservative. It assumes that all shark mortality arises from the fin trade, and no extra mortality occurs.

Finally, observed exploitation rates in individual fisheries were compared here against the intrinsic rebound potential of exploited shark populations. The rebound potential represents the maximum rate of increase (r) of a population given its life history characteristics (average annual fecundity of females, maturity age, maximum age, natural mortality rate), and hence its ability to withstand fishing or recover from excessive fishing mortality under ideal environmental conditions. Estimates of r for individual shark species were obtained from Smith et al. [22] or calculated using the methods outlined in Smith et al. for 62 shark species where adequate life history data existed. The proportion of shark populations where the realized rate of fishing mortality exceeded its rebound potential was calculated from these data. Those species where the exploitation rate exceeded the rebound rate were deemed at risk of further depletion and extinction.

3. Results

Each year, global landings of sharks and other fisheries resource species are reported by fishing states to the FAO (Fig. 1). Since 1950, *Chondrichthyes* (sharks, rays, skates and chimaeras) have comprised between 1% and 2% of the total landings (Fig. 1A, average proportion of 1.2%). Sharks made up about half of the total *Chondrichthyes* landings over that time frame (Fig. 1B). Both shark and total *Chondrichthyes* landings have risen sharply from 1950s to the late 1990s, and have since declined slightly (Fig. 1B). Over this time frame, shark landings have increased 3.4-fold from 120,677 t in 1950 to 414,345 t in 1997, and since then have declined by 7.5% to 383,236 t in 2010. By comparison, the reported landings of skates, rays, and chimaeras increased 3.6-fold over the same period, peaking at 556,470 t in 2003, but since declined by 26.5% to 353,549 t in 2010. As such, *Chondrichthyes* landings showed a trajectory that is similar to global fish landings, which experienced a steady increase from 1950s to 1990s followed by a slow decline (Fig. 1A); however, *Chondrichthyes* displayed a later peak than global landings, and a sharper decline since that peak (Fig. 1B).

Regionally, from the 1990s until the present day, reported landings of sharks and their relatives have remained approximately stable in Europe, the Americas and Oceania, while they have increased in Africa, and fallen in Asia, which on average accounted for 52% of *Chondrichthyes* landings worldwide (Fig. 1C). While reported landings have generally been stable or declining, the trade volume of shark fins appears to have sharply increased since the late 1980s. No apparent evidence was found of a decline

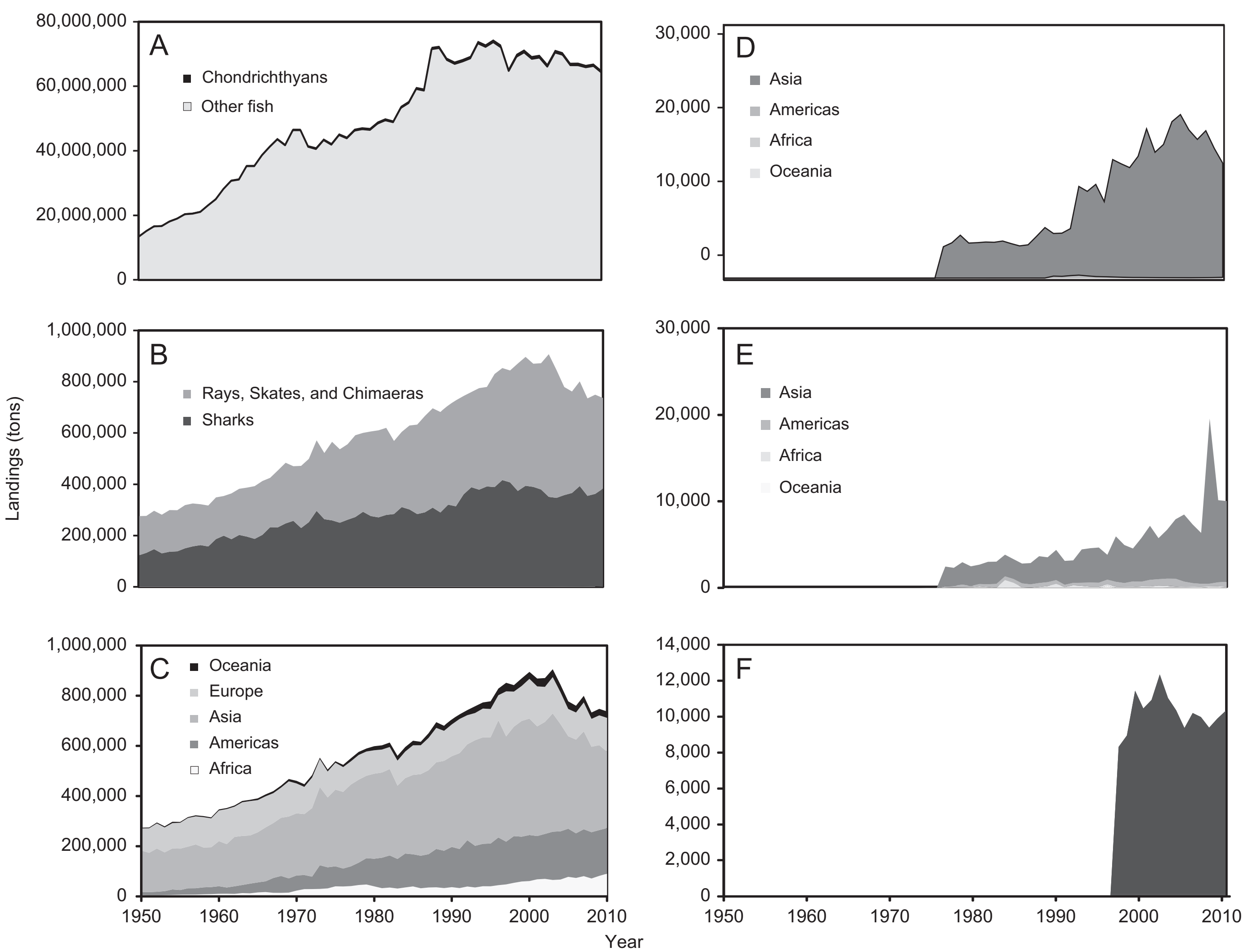

Fig. 1. Global landings trends. (A) Reported landings of wild-caught bony fish and *Chondrichthyes*, as derived from FAO landings data. (B) Reported FAO landings of sharks versus other *Chondrichthyes* (rays, skates and chimaeras). (C) Reported landings of *Chondrichthyes* by region. (D) Trade in shark fin imports and (E) exports as reported by FAO. (F) Trade data for shark fin imports to Hong Kong as reported by the Government of Hong Kong Department of Aquaculture and Fisheries.

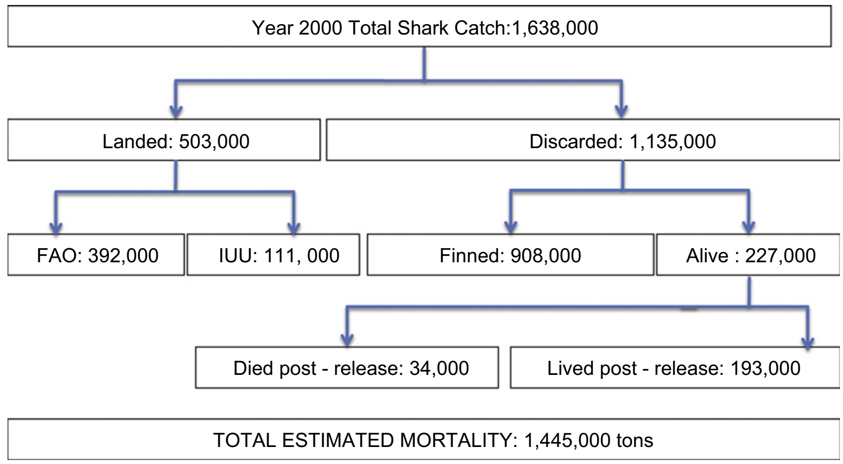

Fig. 2. Estimating global shark mortality for the year 2000. Included are reported (from FAO) and illegal, unreported, and unregulated (IUU) landings as well as shark discards. Total mortality was calculated as the total catch minus the number of sharks which survived discarding. All figures were rounded to nearest 1000 metric tons.

in shark fin imports (Fig. 1D) or exports (Fig. 1E) following the establishment of finning bans in the mid-1990s. This observation appears corroborated by the lack of a downward trend in trade data for shark fins imported into the major Hong Kong market (Fig. 1F). Thus finning regulations do not appear to have reduced the volume of fins traded in global or regional markets. According to FAO commodity figures, the total import value of shark fin products ranged from about USD 20 million in 1976 to a high of USD 455 million in 2000, and has since fluctuated between USD 306 and 419 million.

Our estimates of total shark catches for the year 2000 including reported and unreported landings and discards are provided in Fig. 2. Reported landings from the FAO database totaled 392,226 t in that year. Global illegal, unregulated and unreported (IUU) catches (excluding discards and artisanal catches) were estimated to average 18.5 Mt for the year 2000 [15]. It was assumed that similar to the reported catches *Chondrichthyes* also made up 1.2% of IUU landings (222,000 t), and sharks made up half of that, or 111,000 t. Hence, total shark landings (reported plus estimated unreported) in 2000 were estimated at about 503,000 t (Fig. 2).

To account for discards, the average catch per unit of effort (CPUE) for sharks caught on pelagic longlines was estimated from a number of published sources (Table 1), which yielded average catch rates of 16.5 (Pacific), 21.2 (Atlantic) and 4.3 (Indian Ocean) sharks caught per 1000 hooks. The global effort of longline fishing in the year 2000 was estimated at 1.4 billion hooks [16] with 728 million hooks set in the Pacific, 518 million in the Atlantic, and 154 million in the Indian Ocean. Multiplied by the ocean-specific catch rates (Table 1), these figures represent a longline shark catch of about 23,656,000 individuals, or 852,000 t assuming 36 kg average weight for pelagic sharks (Table 2). Pelagic sharks made up 52% of the identified shark catch in the FAO data, as opposed to coastal and deepwater sharks (48% of identified catch). Hence it was assumed that the estimate derived above from pelagic longlines (852,000 t) represents about 52% of the total catch. This raised the total catch estimate for all fishing gears to 1,638,000 t (Fig. 2). When the estimated landed catch (503,000 t) was subtracted, a global estimate of total shark discards (1,135,000 t) was derived.

According to available data (Table 3) the average rate of shark finning in 2000 was 80%. This high percentage was likely due to the high demand for the fins, their high value, as well as the lack of effective finning regulations in most fishing areas. Thus it was estimated that 80%, or 908,000t of discarded sharks, were finned, while the remainder (227,000 t) were released alive. A proportion of the sharks that are released alive suffer post-release mortality due to injury and stress. Published estimates of post-release mortality are in the order of 15% or higher [12,23]. Thus it was assumed here, that 15% of released (non-finned) sharks died from fishing-related injuries (34,000 t) and 85% survived (193,000 t). Combining reported and unreported catches, as well as dead or moribund discards, the total fishing mortality for sharks in 2000 was estimated here at 1,445,000 t (Fig. 2). Out of this, 1,409,000 t of landed catch plus finned discards were available to supply the fin trade. This is close to the independently derived median estimate for the 2000 shark fin trade of 1,700,000 t [9].

Using the average shark weights given in Table 2, these masses were converted into numbers of sharks. Using the median estimate of 20.8 kg for all sharks (Table 2), it was here calculated that the total mortality of 1,445,000 t translates into 69,471,000 shark individuals. However, accounting for the fact that the species composition of the FAO catch is partly known (in 2000: 82,582 t small coastal species, 111,858 t large pelagic, 5004 t deepwater species, and 182,782 t unidentified) and that these groups have known average weights (see Table 2, and assuming 20.8 kg for unidentified species), it was calculated that at least 49,011,000 sharks comprised the FAO reported landings in 2000. Assuming 20.8 kg per shark for the remaining catch (IUU and discarded dead sharks) a conservative mortality estimate of 99,618,000 sharks in 2000 was computed. This value is sensitive to our estimated average weights and species composition of the shark catch derived from published data. For example, one might assume that the species composition of the FAO species-identified catch also applies to the unidentified sharks reported to FAO; this would yield 74,321,000 sharks in the FAO catch, and 124,928,000 sharks in total including IUU and discards. Or one might assume the same species composition for the IUU catch; under this scenario the total mortality estimate increases to 140 million individuals. When assuming that both IUU and discards have a catch species composition similar to the reported FAO catch, this total estimate increases to 273 million sharks.

It is unclear how these figures might have changed since 2000, given changes in finning legislation in several jurisdictions (e.g. USA, Canada, Europe, and Australia) and the recent establishment of shark sanctuaries in others (Palau, Maldives, Honduras, Bahamas, and Tokelau). From 2000 to 2010 the FAO landings of sharks declined only slightly (by 2.3%) to 383,236 t. Assuming that both discards and IUU fishing declined by a similar fraction between 2000 and 2010, one would estimate total mortality in 2010 at 1,412,000 t, or between 97 and 267 million sharks, depending on the chosen scenario of species composition and average weights.

Using the above estimates, combined with independent figures, a total exploitation rate *U* (catches over biomass, in percent per year) for global shark populations was calculated (Table 4).

Table 1
Observed catch per unit effort of sharks in longline fisheries.

Fishery	Ocean	Region	Year	CPUE	Hooks	Ref.
Swordfish	Pacific	Southeast	2001–2006	6.9	155,060	[37]
Swordfish	Pacific	Eastern Central	1994–2006	16.7	NA	[38]
Swordfish and tuna	Pacific	Southeast	2004	3.6	72,090	[39]
Swordfish and sharks	Pacific	Northwest	2005	38.7	19,800	[40]
Swordfish and sharks	Pacific	Northwest	2005	91.1	28,800	[40]
Swordfish and sharks	Pacific	Northwest	2002–2003	47.8	36,480	[41]
Tuna	Pacific	Eastern Central	2006	2.6	180,000	[42]
Tuna	Pacific	Western Central	2005–2006	2.3	75,101	[43]
Tuna	Pacific	Southwest	1990–1998	7.5	12,725,046	[44]
Tuna	Pacific	Western Central	2005–2009	3.6	NA	[45]
Tuna	Pacific	Western Central	2005–2008	1.2	95,150	[46]
Tuna	Pacific	Eastern Central	1994–2006	2.2	NA	[38]
Tuna	Pacific	Eastern Central	2005–2006	3.4	2,773,427	[47]
Tuna and billfish	Pacific	Western Central	2005	3.3	44,100	[48]
Sharks	Pacific	Eastern Central	2004	25.2	15,200	[49]
Sharks	Pacific	Eastern Central	2005–2006	60.0	18,800	[50]
Mahimahi, tuna, billfish and sharks	Pacific	Eastern Central	2007	10.6	43,424	[51]
Mahimahi, tuna and sailfish	Pacific	Eastern Central	1999–2008	4.6	1,974,700	[52]
Mahimahi	Pacific	Eastern Central	2004–2006	10.6	33,876	[53]
Bigeye tuna	Pacific	Western Central	2005–2006	4.4	62,464	[54]
Tuna and billfish	Pacific	Central	1990–1999	7.8	10,944,000	[55]
Average Pacific				16.5		
Swordfish	Atlantic	Southwest	2003–2004	7.2	16,624	[56]
Swordfish	Atlantic	Northwest	2002	31.3	427,312	[57]
Swordfish	Atlantic	Southeast	2000–2005	23.3	447,000	[58]
Swordfish	Atlantic	Western Central	1992–2000	11.1	413,873	[59]
Swordfish	Atlantic	Southeast	1998–2005	2.9	880,000	[60]
Swordfish and tuna	Atlantic	Northwest	2001–2006	18.3	624,854	[61]
Swordfish and tuna	Atlantic	Western Central	2003–2004	5.7	30,600	[62]
Swordfish and tuna	Atlantic	Western Central	1992–2003	10.8	NA	[63]
Swordfish and tuna	Atlantic	Mediterranean	1998–1999	0.5	1,582,000	[64]
Swordfish and sharks	Atlantic	Northeast	2000–2003	32.5	267,109	[65]
Swordfish and sharks	Atlantic	Northeast	2000	14.4	139,500	[66]
Swordfish, tuna and sharks	Atlantic	Southwest	2004–2008	26.7	145,828	[67]
Swordfish, tuna and sharks	Atlantic	Southeast	2000–2005	85.3	8,829,000	[58]
Tuna	Atlantic	Southwest	2006–2007	17.2	7800	[68]
Tuna	Atlantic	Southeast	2000–2005	12.4	71,800	[58]
Tuna	Atlantic	Southeast	1998–2005	15.3	3,520,000	[60]
Tuna	Atlantic	Atlantic	1995–2003	3.4	4,318,119	[69]
Tuna	Atlantic	Eastern Central	2007–2008	2.8	226,848	[70]
Tuna and billfish	Atlantic	Northwest	1990–1999	30.6	1,116,000	[55]
Tuna and billfish	Atlantic	Southwest	2006–2007	2.5	50,170	[71]
Sharks	Atlantic	Northwest	1991–1992	23.6	17,526	[72]
Black scabbardfish	Atlantic	Eastern Central	2009	88.1	4700	[73]
Average Atlantic				21.2		
Swordfish and tuna	Indian	Eastern	NA	3.9	6226	[74]
Swordfish and tuna	Indian	Western	2004–2006	3.6	29,449	[75]
Swordfish and tuna	Indian	Western	2009–2010	11.8	14,112	[76]
Swordfish, tuna and sharks	Indian	Eastern	2004	4.9	3871	[77]
Tuna	Indian	Indian	2004–2008	0.6	14,121,000	[78]
Tuna	Indian	Eastern	2003–2011	2.3	522,992	[79]
Tuna	Indian	Eastern	2005–2011	5.9	38,333	[80]
Tuna	Indian	Eastern	2011	1.2	8375	[81]
Tuna	Indian	East-West	2000–2006	4.9	2,476,148	[82]
Average Indian				4.3		

The global biomass of elasmobranchs before the era of modern fishing was estimated by Jennings et al. [18] as 86,260,000 t. Assuming that half of these elasmobranchs are sharks, a biomass before fishing of 43,130,000 t of sharks was estimated. Conservatively assuming 50% depletion of sharks over the history of modern fishing, a contemporary biomass estimate of 21,565,000 t of sharks was derived. Total mortality was estimated to be 1,445,000 t in 2000 (Fig. 2), which when divided by total biomass, yields an estimated exploitation rate of 6.7% per year (Table 4). Using an alternative mortality estimate of 1,700,000 t, a figure that was independently derived from the fin trade [9], an annual exploitation rate of 7.9% was computed. Averaging across actual exploitation rates from published stock assessments and other sources given in Table 5, an independent estimate of 6.4% exploitation rate was derived. These three estimates are remarkably similar, considering that they were derived by entirely independent sources using different assumptions.

Comparing actual exploitation rates (Table 5; Fig. 3A) to calculated rebound rates of shark populations in general (Fig. 3B), and individual shark populations for which exploitation rates were estimated in particular (Fig. 3C), it was found that exploitation rates (Fig. 3A, Median $U=0.064$) on average exceed the median rebound rates (Fig. 3B, Median $r=0.049$) by about 30%, which is unsustainable over the long term. Notably, the rebound rates for most species were significantly below the three independent estimates of exploitation rates derived in this paper (Table 4). This suggests that the majority of shark populations will continue to decline under current fishing pressure (Fig. 3C).

Table 2
Average shark weights.

Species group	Species	Region	Year	Weight (kg)	Ref.
Large Coastal	2	NE Atlantic	1992–1999	34.0	[83]
Large Coastal	10	North and South Atlantic	2008	58.6	[84]
Large Coastal	2	SW Atlantic	2007–2008	85.0	[70]
Large Castal	5	SW Indian Ocean	1984–2006	46.2	[82]
Large Coastal	11	NW Atlantic	2004	26.5	[85]
Median				46.2	
Pelagic	3	Mediterranean	1998–2001	23.0	[64]·
Pelagic	2	North Pacific	1970–1992	17.0	[86]·
Pelagic	1	South Pacific	1988–1990	8.0	[87]·
Pelagic	6	NW Atlantic	1986–2000	34.0	[88]·
Pelagic	3	North and South Atlantic	1994–2003	38.0	[89]·
Pelagic	3	NW Atlantic	1961–1989	78.0	[90]·
Pelagic	9	North and South Atlantic	2008	76.0	[84]·
Pelagic	4	SW Atlantic	2007–2008	42.0	[70]·
Median				36.0	
Small Coastal	1	SW Atlantic	2005	1.0	[91]
Small Coastal	6	North Aegean Sea	2005–2008	8.0	[92]
Small Coastal	4	NE Atlantic	1992–1999	2.3	[83]
Small Coastal	3	SW Indian Ocean	1984–2006	15.0	[82]
Small Coastal	3	NW/SW Atlantic	1993–2005	2.0	[93]
Median				2.3	
Deep-water	2	NE Atlantic	1993–2000	2.6	[94]
Deep-water	4	North Aegean Sea	2005–2008	11.4	[92]
Deep-water	4	NE Atlantic	1999	5.6	[95]
Deep-water	2	SW Atlantic	2007–2008	3.0	[70]
Deep-water	14	NE Atlantic	1984–1997	9.0	[96]
Median				5.6	
Overall Median				20.8	

Table 3
Published estimates for the proportion of sharks that are finned in various fisheries around the world.

Fishery	Flag	% Finned	Comments	Ref.
Swordfish	USA (Hawaii)	65.0	Pre-regulations (2002)	[38]
Swordfish	Italy	0.0	No market	[38]
Tuna and Swordfish	South Africa	100.0	Pre-regulations (1998)	[38]
Tuna	USA (Hawaii)	76.0	Pre-regulations (2002)	[38]
Tuna	Fiji	84.0		[38]
Tuna	New Zealand	83.8		[44]
Tuna	China, Micronesia	96.8		[45]
Tuna	Unknown	67.8		[97]
Median		79.9		

4. Discussion

The primary goal of this paper was to estimate total catch and fishing-related mortality for sharks worldwide, and to derive an average exploitation rate from these estimates (Table 4). Due to the limited availability of data, particularly for shark discards, this work required a number of assumptions, as detailed above. Yet it allows placement of lower and upper limits on global shark mortality, here estimated to range from 63 to 273 million sharks, with a conservative estimate of $\sim$100 million sharks in the year 2000, or $\sim$97 million in 2010.

At the lower end, one might unrealistically assume that landings reported to the FAO represent all shark mortalities. When accounting for the average weight of different species groups, a minimum estimate of 49 million sharks can be derived from the FAO landings data. Yet this does not account for unreported and illegal catches. If we estimate an average rate of illegal, unregulated and unreported (IUU) fishing, we arrive at a total of 63 million sharks per year for the year 2000. This minimum estimate of global shark mortality changes only slightly from 2000 to 2010 (61 million sharks) as reported shark landings remained near-constant over the decade. This number is also similar to the upper estimate of shark mortality from the fin trade of 73 million individuals [9].

The abovementioned minimum estimate of shark mortality does not include discards and artisanal fishing since these sources of mortality are not accounted for in the FAO and IUU data. In the present paper these numbers are estimated for the first time. While the total catch rate of sharks in global longline fisheries could be well estimated from published data, data of similar quality for other fishing gear types that catch sharks, such as purse seines, gillnets, and trawls, were not available. Hence it was estimated here (from the FAO data) that about 52% of sharks are caught by longlines, with the remaining 48% caught by all other types of gear combined. This likely underestimates the catches of sharks in other fishing gear; trawls for example can catch very large numbers of small coastal sharks, most of which are discarded [7]. Hence the estimate for total mortality including discards is still likely conservative at 100 million sharks in 2000.

These calculations carry uncertainties and should be interpreted with some caution. The number of dead sharks, for example, is sensitive to the assumed percentage of small coastal sharks in the catch. If it is assumed that these are represented in the total catch (including discards) with the same proportion as in the reported and species-identified catch, the total mortality estimate increases to 273 million sharks, which represents an upper limit of shark mortality estimated here. Another uncertain value is the shark mortality from artisanal and recreational fishing, which is only partially accounted for in this analysis, a fact that again renders the estimate of 100-million sharks killed annually conservative.

Finally, the proportion of sharks that are killed for their fins is well known for the early 2000s (Table 3). However a number of regions now have anti-finning legislation that may reduce the incidence of finning and discarding of carcasses, and hence possibly reduce the mortality of sharks. Yet, despite these legislative changes there is presently no apparent sign of leveling off in the global fin trade (Fig. 1D–F). Nor is there much of a decline in the reported global catches of sharks (Fig. 1B).

Several explanations may account for these observations of near-stable catches and fin trade volume. First, fishing effort likely has been geographically displaced over the last decade as the primary fishing grounds supplying the fin trade in the 1990s and early 2000s became increasingly depleted or regulated. Additionally, catch levels may have experienced a certain amount of resiliency if fishers started using other, lower-value species or smaller individuals that were previously discarded. The species composition of the fin trade has not been assessed for more than a decade [9], hence this should become a research priority. Further, the apparent failure of anti-finning laws to curb global mortality may indicate that these laws have yet to be adequately enforced [24]. On the other hand, anti-finning laws primarily address animal welfare and food security issues (i.e. to reduce waste). Although an important first step, these policies are not explicitly designed to reduce catch or ensure sustainability. The premise that anti-finning legislation would contribute to sustainable fisheries rests on the assumption that most fishermen target sharks for their fins only, and would refrain from targeting sharks if they had to retain the carcass. This assumption is weak. Many

Table 4
Summary statistics for the exploitation of global shark populations.

Measure	Year	Estimate	Unit	Comments	Ref.
Removals					
All Elasmobranchs	2000	894,802	tons	Reported catch only	[13]
Sharks	2000	392,226	tons	Reported catch only	This study
Sharks	2000	38,000,000	Individuals	Fin trade only (median estimate)	[9]
Sharks	2000	1,700,000	tons	Fin trade only (median estimate)	[9]
Sharks	2000	99,617,577	Individuals	All sharks, total mortality	This study
Sharks	2000	1,444,847	tons	All sharks, total mortality	This study
Biomass and abundance					
Elasmobranch biomass	NA	86,260,000	tons	Sharks and rays, before fishing	[18]
Shark biomass	NA	43,130,000	tons	Assuming 50% sharks	This study
Shark biomass	2000	21,565,000	tons	Assuming 50% depletion by 2000	This study
Shark abundance	2000	1,036,778,846	Individuals	Assuming 20.8 kg/shark	This study
Exploitation rate					
Shark exploitation rate	2000	6.7	Percent/yr	Based on total biomass	This study
Shark exploitation rate	2000	7.9	Percent/yr	Based on fin trade statistics	[9]
Shark exploitation rate	2000	6.4	Percent/yr	Based on assessments	This study

Table 5
Published values of instantaneous fishing mortality (F) and exploitation rate (U) for assessed shark populations.

Species name	Common Name	F	U	Ref.
Rhizoprionodon terraenovae	Atlantic sharpnose	0.460	0.369	[98]
Squalus acanthias	Spiny dogfish	0.206	0.186	[21]
Carcharhinus porosus	Smalltail	0.193	0.176	[99]
Sphyrna tiburo	Bonnethead	0.187	0.171	[21]
Sphyrna lewini	Scalloped Hammerhead	0.160	0.148	[100]
Prionace glauca	Blue	0.160	0.148	[101]
Alopias pelagicus	Pelagic thresher	0.150	0.139	[102]
Carcharhinus plumbeus	Sandbar	0.130	0.122	[103]
Carcharhinus plumbeus	Sandbar	0.123	0.116	[21]
Lamna nasus	Porbeagle	0.090	0.086	[104]
Isurus oxyrinchus	Shortfin mako	0.066	0.064	[105]
Triakis semifasciata	Leopard	0.061	0.059	[106]
Lamna nasus	Porbeagle	0.056	0.054	[104]
Carcharhinus obscurus	Dusky	0.053	0.052	[107]
Prionace glauca	Blue	0.047	0.046	[101]
Carcharhinus limbatus	Blacktip	0.041	0.04	[21]
Carcharhinus acronotus	Blacknose	0.031	0.031	[21]
Isurus oxyrinchus	Shortfin mako	0.028	0.028	[108]
Prionace glauca	Blue	0.020	0.02	[108]
Carcharhinus limbatus	Blacktip	0.003	0.002	[21]
Carcharhinus isodon	Finetooth	0.001	0.001	[21]
Median		0.066	0.064	

countries consume shark meat [25] and fishermen opt to land whole sharks, even if the meat is not as valuable as the fins. Several at-risk shark species are generally kept rather than being finned in certain pelagic fisheries where freezer space is limited [24].

It is not surprising that anti-finning measures have been introduced widely given the intense public pressure that arose, especially since anti-finning laws are more palatable to industry than stringent catch reductions when local markets for the meat exist. In contrast, the monitoring, assessment and enforcement capacity required to sustainably manage shark fisheries is often perceived by regulatory agencies as being prohibitively costly relative to the simple adoption of anti-finning legislation. Regardless, some nations have recently invested in sustainable shark fisheries management, introducing catch limits, effort control, time-area closures, and other protective measures for the most vulnerable species. In some cases, such local measures appear to have been successful in halting declines [8]. The findings reported here highlight the fact that shark conservation policies generally need to focus on sustainability, as there is no evidence that a

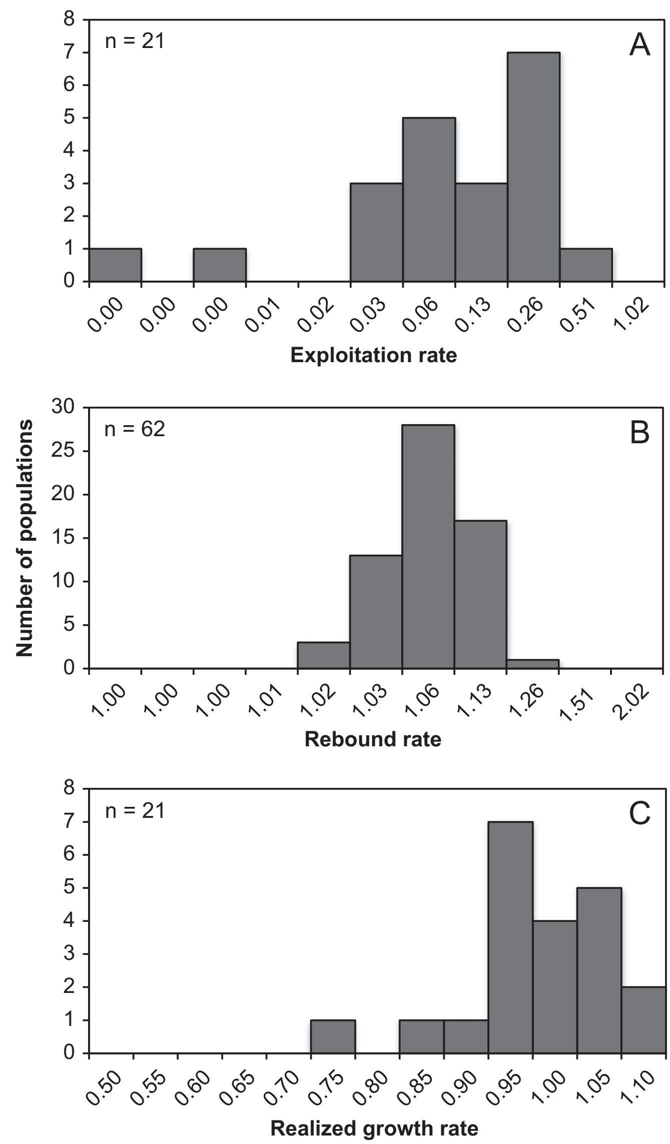

Fig. 3. Exploitation rates versus rebound potential of shark populations. (A) Exploitation rates of 21 assessed populations (in % of biomass exploited per year). (B) Maximum potential rebound rate (% increase per year) of 62 species with available data. (C) Realized growth rates calculated by subtracting exploitation rate from the maximum rebound potential (declining populations are < 1.00).

Table 6
IUCN extinction risk status of global shark populations (CR=critically endangered, EN=endangered, EN=endangered, VU=vulnerable, LC=least concern, DD=data deficient).

Order	CR	EN	VU	NT	LC	DD	ALL
Carcharhiniformes	7	10	21	38	67	120	263
Heterodontiformes	0	0	0	0	4	5	9
Hexanchiformes	0	0	0	3	0	2	5
Lamniformes	0	0	10	1	2	2	15
Pristioforiformes	0	0	0	1	3	2	6
Orectolobiformes	0	0	7	11	8	12	38
Squaiformes	1	0	6	13	35	63	118
Squatiniformes	3	4	4	1	2	5	19
Total species	11	14	48	68	121	211	473
Percentage of assessed	2.3	3.0	10.1	14.4	25.6	44.6	100
Percent of non-DD	4.2	5.3	18.3	26.0	46.2	NA	NA

legislative focus on anti-finning has reduced global landings and shark mortality rates.

From a legislative perspective, an important question to consider is what proportion of shark species may be at risk from extinction? According to the International Union for the Conservation of Nature (IUCN) Shark Specialist Group, 28% of assessed and non-data deficient shark species are globally at risk of extinction, i.e. classed as vulnerable, endangered or critically endangered (Table 6). A small number of these species are now receiving protection through national and international agreements. The white shark, whale shark, and basking shark, for example, are protected under the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). From the analyses presented here, a larger proportion of species appear to be at risk. According to available assessments, 48% of exploited shark populations were fished above their rebound rate, and 68% of species had rebound rates that were below the median global exploitation rate (6.7%). While these are rough generalizations based on global averages, it is here noted that the IUCN Specialist group results (Table 6) seem conservative, when compared to an analysis of exploitation rates (Fig. 3). Note that the actual status of individual species varies by region, and is influenced by local regulations, targeting practices, and effort allocation (e.g. [8]).

Beyond these species-level risks, there are concerns about the potential ecosystem consequences of depleting shark populations. Fortunately, there are a growing number of empirical studies that address the ecological consequences of declines in shark populations, which vary across taxa and ecosystems [1,6]. Time series data suggest that wider community rearrangements often follow declines in shark populations [1] and that the removal of large-bodied coastal sharks that prey upon other large-bodied taxa are likely to have cascading consequences for highly productive coastal ecosystems that support other fisheries [6,26]. Lower impacts of shark removals have been predicted by models for some small coastal species [27] and pelagic sharks, which may fill similar niches to billfish and tuna [28]. More broadly, however, across multiple environments on land, in lakes, rivers, and in the sea, the removal of large-bodied predators is commonly associated with large-scale changes in ecosystems [29]. Therefore, a precautionary approach should apply to shark management. The loss, especially of larger apex predators, could and has led to unexpected disruptions of ecosystems and non-shark fisheries [30].

Given the results of this paper, and much previous work on the vulnerability of sharks to overfishing, it is imperative that robust strategies for shark management and conservation be designed. This was formally recognized by the FAO in 1999, when it published an International Plan of Action for Sharks (IPOA-Sharks), a voluntary policy instrument within the framework of the Code of Conduct for Responsible Fisheries [10]. Although all concerned states are encouraged to implement it, progress at the national level has been slow [11], and concerns over the possible extinction of vulnerable species are mounting [2,3,31]. In a recent paper [29], evidence for the rebuilding of depleted elasmobranch populations under management was evaluated and these authors found little general support as of yet that rebuilding was occurring [32].

At the same time it appears that the demand for shark fins remains high (Fig. 1D–F), and there is a general concern that localized protective measures just displace the problem into less regulated areas, including many developing countries and the high seas [19]. Existing finning bans are an important first step, but they may be ineffective at reducing overall shark mortality, as there is no evidence that global shark catch or shark fin trade is declining. Given the failure to effectively reduce the unsustainable mortality of sharks on a global scale, there appears a need for a more binding international agreement on the protection of sharks. This could be similar to what has been done for the global conservation of whales through the establishment of the International Whaling Commission [5]. In that case, a globally threatened group of large marine animals was effectively saved from extinction by imposing stringent global catch regulations, and ultimately a global moratorium on commercial whaling.

If the goal was to at least partially rebuild depleted shark populations worldwide, what actions would be required? Caddy and Agnew [33] and Worm et al. [34] have discussed management options that exist for rebuilding fish populations, and analyzed the empirical evidence for successful recovery; Ward-Paige et al. [32] recently reviewed the same issue for sharks. These authors concluded that rebuilding depleted stocks is demonstrably possible, and occurs where a number of management instruments are combined to reduce mortality to an appropriately low level [32–34]. This level depends both on the status of the stock, and its productivity, or rebound potential [33]. As most shark populations have low productivity compared to other fish stocks, and stock status is typically poor or unknown, the case for ensuring a large decrease in catches and the establishment of a moratorium on fishing appears strong [32,33]. In the absence of a complete moratorium, the rebuilding of depleted shark populations requires very stringent controls on exploitation rates, the enforcement of appropriately low mortality rates, the protection of critical habitats, monitoring, and education [32]. Such controls have been implemented with some success in parts of the United States, for example [8], but would be more difficult to enforce elsewhere [15,19,35]. Given that the costs of these measures can be considerable and are currently carried by tax payers in shark fishing nations, some of this burden could be shifted to the shark fishing and fin export industries. Shark fins are a luxury product [25], which means that demand is unlikely to be curbed by modest price increases. Thus, imposing taxes on the export or import of shark fins will generate income that could be directed to these domestic shark fisheries management efforts.

Another option is to focus on the most vulnerable species, particularly those that are heavily affected by the global fin trade. CITES currently protects three of the most charismatic species, the whale, basking, and white sharks. These species are well-known and support large dive and ecotourism industries [36] hence there is also an economic incentive for their protection. Many other species, however, are of similar conservation concern [3], yet their attempted listing under CITES has so far failed due to opposition from shark-fishing and -consuming countries. In any case, trade bans for the most depleted species need to be combined with scientifically-based catch limits, and appropriately-sized protected areas, such as the shark sanctuaries recently established by a handful of developing nations. Given the continuing high trade volume for shark fins (Fig. 1D–F), large unreported catches and discards (Fig. 2), and excessive exploitation rates (Fig. 3), it is here suggested that protective measures have to be scaled up significantly in order to avoid further depletion and the possible extinction of sharks, with likely severe effects on marine ecosystems around the world.

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