Rev Fish Biol Fisheries (2008) 18:427–442
DOI 10.1007/s11160-008-9084-z

Shark bycatch and depredation in the U.S. Atlantic pelagic longline fishery

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Received: 21 December 2007 / Accepted: 2 April 2008 / Published online: 6 May 2008

Abstract The non-target bycatch of sharks in pelagic longline (PLL) fisheries represents a potential source of compromise to shark populations worldwide. Moreover, shark bycatch and depredation (damage inflicted on gear, bait, and catch) complicates management of sharks and other species, and can undermine the operations and financial interests of the pelagic longline industry. Thus, deducing means to reduce shark interactions is in the best interest of multiple stakeholder groups. Prior to doing so, however, the extent, cause and effect of these interactions must be better understood. In this review we address or conduct the following in relation to the U.S. Atlantic, Gulf of Mexico and Caribbean PLL fishery: (1) U.S. management governing shark interactions in the Atlantic; (2) the primary species encountered and historical shark catch data associated with PLL fishing in the Atlantic; (3) a historical comparison of area-specific shark species catch records between the two primary sources of shark catch data in this fishery; (4) the conditions and dynamics that dictate shark interactions in this fishery, and potential means to reduce these interactions, and; (5) a synthesis of the estimated impacts of this fishery on shark populations relative to other fisheries in the Atlantic. As has been found in other PLL fisheries, the blue shark (*Prionace glauca*) is clearly the shark species most commonly encountered in this fishery in the Atlantic, and receives the majority of attention in this review. U.S. management areas with high relative shark species diversities had a greater divergence in historical shark species percent-compositions between data sources (Pelagic Observer Program versus mandatory pelagic Logbook databases); this complicates the ability to conclude which species are most impacted by PLL fishing in those areas. The current fishing effort by the U.S. PLL fleet is small compared to that of PLL fishing targeting sharks in the Atlantic by non-U.S. fleets, and therefore poses a comparatively lower threat to the stability of Atlantic shark populations. However, incidental shark encounters are inevitable in U.S. Atlantic PLL fishing operations. Thus, it is in the best interest of all stakeholders in the Atlantic to better understand the extent and conditions governing these interactions, and to explore methods to reduce both their occurrence and those aspects leading to higher rates of incidental shark mortality.

Keywords Bycatch · Depredation · Shark · Pelagic longline fishing · Mitigation

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Introduction

It is widely held that the incidental capture of sharks in worldwide fisheries represents a massive challenge to the proper management and conservation of this group (e.g., Gilman et al. 2007a; Barker and Schluessel 2004). As in high-seas commercial fisheries around the globe, sharks compose the highest percentage of non-target bycatch in the U.S. Atlantic pelagic longline (PLL) fishery for swordfish (*Xiphias gladius*), tunas (Northern bluefin [*Thunnus thynnus*]; yellowfin [*Thunnus albacares*]; and bigeye tuna [*Thunnus obesus*]), and tuna-like species (Gilman et al. 2007a; Beerkircher et al. 2002). Although rarely targeted in U.S. domestic PLL operations, sharks and rays constituted 25% of the overall catch in this fishery between 1992 and 2003 according to observer data (Table 1) (Abercrombie et al. 2005). When accounting for pelagic longlining by foreign fishing fleets, it has been estimated that number of individuals and overall shark biomass captured by this method in Atlantic waters is vast, rivaling both the Indian and Pacific oceans (Bonfil 1994). Sharks are also among those species responsible for depredation—inflicting damage upon bait, gear or hooked target catch in this fishery (Gilman et al. 2007a; Hoey and Moore 1999).

In the Atlantic, the sharks most commonly encountered in PLL operations are species of the family Carcharhinidae, and, to a lesser extent, the family Lamnidae. As several of these species are either prohibited from being landed or lack appreciable commercial value, discard rates are high. For these reasons, interactions with sharks in the domestic PLL fishery are typically perceived as a relative nuisance, hindering commercial operations for tuna and swordfish namely through damage to and loss of gear, target catch (via depredation) and valuable fishing time (Gilman et al. 2007a).

Concurrently, physiological stress and physical trauma imposed during capture and handling can compromise the ultimate post-release survival of discarded by-caught sharks (Skomal 2007; Bonfil 1994; Berkeley and Campos 1988). Discard mortality inflates total fishing mortality (F) and when coupled with directed landings, has imperiled shark populations around the globe (Musick et al. 2000). The control of unintended shark interactions therefore benefits not only the longline fishing industry, but also the viability of certain shark populations. Importantly, bycatch issues have been instrumental in prompting several regulatory measures imposed upon the Atlantic PLL fleet. It is therefore clear that mitigating the extent of incidental takes in this fishery, including sharks, will mutually benefit industry, management and conservation communities alike.

In the following we address the estimated extent of shark bycatch, the species composition of this catch, and, to a lesser extent, the issue of shark depredation in the U.S. Domestic PLL fishery of the Atlantic, Caribbean and Gulf of Mexico. We analyze the cohesion between available data sources, and present ongoing research and potential strategies to reduce the rate of shark interactions in this fishery. Before mitigation strategies can be initiated, however, it is first essential to fully explore the extent and nature of the shark interactions.

Table 1 Reported catch by scientific observers on U.S. pelagic longline vessels between 1992–2003 (data obtained from Abercrombie et al. 2005)

Catch reported	Percent of overall catch
Swordfish	27.3
Sharks/rays	24.8
Yellowfin/bigeye/bluefin tuna	21.1
Finfish	17.8
Other tuna species	3.9
Other billfish	3.5
Unknown species	1
Marine turtles, marine mammals, and birds	0.7

Geographic fishing zones and fleet characteristics

The U.S. Atlantic, Caribbean and Gulf of Mexico PLL fishery is typically analyzed and managed according to 11 distinct statistical areas (Fig. 1). Within this geographic domain, there have conventionally been five sub-fisheries composing the overall domestic operation: the Caribbean Island Tuna and Swordfish fishery; the Gulf of Mexico Yellowfin Tuna fishery; the South Atlantic Florida East Coast to Cape Hatteras Swordfish fishery; the Mid-Atlantic Swordfish and Bigeye Tuna fishery; and the U.S. Atlantic Distant Water Swordfish fishery. A smaller-scale PLL operation also targets wahoo (*Acanthocybium solandri*)

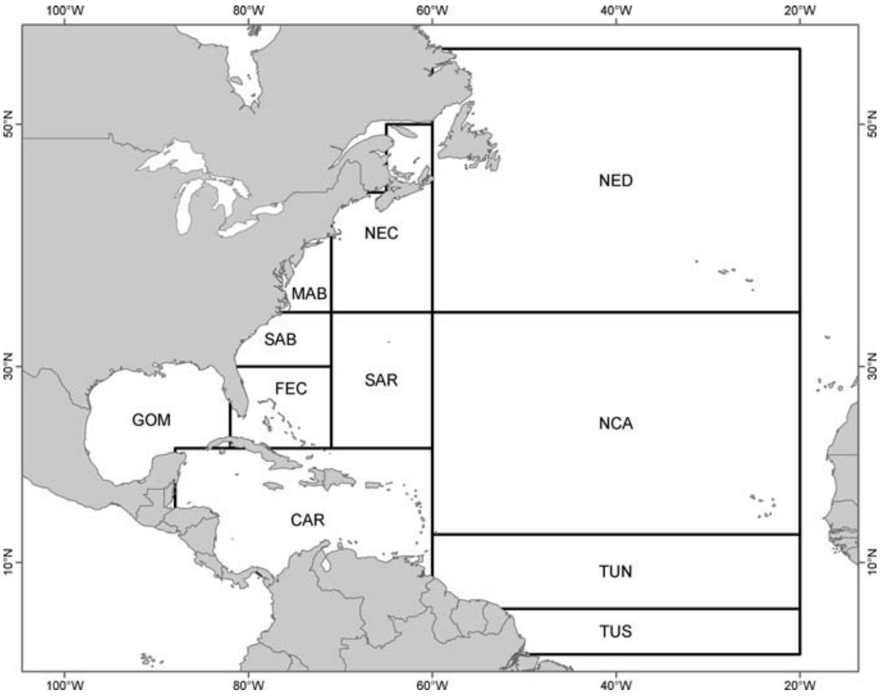

Fig. 1 Designated management zones of the U.S. pelagic longline fishery. Acronyms are defined as follows: 1, Caribbean (CAR); 2, Gulf of Mexico (GOM); 3, Florida East Coast (FEC); 4, South Atlantic Bight (SAB); 5, Mid Atlantic Bight (MAB); 6, Northeast Coastal (NEC); 7, Northeast Distant (NED); 8, Sargasso (SAR); 9, North Central Atlantic (NCA); 10, Tuna North (TUN); and 11, Tuna South (TUS). Source data for map production provided by Lance Garrison and NOAA Fisheries (USA)

and dolphin-fish (*Coryphaena hippurus*) in the Atlantic. These fisheries, which are comprehensively described in the Consolidated Highly Migratory Species Fishery Management Plan (HMS FMP) (NMFS 2006a), are diverse in their fishing regimes, gear types, ranges and degree of transience, vessel numbers and sizes, and whether seasonal or perennial in operative nature. As such, these fisheries tend to traverse and operate in more of the statistical areas than implied solely by their descriptive titles.

Although varied according to target species and conditions, the gear typically employed by the U.S. domestic PLL fleet is of the “Florida-style” (Beerkircher et al. 2002; Berkeley et al. 1981). However, various gear (and bait) requirements to be described in the sections that follow, have been instituted in recent years to mitigate bycatch of marine mammals, sea turtles and alternative species (NMFS 2006a).

Regulations imposed on the U.S. domestic PLL fleet have reduced the numbers of permitted and active vessels to approximately 80 to 100 operating collectively in the Atlantic Ocean, Gulf of Mexico, and Caribbean Sea (NMFS 2006a). Accordingly, the extent that sharks are impacted by this fishery has also likely been reduced. Although lobbied to do so by the International Commission for the Conservation of Atlantic Tunas (ICCAT), international fleets are not governed by U.S. management policy regarding strategies to reduce bycatch of marine mammals and sea turtles (PLTRT 2006), nor are the data of landings and discards from these international operations reflected directly in domestic assessments. U.S. domestic fisheries data are thus not accounting for the presumably high number of sharks encountered by international vessels in non-U.S. Atlantic waters.

Management parameters

The management of Atlantic highly migratory species in the United States is dually governed by the Magnuson-Stevens Fishery Conservation and Management Act (reauthorized as the Sustainable Fisheries Act) and Atlantic Tunas Convention Act (ATCA) (NMFS 2006a). Pelagic species other than billfishes (family Istiophoridae) have been managed under the Fishery Management Plan for Atlantic Tunas, Swordfish, and Sharks (ATSS FMP; NMFS 1999). However, this FMP was merged with the Atlantic Billfish FMP (implemented in 1988) in October 2006 creating the Consolidated HMS FMP, which instituted further management actions, including additional bycatch mitigation strategies. The basis for these inclusions centers on, among other facets, the adoption of regulations upheld or recommended by international bodies. For instance, the ATCA includes provisions that authorize the National Marine Fisheries Service (NMFS) to promulgate actions recommended by ICCAT in regard to HMS in the Atlantic (PLTRT 2006).

Shark management

In general, the extent of U.S. management attention dedicated to sharks is considerable. In addition to ICCAT reporting, this can be attributed to several actions: the establishment of the ATSS FMP; the International (FAO 1999) and U.S. (NMFS 2001) Plans of Action for the Conservation and Management of Sharks; and additional publications reporting alarmingly heavy declines in global shark populations (e.g., Baum et al. 2003). From 1993 until the approval of the ATSS FMP, shark management in the Atlantic PLL fishery was governed by the Federal Management Plan for Sharks of the Atlantic Coast (NMFS 1993; 2006a, b). This plan established the following categorical designations for the management of sharks based upon typical domains and morphometric characteristics: small coastal; large coastal; and pelagic sharks. The FMP also instituted several measures including an indirect ban on "finning". In 1999, the ATSS FMP was implemented, heightening management priority in the Atlantic PLL fishery for sharks through such acts as instituting bag limits and size quotas (NMFS 2006b). Amendment 1 to this FMP (NMFS 2003) provided further supplementation, enforcing limitations on fishing through area closures and additional policies. In addition, NMFS prohibited PLL fishing in the Florida East Coast, Charleston Bump, DeSoto Canyon, and Grand Banks areas beginning in 2000 and 2001 as a means to reduce bycatch of juvenile swordfish, billfish, and sea turtles. Although an incidental consequence, the restricted ability to fish also prevents taking sharks in these geographic areas. Concurrently, the Shark Finning Prohibition Act (2000, 2002) enforced tight restrictions against the exclusive take of fins from individual animals (NMFS 2006b).

Certain shark species cannot be landed, but instead must be discarded with minimal physical harm and without removal from the water (NMFS 2003). The prohibited coastal and pelagic species most likely to be encountered during PLL operations include the night shark (*Carcharhinus signatus*), the dusky shark (*Carcharhinus obscurus*), the longfin mako shark (*Isurus paucus*) and the bigeye thresher shark (*Alopias superciliosus*). In contrast, several species caught in U.S. pelagic operations can be retained assuming adherence to accompanying regulations. These include large coastal sharks such as the tiger shark (*Galeocerdo cuvier*) and the silky shark (*Carcharhinus falciformis*) as well as pelagic sharks such as the shortfin mako shark (*Isurus oxyrinchus*), the common thresher shark (*Alopias vulpinus*), the porbeagle shark (*Lamna nasus*), the oceanic whitetip shark (*Carcharhinus longimanus*) and the blue shark (*Prionace glauca*) (NMFS 2003). Upcoming changes through the implementation of Amendment 2 to the Consolidated HMS FMP may only permit the retention of the sandbar shark (*Carcharhinus plumbeus*) to vessels operating within a newly established research fishery and would make porbeagle sharks a prohibited species (NMFS 2007a).

Importantly, the U.S. has no governance over the landing of sharks in international waters by non-U.S. vessels, where a high proportion of Atlantic shark landings reportedly occur (Crowder and Myers 2001). Moreover, there remains a paucity of direct management and enforcement by ICCAT regarding sharks taken in international waters.

Background on available data sources

Due to elasmobranch management and conservation not historically being deemed priorities, and the perceived and substantive difficulty in accurately quantifying shark bycatch (Bonfil 1994), there has until recent years been an under-analysis of the extent of global shark bycatch and its impacts on population abundances. Although not to the same extent as with cetaceans and sea turtles, management and conservation attention dedicated to incidental shark interactions in the U.S. PLL fishery has, however, heightened in recent years, resulting in a variety of reports, peer-reviewed publications, and documents addressing shark bycatch in this fishery. Much of this literature was based on shark catch, discard, and landings data collected prior to the increased fisheries data collection procedures for elasmobranchs now in place. For the U.S. domestic fishery, these include dealer reports, tournament and weigh-out records, survey data and, most extensively, Pelagic Observer Program (POP) data (since 1992) and mandatory pelagic Logbook (Logbook) data (since 1982). Additionally, the Canadian Observer Program has recorded catches in the North Atlantic.

Despite attempts by authors to reconcile these various data sources, the capacity to utilize these data for management purposes has been limited. This is primarily due to the diversity of the reporting sources, and multitude of confounding fishing, geographical, and reporting variables (Crowder and Myers 2001). In addition, the lack of emphasis on sharks in earlier years presumably resulted in cases of non-reporting and misidentification. Additional variables that compromise management's use of these data include the following: large geographic regions encompassing the reporting areas; shifts in gear regimes; regulatory transitions; diversities in fishing strategies or target species; skewed data from disproportionately high sharks takes from limited but often uncharacteristic (and under-described) sets or conditions (Hoey and Moore 1999); and in relation to abundance trends, the uncertainty in the rates of discard mortality for sharks following longline capture (Bonfil 1994). Because identifying the species responsible for depredating gear, bait, and target catch is not always possible, establishing the rates of shark depredation in the PLL fishery has also remained unresolved in associated reporting (L. Beerkircher, NMFS, pers. comm.).

Finally, much of the available literature on shark interactions was produced prior to the mandatory changes in gear and bait regulations for the U.S. PLL fleet in 2004. There is little recent literature concerning shark interactions and the new gear configurations or comparisons between configurations. Moreover, until a more substantial time period has elapsed, it would be inappropriate to ascribe any annual changes observed in shark catch-per-unit-effort (CPUE) to the adoption of these mandatory shifts.

Methods for shark catch analysis

POP and Logbook databases are the principle recording and data sources documenting shark catches in the U.S. commercial PLL fishery. However, no attempt has been made to evaluate the consistency between these two data sources in resolving the relative species-specific shark catch rates according to region. Establishing whether the POP and Logbook databases are strong proxies for one another as indicators of shark species makeup in a given area will help elucidate the efficacy of both past and future independent and joint uses of these data sources, and strengthen convictions regarding which shark species are most impacted by PLL fishing in particular statistical areas. To address this, we conducted a pairwise analysis of the two independent time-series datasets for the years 1992–2005, the period in which data was made publicly available for both sources by the NMFS Southeast Fisheries Science Center (SEFSC) (http://www.sefsc.noaa.gov/commercialprograms.jsp). POP data, which is well described in Beerkircher et al. (2002), is collected in a limited number of fishing trips, whereas mandatory Logbook data is representative of a far more extensive sample of trips. The criterion for inclusion of a particular statistical area in the analysis was a minimum of 1000 sharks independent of species reported in the POP database for the years 1992–2005 collectively (number of trips with POP observers, and not necessarily shark catch rates, governed shark catch levels being inferior to this minimum level). Six statistical areas shown in Fig. 1 (MAB, NED, NEC, SAB, FEC, and GOM) met this criterion and shark species catch compositions per year were derived for each independently. As it is not only the variance between numbers of trips, but also the fact the trips and precise coordinates generating the data themselves were different, the analysis utilizes a conservative percentage as opposed to raw number approach for sharks per data source, species, and year. Assessing shark catch of species against each other also helps offset the fact that CPUE is not calculated for this analysis. Overall sharks in a given year and area considered only those 19 species/categories commonly reported by both data sources. Independent samples t tests were used to compare percent shark species between POP and Logbook for the 1992–2005 period. Because the category was absent from the Logbook database, skates/rays was excluded from this analysis. Mean percentages ±95% Confidence Intervals are presented for these results for each statistical area. To account for the 19 species compared for each year within given areas, a Bonferroni correction was performed, and results considered significant according to $\alpha = 0.003$.

Results and discussion of shark catch analysis

All pairwise comparisons for the analysis of shark catches by POP and Logbook data are illustrated in Fig. 2(a–f). When accounting for the period 1992–2005, catch percentages by species represented by the POP database strongly mirrored Logbook data for the NEC (Fig. 2a) and NED (Fig. 2b), with no significant differences found between shark species percentages in either area. In contrast, the others areas, most notably the GOM (five species with significant differences) (Fig. 2c) and SAB (four species with significant differences) (Fig. 2d), exhibited a weaker correspondence in shark species percentages between the two data sources. The likely explanation for this involves the range in diversities of the sharks that were caught in the different statistical areas. Pooled 1992–2005 data reveal that over 90% of the shark catch was composed of only two species (blue and shortfin mako sharks) in both the NEC and NED, both easily identifiable. Conversely, the other areas possessed a higher diversity of shark species more routinely captured, especially coastal requiem sharks that are less distinguishable from one another for identification purposes. These factors increased the probability for shark misidentifications and the likelihood that disproportionate catches of certain species occurred due to atypical sets or conditions, or, when regulations allowed, from the purposeful targeting of coastal sharks in select U.S. commercial PLL trips as alluded to by Hoey and Moore (1999). Interestingly, PLL fishers consistently attempted to categorize captured sharks as a particular species, as indicated by the negligible number of “unidentified sharks” in Logbook database across years and statistical areas. This differs from the POP database where observers more commonly labeled cryptic sharks as “unidentified sharks” (Fig. 2a–f). The resolve to identify species by fishers could have led to higher rates of misidentifications, particularly for cryptic congeneric species such as dusky, sandbar and silky sharks.

In addition, the low relative number of POP trips in relation to Logbook trips increased the chances that seasonality or precise geography within a statistical area influenced shark catch compositions. For example, the blacktip shark was the prevailing species listed in the Logbook for the GOM, significantly outweighing the proportion of that species documented by the POP, which instead was dominated by the silky shark. The MAB (Fig. 2e) had moderate consistency between the two data sources (two species with significant differences), representing a convergence of that found in the GOM at one extreme, and NEC and NED at the other. Although like in the NEC and NED blue sharks had the highest catch rates in the MAB, diversity of sharks captured exceeded that found in those areas, and, due to the reasons discussed, the moderate percentage of coastal sharks increased the potential for variability between the databases. Indeed the two species that differed significantly between POP and Logbook in the MAB were the coastal blacktip and sandbar sharks.

In general, it appears that areas with lower shark diversity such as the NEC and NED are more amenable to analysis through either POP or Logbook as proxies for each other. In contrast, the interchangeable use of the data sources for analysis of the catch rates in regions of higher shark diversity (e.g. FEC (Fig. 2f)) should be conducted with caution. Ideally, both data sources should be utilized, but the discrete characteristics associated with each considered, when assessing shark catches by the U.S. domestic PLL fishery.

Incidental shark takes in the Atlantic

General takes according to species

Although routinely caught in Atlantic PLL operations, shortfin mako and common thresher sharks will not be addressed to the same degree here. Due to existing market values, these species and to a lesser extent select coastal species, represent the elasmobranchs more regularly landed when caught by U.S. commercial PLL operations during open seasons in the Atlantic. Although not necessarily targeted as the sole basis of a trip as are tuna or swordfish, the incidental capture of these species is preferred over that of tiger or blue sharks, which hold minimal commercial value in the U.S.

Many reports pertaining to the U.S. Atlantic PLL fishery, most notably those submitted to ICCAT, have addressed shark landings and bycatch since the mid-1990s, when the management of sharks began receiving heightened attention. POP and Logbook data have been the dominant data sources for the bulk of this output, with several other sources providing valuable direct or ancillary data.

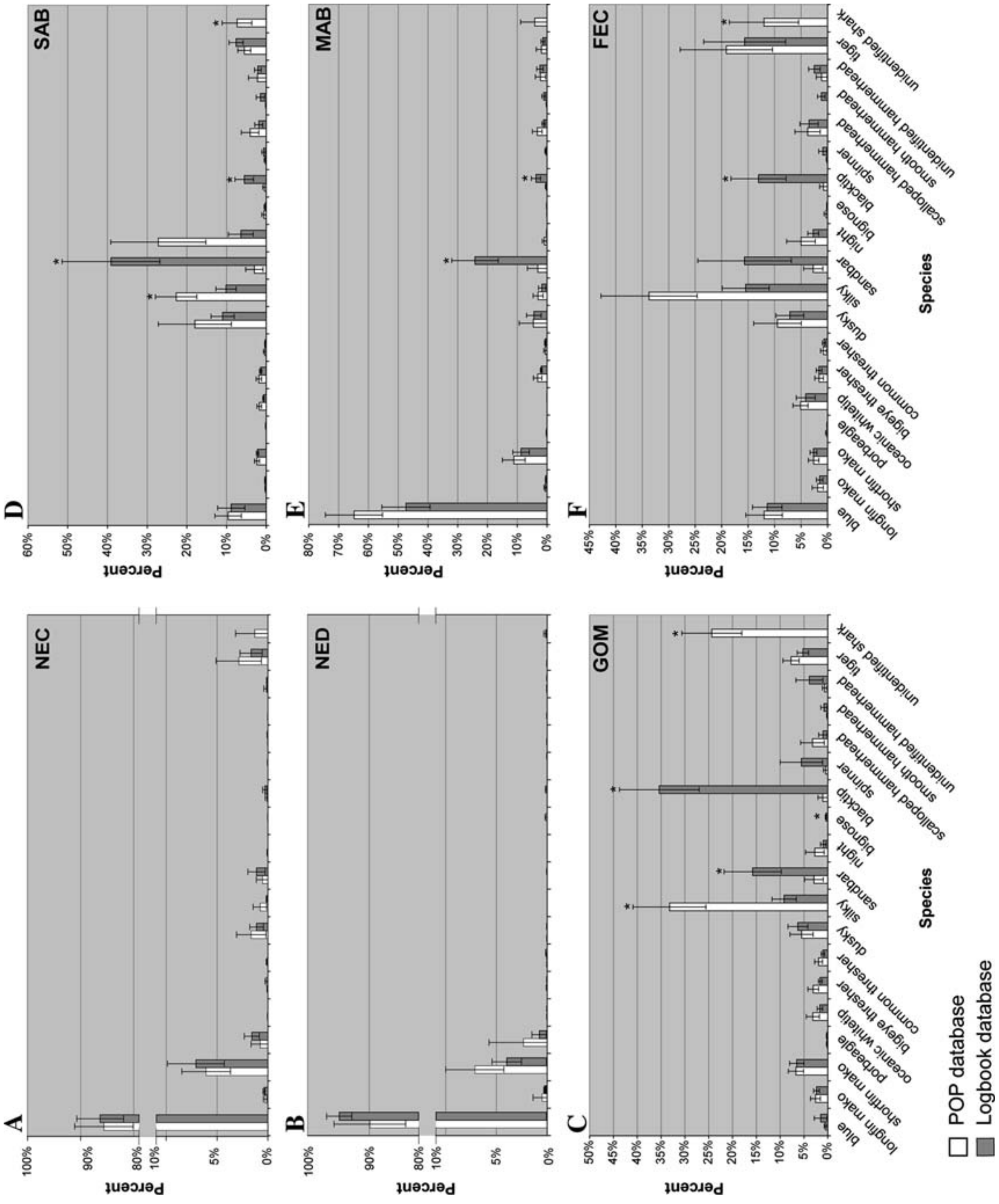

Fig. 2 (**a**–**f**) Pairwise comparison (POP versus Logbook databases) of mean shark catch percentages (±95% CI) in designated statistical areas (see text and Fig. 1) for the period 1992–2005. Percentages in a given year were derived by dividing the total number of individuals of a given species by the total number of sharks caught that year represented by the 19 species/categories common to both POP and Logbook (excluding skates/rays, or species that were listed exclusively in one database or the other). The designation of unidentified shark was derived in the Logbook database by pooling of the separate categories for other coastal and other pelagic sharks and in the POP database by pooling the categories sharks/requiem and sharks. Total shark catches for a given species in the Logbook were derived by pooling the categories kept, discarded alive and discarded dead for that species. Three species not alluded to elsewhere in the text are presented in this figure: the spinner (*Carcharhinus brevipinna*), bignose (*Carcharhinus altimus*), and smooth hammerhead (*Sphyrna zygaena*) sharks. Asterisks represent significant ($P < 0.003$) differences between POP and Logbook pairwise mean percentages for a given species

Independent of region, blue sharks represent by far the most frequently captured shark in U.S. Atlantic PLL operations, constituting 17–32% of the overall catch reported in this fishery between 1987 and 1995 (Cramer 1997). This is consistent with the findings from fishery-independent data sources that blue sharks represent by far the most abundant pelagic shark in the Northwest Atlantic (Simpfendorfer et al. 2002). The species reportedly comprises 50% of the universal Northwest Atlantic PLL bycatch, a group of species not comprised exclusively of sharks (Crowder and Myers 2001). A conventionally unwanted species in domestic tuna and swordfish operations, blue shark discards peaked at an estimated 29,000 individuals in 1993 (NMFS 2006b). As of 2000, estimated annual discards for the species were set at 1,575 metric tons (mt) based on POP data (Harrington et al. 2005). In comparison, silky shark discards (mt) were predicted to be (163); dusky shark (113); sandbar shark (40); bigeye thresher shark (39); and the scalloped hammerhead shark (*Sphyrna lewini*) (32) (Harrington et al. 2005). In an analysis by Hoey and Moore (1999) of the POP data spanning 1990–1997, the following positively identified shark species were captured in descending order by number independent of area-caught or season: blue shark (19,264); silky shark (1,905); mako shark (1,726); dusky shark (1,122); hammerhead shark (multiple sp., 725); tiger shark (351); common thresher shark (348); sandbar shark (333); oceanic whitetip shark (262); blacktip shark (*Carcharhinus limbatus*) (92); and porbeagle shark (45). When taking into account the relative scarcity of blue sharks in more southern fishing zones (e.g., GOM), the magnitude of these disparities highlights both the comparative dominance of blue versus other shark species as bycatch in this fishery, and the disproportionate numbers of blue sharks taken in their prevalent take zones.

It has been reported that Canadian observers may only be documenting blue shark catches brought on deck, and therefore not accounting for any blue sharks that despite initially becoming hooked, had bitten through leaders and escaped prior to being landed (DFO 2002; Campana et al. 2005). Thus, blue shark catches may also be underreported in that fishery, an outcome not implausible for the U.S. domestic fishery as well. However, blue sharks have generally exhibited low mortality with regards to interactions with PLL gear. Low blue shark mortality at the time of capture has been observed, where dependent upon the study, 7–19% of the all blue shark discards were classified as deceased at the time of release (e.g., Cramer 1997; Campana et al. 2005). Diaz and Serafy (2005) reported that 69% of longline-caught blue sharks were released alive, but found mortality to inflate as animal size decreased.

Logbook data has reported an oscillating but declining trend in blue shark catch numbers during recent years (Crowder and Myers 2001; NMFS 2006b). Thus, in studies equating catchability (CPUE) with indices of abundance, Atlantic blue sharks are among those species reported to have undergone considerable population declines (Baum et al. 2003). The use of CPUE as an index of abundance, however, has been reported as problematic (Cooke and Beddington 1984). Accordingly, the extent of the reported blue shark decline (~60% since 1986) postulated by Baum et al. (2003) has been questioned by several authors on the basis that other factors aside from a decline in abundance could have explained the observed depression in CPUE (e.g., Campana et al. 2005). It is acknowledged, however, that the species has likely endured some level of decline in recent years (Brooks et al. 2005; Campana et al. 2006). If the supposition is true that virtually all PLL-caught blue sharks are discarded alive, the declines in abundance surmised by certain authors would only be conceivable due to a climb in natural mortality, high rates of delayed mortality due to lethal consequences from hook retention (Borucinska et al. 2002), an increase in landings of the species by non-U.S. fleets in North Atlantic high seas fisheries (Mejuto et al. 2005), or high discard mortality rates associated with capture in other fisheries, such as in the Northeast Atlantic drift gillnet albacore fishery where blue shark mortality has been reported as 91% at the time of discard (Rogan and Mackey 2007). The extent and primary stimuli for shifts in blue shark abundance remain uncertain.

Aside from the blue shark, recent declining trends in CPUE for other shark species caught in the U.S. Atlantic PLL fishery have been reported (e.g., Baum et al. 2003; Baum and Myers 2004). A similar pattern since the mid-1990s has been echoed via observer reports from Japanese vessels operating in the Atlantic (e.g., Senba and Nakano 2005). Whether or not a true reflection of declines in abundance, the decreases in catchability could also be explained by underreporting, increased bite-offs from lighter gear (Brooks et al. 2005) and the historical use of J-hooks, changes in observed fishing effort due to changes in gear or fishing distribution (Beerkircher et al. 2002), and speculatively, the potentially successful establishment of fishing strategies and gear configurations by industry to reduce shark interactions.

Takes according to region and alternative factors

The CPUE of blue sharks on the Grand Banks peaks in the summer months with reported rates of 0.10 (Cramer 1997c). This differs with the CPUE estimates of 0.001 in more southeast zones (GOM, SAB, and FEC). As a function of the high catch rates for the species in North Atlantic areas like the Grand Banks, Canadian fisheries account for a very high overall percentage of blue shark bycatch (DFO 2002). Blue sharks are also the primary bycatch species for the Northeast Distant (NED) fleet that targets swordfish (Hoey and Moore 1999).

Along with season and depth, behavioral thermoregulation also appears to be an important variable dictating the catch rates of blue sharks. Although widely distributed and known to conduct trans-Atlantic migrations (e.g., Stevens 1976; 1990), blue sharks appear to prefer cooler waters within their tropical, subtropical, and temperate domains. Catch rates of blue sharks have been found to decline by 9.7–11.4% in response to an only 0.6 °C increase in sea surface temperature (Watson et al. 2005). Not surprisingly, it has also been shown that blue sharks tend to prefer sub-surface depths that possess cooler temperatures (e.g., Simpfendorfer et al. 2002). However, more comprehensive studies on blue shark distribution according to full water column temperature profiles and thermocline dynamics are necessary before amending fishing practices in accordance with patterns in seawater temperatures.

In a study that assessed catch characteristics in the SAB and FEC statistical areas, a standardized CPUE estimate was derived for the shark species aggregate captured in PLL operations from 1992 to 2000 (Beerkircher et al. 2002). As referenced, silky sharks are second only to blue sharks in the total number of catches in this fishery. However, in assessments of the SAB and FEC exclusively, silky sharks were the predominant species captured (Beerkircher et al. 2002). Dusky and night sharks also exceeded blue sharks for CPUE and overall catch numbers. When evaluating the years 1992–2000, Beerkircher et al. (2002) also report a decline in silky, night, and scalloped hammerhead sharks in relation to 1981–1983 estimates taken from Berkeley and Campos (1988). These downward trends may reflect shifts in abundance, but could also be indicative of spatial and gear factors that have served to reduce catchability (Beerkircher et al. 2002).

Shark depredation

Depredation, the partial or complete removal of hooked fish and bait from fishing gear by non-target animals, can significantly hinder PLL operations and translate into appreciable losses of time and money (Gilman et al. 2007a). POP data indicates that of all damage imposed on the catch between 1990 and 1997 (4% of total observed catch), 68% occurred on catches of swordfish, yellowfin and bigeye tuna collectively (Hoey and Moore 1999). Sharks are presumed to represent one of the groups most responsible for depredation in U.S. domestic PLL operations. Although damaged catch has been reported in assessments of catch disposition by several authors (e.g., Hoey and Moore 1999; Beerkircher et al. 2004; Diaz 2006; Kerstetter and Graves 2006b), identifying the precise species responsible for the depredation is difficult (L. Beerkircher, NMFS, pers. comm.). The point of interaction is rarely if ever observed to confirm positive identification. In addition to sharks, cetaceans are also responsible for damaging catch, and pilfering baits and gear (Hoey and Moore 1999). In fact, depredation by marine mammals could equal or even exceed that by sharks in certain areas such as the MAB (L. Beerkircher, NMFS, pers. comm.). To facilitate the ability to distinguish between the depredating species, NMFS has recently implemented a new data collection protocol requiring more comprehensive reporting details (NMFS 2007b). However, even if able to distinguish the damage done by sharks versus other taxa, confirmation of the precise species of shark responsible, aside from the unambiguous bite of the cookie-cutter shark (*Isistius brasiliensis*), will remain extremely difficult. However, accounting for bite characteristics, and auxiliary factors such as the CPUE, abundance, distribution, and behavioral tendencies of potential depredating species may enable assured distinction between sharks and additional species, as well as between families of sharks.

Intuitively, longer soak times simply increase the probability that shark interactions with PLL gear will occur. In addition, when soak-times are extended, animals that become hooked are more likely to weaken or die and are thereby much easier targets for depredation by scavenging species such as blue sharks (Ward et al. 2004). Therefore, a reduction in soak times is a straightforward approach that can mitigate the rates of shark interactions.

Potential strategies to reduce shark interactions or mortality

Fishing practices

A comprehensive Atlantic Pelagic Longline Take Reduction Plan (APLTRP) was submitted to NOAA in 2006. Although not its objective, it is conceivable that some of the plan's measures intended by the Pelagic Longline Take Reduction Team (PLTRT) to reduce the number of serious injury interactions with pilot whales (*Globicephala* spp.) and Risso's dolphin (*Grampus griseus*) could have unintended benefits for sharks. The applicable proposals described in the PLTRP include proper handling protocols; mandatory mainline, gear and bait requirements to be discussed in greater detail shortly; and additional time-area closures.

There are also existing regulations applying to the Atlantic and GOM bottom longline fishery that may be effective tools in increasing post-release survival for sharks taken by PLL (NMFS 2006a). These include the immediate release of all non-target bycatch; the use of line-cutters and dip-nets for release purposes; and the maintenance of seawater flow across the gills (as must be maintained in sawfish caught by bottom longline). However, these should be viewed as techniques that could potentially reduce the detrimental effects from, rather than the rates of, interactions.

Additional studies have directly or indirectly suggested possible methods to reduce the number of shark interactions (Table 2). POP data indicates that overall shark catch rates have sometimes been skewed by sets landing disproportionately high shark catches (Hoey and Moore 1999). As previously touched upon, in certain instances this has been attributed to alterations in fishing strategy used to purposefully land increased numbers of coastal sharks (Hoey and Moore 1999). Alternatively, a particular set of conditions may unintentionally translate into higher catch rates. Whether or not intended, these particular sets can be analyzed for environmental and operative factors that may have contributed to the higher catch rates of sharks. A reversal in such measures could theoretically help circumvent high numbers of shark interactions in the future, or enhance the survivorship of discards. Modified techniques that have been used to land more sharks include fishing in more shallow absolute water depths, increasing the numbers of hooks deployed between floats, and generally setting gear closer to the bottom, presumably to land more coastal sharks during opened seasons (Hoey and Moore 1999). These strategies are likely to yield high shark catch rates under certain conditions, at least in relation to large coastal species. For instance, POP data has revealed that 67% of silky sharks taken in the GOM were caught in depths <1000 meters (m), while the majority of dusky sharks (SAB) were captured in absolute water depths of <500 m. As a basis of comparison, blue sharks and tuna were caught most frequently beyond the 1000-m depth contour, while mako and common thresher sharks very close to that threshold (Hoey and Moore 1999). In the GOM, conditions for highest silky shark catches closely resembled those for swordfish, morning gear retrievals from <1000-m depths. The avoidance by tuna-targeting vessels of areas (shallow absolute water depths, <500 m, in the GOM, SAB, and FEC) and diurnal periods where swordfish catches are high should thus simultaneously reduce incidental silky shark catches (Hoey and Moore 1999).

Additional studies have also documented the effects of gear shifts on CPUE. For example, comparisons of composite rope-steel ("Yankee") and monofilament gangions in one study yielded a lower CPUE of juvenile sandbar sharks (Branstetter and Musick 1993). In another study, the percentage of blue sharks captured with the use of monofilament gangions (66%) exceeded that when employing

Table 2 Newly established or pre-existing strategies that could potentially reduce the rate of shark interactions during pelagic longline fishing operations

Potential strategy	Findings of consequence	Prominent species assessed	Reference
A reduction in soak time	Capture rates of a majority of sharks increase with soak time	Blue shark	Ward et al. (2004)
Fishing in deeper absolute water depths	Opposite practices have increased catch rates	Coastal sharks[a]	Hoey and Moore (1999)
Decreasing the number of hooks deployed between floats			
Setting gear farther from the seafloor			
Utilizing composite rope-steel and monofilament gangions	Reduction in the CPUE of juvenile sharks	Sandbar shark	Branstetter and Musick (1993)
A switch from mono- to multifilament gangions	Higher percentage of sharks in study were caught by monofilament (66%) rather than multifilament gangions (34%)	Blue shark	Stone and Dixon (2001)
The use of circle hooks[b]	Higher rate of capture than with J-style hooks	Blue shark	Watson et al. (2005)
	No discernable difference in blue shark catch rate between hook types		Yokota et al. (2006)
			Kerstetter et al. (2006)
			Kerstetter and Graves 2006b
The use of mackerel baits	Reduction in catch rates associated with both circle and J-style hooks		Watson et al. (2005)

[a] For species in this category see Bonfil (1994) or NMFS (1999)

[b] Now mandatory

multifilament gangions (34%) (Stone and Dixon 2001). Shortfin mako shark catches exhibited the same pattern (60% and 40% for 'mono' and 'multi' respectively). Stone and Dixon (2001) surmised that the relative aversion to the multifilament gangion could have been a function of strong visual acuity, a trait shared by pelagic predators that often hunt nocturnally. Investigating the effects of these alternate gears on additional elasmobranch species, along with their effects on catch rates of commercial species targeted in the PLL, is certainly warranted for standardizing historical catch rates.

Shifts in gear regimes can influence the catchability of both targeted and non-targeted species. Several studies have addressed the effects on catch rates, location of hooking (e.g., internal versus external; gut versus mouth hooking), and resulting injuries and mortalities induced by differing hook types in teleosts (e.g., Bacheler and Buchel 2004; Cooke et al. 2005), pelagic teleosts (e.g., Domeier et al. 2003; Kerstetter and Graves 2006a; Kerstetter et al. 2006; Kerstetter and Graves 2006b) and in sea turtles (see Garrison 2003; Watson et al. 2005).

Among the studies considering shark catchability as a function of hook or bait type, the results are inconclusive regarding catch rates and the use of circle hooks. Watson et al. (2005) found circle hooks to yield higher catch rates of blue sharks than with J-style hooks, independent of bait type. This discrepancy, however, was acknowledged as a possible function of increased bite-offs of the monofilament leaders (and thus high undocumented blue shark catch) due to the swallowing and deeper lodging of J-style hooks. Otherwise, studies have uniformly found no conspicuous effect between the hook types on blue shark catch rates (Yokota et al. 2006; Kerstetter et al. 2006; Kerstetter and Graves 2006b). Although hooking has been found to be deeper (e.g., esophageal or stomach) in J-style than in circle hooks independent of bait type and offset (in circle hooks), catch mortalities of blue sharks have not differed accordingly (Yokota et al. 2006; Kerstetter and Graves 2006b; Kerstetter et al. 2006). The lack of difference is likely ascribable to the species already displaying high hooking survivorship, whereby discerning a difference due to hook type is confounded. In general, studies evaluating the effects of variable hook or bait types on catch rates (Yokota et al. 2006; Watson et al. 2005; Kerstetter and Graves 2006b) have found that the use of 18/0 (non-offset) circle hooks compared to 9/0 and 10/0 J-style hooks (in some cases in conjunction with mackerel bait) reduce the bycatch of sea turtles, increase the catch of target species such as yellowfin and bigeye tuna, increase the number of animals hooked in the mouth or jaw as opposed to the esophagus or gut, and mitigate the degree of hooking mortality and (estimated) post-release mortality of by-caught species. Interestingly, it has been found that the use of mackerel baits reduced the blue shark catch rates associated with both circle (31%) and J-style (40%) hooks (Watson et al. 2005), suggesting that a switch in bait regimes rather than hook type may hold more influence on mitigating shark bycatch. Although not a direct consequence of these studies, NMFS instituted a policy in August 2004 requiring all PLL vessels, time and area-independent (excluding the NED), to use only 16/0 or larger non-offset circle hooks or 18/0 or larger circle hooks with an offset not exceeding 10 degrees (NMFS 2005; NMFS 2006). Moreover, only whole finfish and squid baits may be utilized in the majority of areas, while only whole mackerel and squid baits may be utilized in the NED (NMFS 2006a). Such policies could secondarily affect sharks.

Table 3 Status of elasmobranchs at time of gear retrieval in the pelagic longline fishery off the southeastern U.S., 1992–2000

Species	*N*	Percent mortality
Silky	1446	66.3
Dusky	679	48.7
Night	572	80.8
Blue	434	12.2
Tiger	263	3.0
Scalloped hammerhead	199	61.0
Oceanic whitetip	131	27.5
Rays	113	0.0
Sandbar	111	26.8
Bigeye thresher	81	53.7
Shortfin mako	80	35.0

Data source: Pelagic Observer Program (POP), obtained directly from Beerkircher et al. (2002)

The potentially positive impact of circle-hook usage on hooking mortality and ultimate discard survivability is not a trivial issue for sharks. Significant interspecific differences in catch mortality rates have been found in sharks captured by bottom (Morgan and Burgess 2007) and pelagic (Beerkircher et al. 2002) longline operations (Table 3). Even if a shark caught by PLL is discarded in seemingly good condition, it may ultimately succumb due to physiological stress imposed during capture and handling (Moyes et al. 2006; Skomal 2007), and cryptic physical injuries incurred while on or while being removed from the hook. Studies have reported on the potentially deleterious consequences of hook retention in blue sharks (Borucinska et al. 2001, 2002). Excluding tiger sharks and rays, most species addressed by Beerkircher et al. (2002) demonstrated moderate to high rates of mortality upon gear retrieval. As previously discussed, even the resilient blue shark has exhibited modest (7–19%) rates of hooking mortality (e.g., Cramer 1997; Campana et al. 2005). Thus, there is room for survival enhancement in even the more resilient shark species.

The management regime shift to circle hooks in the U.S. PLL fishery in 2004 has likely resulted in a still unquantified change in shark catch rates. Future analyses of shark CPUE changes via POP or logbook data will require careful comparison to account for the change in catchability between the two hook types. There are reportedly several ongoing studies assessing the catch rate and hooking injury effects of circle hooks on a wide array of shark species caught in PLL operations. Promulgation of the their findings, along with the continued investigation of the effects of both hook and bait types in additional species of sharks caught by PLL, is essential in light of these mandatory gear shifts.

Shark repellants

Historically, there have been numerous measures designed, tested and implemented to repel sharks (see Sisneros and Nelson 2001). The primary impetus behind the majority of these has been to deter shark attacks on humans. In response to the negative implications associated with incidental takes of many shark species in the PLL fishery, however, attention related to technologies with potential hook-repelling implications has heightened in recent years.

At present, investigators and companies are reportedly augmenting previously successful demonstrations of chemical aversions in tropical reef-oriented shark species by field-testing semiochemicals and other chemical synthetics repellants in pelagic species such as blue sharks (Shark Defense 2007). Although not yet reported in the literature, these agents could be effective repellents. Sharks have exhibited aversions to certain chemicals, including ammonium acetate (a major component in decaying shark flesh) and other semiochemicals emitted from predators (Sisneros and Nelson 2001). However, the methods of application and the deployments of such technologies in real time remain uncertain. Field investigation into the efficacy of these practices has also proven challenging in that it is supposedly difficult to administer and monitor the repellants in a controlled fashion.

Most recently, the World Wildlife Fund's (WWF) 2006 International 'Smart Gear" Competition grand prize was awarded for an approach intended to deter sharks from interacting with hooks. The premise, deployment of a highly powerful but small magnet above the shaft of a hook, is meant to repel sharks through an overstimulation of their acutely sensitive electromagnetic receptors. At present, the magnets have successfully deterred lemon (*Negaprion brevirostris*) and nurse (*Ginglymostoma cirratum*) sharks and have shown little interference on targeted species. Several additional studies assessing responses in sharks to magnets and electropositive rare-earth metals, including those on certain species caught in PLL operations, are reportedly in progress. However, the practical utility of implementing these approaches in the PLL fishery has yet to be documented in a peer-reviewed publication.

Synthesis and next steps

Shark bycatch and depredation represent substantive issues that have impacted the proper management and population stability of sharks in global PLL fisheries, and have negatively impacted the fishing operations and financial interests of PLL fishing industry itself (Gilman et al. 2007a). However, the reduction in U.S. commercial PLL fishing effort in recent years has presumably reduced the relative scale of impacts by this fishery. Excluding 1991 for which data was absent, the average annual catch weight of blue sharks from 1990 to 1999 was more than 50-fold higher in recreational (hook) than in U.S. commercial PLL fisheries (annual range of 9–340 mt [annual mean value of 114 mt] for recreational; 0.12–8.00 mt [annual mean value of 2 mt] for commercial) (Cortés 2002). So in fact, targeted or incidental capture of sharks in U.S. recreational (hook) fisheries may have posed a more significant threat to certain shark populations even before fishing effort by the U.S. domestic PLL fleet decreased to it current levels, and presumably continues to eclipse commercial catch rates of certain pelagic shark species. In addition, the current fishing effort by the U.S. PLL fleet appears, according to ICCAT, diminutive in relation to landed and discarded pelagic sharks captured in international Atlantic waters by non-U.S. fleets (Table 4) (ICCAT 2007). Hence, shark landings and discards by the U.S. commercial PLL do not represent the hazard to certain populations that other fisheries pose. Nevertheless, as is the case in other oceans, shark encounters are inevitable in U.S. Atlantic PLL fishing operations. It is therefore in the best interest of all stakeholders to better understand the extent and dynamics of shark interactions, and to explore methods to reduce these interactions in the Atlantic.

Table 4 ICCAT total reported collective landings and discards (metric tons) from pelagic longline and other surface gears from 1995–2005

	USA	Spain	Portugal	Japan
Blue	3593	21,1583	54,077	9443
Shortfin mako	4662	25,901	8348	7934
Porbeagle	189	237	194	27
Oceanic whitetip	48	25	0	NA
Total	8492	237,746	62,619	17,404

To address this, an analysis of the primary available data sources (POP and Logbook) was necessary. We compared these two data sources across shark species, year and statistical area, and found the two sources to agree only in areas low in both species diversity and ambiguity in species identification. This agrees with other reports of concordance in species catch rates between the two data sources, such as the case with the easily distinguished blue and shortfin mako sharks (e.g., Brooks et al. 2005). Coastal species, from the family Carcharhinidae are far more indistinct, and likely misidentified at a high rate by fishers (Logbook) and Observers (POP). That coupled with other factors discussed herein likely explains the great disparities between POP and Logbook databases in annual catch composition in statistical areas where these coastal shark species occur more frequently during PLL operations. Additional analyses of season, water temperature profiles, and depth of fishing are necessary to establish a more thorough understanding of the conditions and areas that govern high rates of shark interactions.

As previously discussed, it is also important to better resolve the sources and rates of shark depredation across a variety of parameters. The prospect of doing so will be strengthened subsequent to the onset of more detailed recording protocols (e.g., estimation of whether a "shark" or "non-shark" is responsible) for damaged catch in the POP.

Anecdotal methods employed by individual fishers to reduce shark bycatch and depredation have been reported in other seas (Gilman et al. 2007a, b). Gaining such insights is an invaluable component to this assessment of the PLL fleet in the U.S. Atlantic. The incorporation of the fishing industry's strategies and viewpoints would thereby represent a logical next step in the assessment, especially in relation to shark bycatch and depredation mitigation practices.

Finally, the continued development, field-testing, and dissemination of new technologies and strategies to help reduce shark interactions in this fishery is imperative. The field testing of such technologies and strategies to reduce shark interactions should be as transparent as possible, and should include collaborative efforts between researchers and commercial fishers. Ironically, the same international fisheries management institutions that have not managed pelagic sharks effectively may serve as the best conduits for exporting shark bycatch reduction technology throughout the global PLL fisheries.

Acknowledgments For detailed worldwide perspectives regarding topics covered herein, we refer readers to the multinational report by Gilman et al. (2007b): Shark Depredation and Unwanted Bycatch in Pelagic Longline Fisheries (http://www.wpcouncil.org/pelagic/Documents/Shark-Longline_Interactions_Report.pdf as of December 17, 2007); and the truncated version of that report published by Gilman et al. (2007a). We acknowledge our co-authors (and respective funding sources) on both publications, most notably lead-author E Gilman for initiating this effort, fostering our involvement, and consolidating the case studies from around the world. We thank L. Beerkircher and D. Kerstetter for providing constructive comments on earlier versions of this manuscript. Funding for this work was provided by NOAA (via the Consortium for Wildlife Bycatch Reduction), and the New England Aquarium.

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