



**Abstract**—Commercial fisheries are recognized as one of the greatest threats to shark populations world-wide, but factors affecting the likelihood of shark mortality during fishery capture are poorly understood. We used the U.S. pelagic fishery logbook data from 1992 through 2008 to quantify the effects of several variables (fisheries regulatory periods, geographic zone, target catch, and sea surface temperature) on mortality of blue sharks (*Prionace glauca*) and tiger sharks (*Galeocerdo cuvier*). Mortality rates and trends in both species closely matched those recorded from other sources, and therefore indicated that the data on sharks discarded dead and discarded alive in the U.S. pelagic fishery logbook are accurate. The introduction of fisheries management regulations (fin weight to carcass weight ratios in 1993 [to prevent finning] and the prohibition of J-hooks in 2004) presumably decreased the immediate mortality rate of captured blue and tiger sharks (by 8.0% in blue sharks after 2004 and 4.4% in tiger sharks after 1993). Other factors that we examined had a statistically significant effect on mortality, but additional variables should be recorded or made available in logbook data to enable the determination of other causes of mortality. Our results show that the U.S. pelagic fishery logbook data can be used as a powerful tool in future studies of the immediate mortality of longline-caught animals.

## Using logbook data to determine the immediate mortality of blue sharks (*Prionace glauca*) and tiger sharks (*Galeocerdo cuvier*) caught in the commercial U.S. pelagic longline fishery

Derek R. Dapp (contact author)<sup>1</sup>

Charlie Huveneers<sup>2</sup>

Terence I. Walker<sup>1</sup>

John Mandelman<sup>3</sup>

David W. Kerstetter<sup>4</sup>

Richard D. Reina<sup>1</sup>

Email address for contact author: [derek.r.dapp@gmail.com](mailto:derek.r.dapp@gmail.com)

<sup>1</sup> School of Biological Sciences  
Monash University  
Wellington Road  
Clayton, Victoria 3800, Australia

Present address for contact author: Washington Department of Fish and Wildlife  
600 Capitol Way North  
Olympia, Washington 98501–1091

<sup>2</sup> School of Biological Sciences  
Flinders University  
G.P.O. Box 2100  
Adelaide, South Australia 5001, Australia

<sup>3</sup> Anderson Cabot Center for Ocean Life  
New England Aquarium  
Central Wharf  
Boston, Massachusetts 02110-3399

<sup>4</sup> Department of Marine and Environmental Sciences  
Halmos College of Natural Sciences and Oceanography  
Nova Southeastern University  
8000 North Ocean Drive  
Dania Beach, Florida 33004

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An estimated one-quarter of all chondrichthyan (sharks, rays, and chimaeras) species are classed as threatened according to the International Union for Conservation of Nature (IUCN) Red List Categories and Criteria, a system for the classification of species by extinction risk, with fishing pressure being the primary threatening process (Dulvy et al., 2014). Targeted shark species often possess protracted life history strategies that make them inherently vulnerable to overfishing (Hoenig and Gruber, 1990; Smith et al., 1998).

These shark species are considered a lucrative target for commercial fisheries and are fished primarily for their flesh and fins (Dent and Clarke, 2015). However, some species are captured incidentally, considered *bycatch*, and discarded either because of low commercial value or in response to fisheries management requirements (also called *regulatory discards*) (Bonfil, 1994). Sharks can experience mortality before processing, retention, or release by fishermen; we refer to such mortality as *immediate mortality* in this study

(synonymous with *at-vessel*, *hooking*, and *initial* mortality; Dapp et al., 2016a). The immediate mortality of incidentally caught sharks can be substantial (Dapp et al., 2016a), and incidental capture has been identified as a major driver of declines in shark populations (Dulvy et al., 2014).

Immediate mortality rates of sharks during longline capture can be influenced by a multitude of factors, such as, but not limited to, capture duration, hook type, hook size, species-specific biology, and crew-specific handling practices (Campana et al., 2009; Morgan and Carlson, 2010; Dapp et al., 2016a, 2016b; Gilman et al., 2016). Factors contributing to the immediate mortality of sharks caught by the U.S. Atlantic pelagic longline fishery have previously been examined by using the data set of the National Marine Fisheries Service (NMFS) Pelagic Observer Program (POP) (Serafy et al., 2012; Gallagher et al., 2014). A recent assessment by Gallagher et al. (2014), who used the POP data set, revealed that hook depth, soak time, sea-surface temperature (SST), target catch (assumed to be either swordfish or species of tunas), and fork length had varying effects on the likelihood of immediate mortality for 12 species of sharks.

We expanded upon earlier research by investigating how additional factors (geographic zone and management regulations) contribute to the likelihood of immediate mortality of longline-caught sharks, using the U.S. pelagic fishery logbook (USPL) data set<sup>1</sup>. Temporal analysis of immediate mortality rates with this data set can provide valuable information on the efficacy of regulatory measures designed to decrease immediate mortality of sharks. For example, Serafy et al. (2012) attributed temporal differences in immediate mortality of several species to management regulations requiring the use of circle hooks during longline fishing. Similarly, zone-specific rates of immediate mortality can provide information on how operational differences between geographic zones and fleets cause variations in immediate mortality.

The USPL data set is the largest U.S. fishery data source available in terms of number of animals caught. The large sample size of this data set makes it more suitable than experimentally derived data sets for analyzing spatiotemporal influences on the mortality rates of sharks. The USPL data set comprises mandatory data recorded by commercial fishermen and has been a valuable resource in previous studies of changes in shark relative abundance or catch rates (Baum et al., 2003; Baum and Myers, 2004; Mandelman et al., 2008; Baum and Blanchard, 2010). However, issues with species identification and misreporting can limit the value of logbook data (Burgess et al., 2005). Accordingly, the accuracy of commercial logbook data should be scrutinized and carefully compared with data collected by trained observers.

Despite these concerns, Mandelman et al. (2008) and Baum and Blanchard (2010) concluded that catch rates for several easily identifiable, commercially valuable, or commonly captured species of sharks in the USPL data set were not significantly different from catch rates recorded in the POP data set. However, several congeneric species that have similar names or are morphologically similar (e.g., silky shark [*Carcharhinus falciformis*], dusky shark [*C. obscurus*], and night shark [*C. signatus*]; longfin mako [*Isurus paucus*] and shortfin mako [*I. oxyrinchus*]; and common thresher shark [*Alopias vulpinus*] and pelagic thresher [*A. pelagicus*]) were consistently misidentified in the USPL data set, even by trained observers (Reardon et al., 2006; Baum and Blanchard, 2010).

We sought to expand upon earlier studies of logbook accuracy by comparing the immediate mortality rates of sharks with accurately recorded catch rates of sharks recorded in the USPL data set to the immediate mortality rates of these species recorded in the POP data set. This comparison allowed us to determine whether records of dead and live discards were accurately recorded in the USPL data set. It is important to appreciate that the USPL was not designed for this purpose; it was implemented as a marine resource management tool to monitor fishery changes in catch per unit of effort (additional information is available from the [web-site](#)). However, if shark mortality is accurately recorded within the USPL data set, the large number of records in the data set will make it a powerful and statistically robust tool for identifying factors that contribute to immediate mortality during longline capture.

For our analysis, we summarized the number of sharks retained, discarded dead, and discarded alive by the U.S. pelagic longline fleet from 1992 through 2008 by using the USPL data set. In addition, we evaluated the accuracy of mortality recordings by commercial fishermen in the USPL data set by comparing our results with the findings from previous immediate mortality studies in which similar species, fishing techniques, and locations were used. If accuracy was validated, we went on to assess factors contributing to the likelihood of shark bycatch being discarded dead to propose new variables that can be included when recording logbook data to enhance data collection.

## Materials and methods

### Overview of the data set and study methods

To achieve our goals, we first screened the USPL data set for the period of 1982–2008 to remove inaccurate records. Quantitative species-specific comparisons of immediate mortality between this data set and other published sources were made to assess the accuracy of the USPL data set. If accuracy was verified, a statistical analysis of shark mortality was then conducted to determine factors correlated with immediate mortality within the USPL data set.

<sup>1</sup> NMFS (National Marine Fisheries Service). Southeast Fisheries Science Center, Miami Laboratory, 75 Virginia Beach Drive, Miami, FL 33149.

## Data screening

Data screening was conducted on the USPL data set to remove longline sets or individual captures that were deemed likely to be inaccurate. A summary of longline sets and individual captures removed from the data set is available in [Supplementary Table 1](#). Longline sets and recorded captures were removed from the analysis in the following cases:

- Longline sets that were made before 1992 because records from 1982 through 1992 did not specify whether discards were alive or dead
- Multiple gear types (e.g., pelagic longline and gillnet or pelagic longline and bottom longline) were used or sets did not use longline gear
- Improbable SST (e.g.,  $<1^{\circ}\text{C}$ ), or no SST was reported
- Location data were likely to be inaccurate because all latitude and longitude values were reported as  $0^{\circ}$ , latitude and longitude values were unreported, or longline set location was recorded outside of the designated geographic zones
- Target catch was not reported as swordfish (*Xiphias gladius*), species of shark, dolphinfish (*Coryphaena hippurus*), or any species of tunas (*Thunnus* spp.). If target catch was not reported as one of these categories, the target catch was specified as *other* and was considered unknown
- Specific groupings (e.g., geographic zones, targeted species, regulatory periods) with less than 100 individuals of a given species
- Longline sets where fishermen retained any individuals of the species being examined. This approach was necessary because the condition of whether sharks were alive or dead was not recorded at the time of processing. Mortality of individuals that were retained was unrelated to the environmental and operational factors examined in our analysis
- Longline sets that targeted sharks, because retention was likely in these longline sets. Longline sets that targeted sharks were included for the analysis of blue shark (*Prionace glauca*) because this species was not typically retained by shark-targeting longline fishermen (i.e., in less than 5% of longline sets that reported targeting sharks before data screening)
- Geographic zone groupings that had less than 100 recorded captures during each regulatory period when interaction effects (blue shark only) were examined. A table that shows excluded groupings and their associated sample sizes can be found in the supplementary materials section ([Suppl. Table 2](#))

Some variables recorded in the USPL were excluded from our analyses. Use of live or dead bait was not included as a factor because the majority of longline sets had either dead or unrecorded bait types (e.g., 99.8% of the examined longline sets that captured blue shark). Gangion length was not included as a factor in the

analysis because the units of measurement (e.g., centimeters and inches) that were used were unspecified and varied among longline sets. Immediate mortality rates during demersal longline sets were not compared with those during pelagic longline sets because the few individuals remaining in the data set after data screening was completed were recorded on demersal longline sets (e.g., less than 0.1% of blue sharks were caught during demersal longline sets). Although the number of hooks between floats has been used in previous studies as a proxy for target catch (Serafy et al., 2012; Gallagher et al., 2014), this variable was not included in our analysis because target catch was explicitly recorded in the USPL, and, therefore, available.

Species-specific immediate mortality rates (expressed as percentages) were calculated by dividing the number of dead discards by the number of total discards. This approach was used because immediate mortality was not directly recorded by fishermen in the USPL, unwanted shark bycatch is typically released by commercial fishermen without bringing it onboard vessels (Moyes et al., 2006), and regulations require that live shark bycatch is released unharmed (NMFS<sup>2</sup>). In addition, we removed from our analysis longline sets that retained (rather than released) individuals of the species being examined.

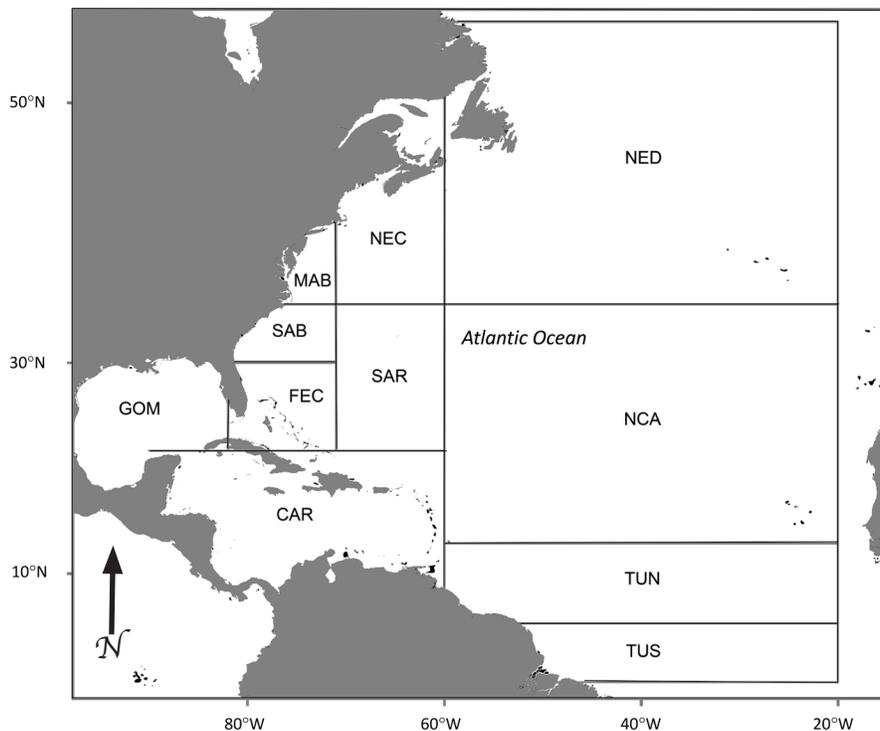
Species that were likely to be identified accurately by fishermen and considered in our analysis included blue sharks, porbeagle (*Lamna nasus*), oceanic whitetip sharks (*Carcharhinus longimanus*), and tiger sharks (*Galeocerdo cuvier*) (Mandelman et al., 2008; Baum and Blanchard, 2010). Although we report the likelihood of retention, being discarded dead, and being discarded alive for 2 occasionally retained species (oceanic whitetip sharks and porbeagles; NMFS<sup>3</sup>), we were unable to analyze the immediate mortality rates of these species using the USPL data set because it could not be determined whether individual animals were alive or dead when landed and retained. Instead, we examined immediate mortality in bycatch of blue and tiger sharks because these species have meat of low value (Vannuccini, 1999; Mandelman et al., 2008; Simpfendorfer, 2009) and are rarely retained by U.S. fisheries (NMFS<sup>4</sup>) and because a metric of dead discards in relation to live discards would accurately reflect immediate mortality rates following capture.

The effect of capture location on immediate mortality was investigated by using the 11 zones of the U.S. pelagic longline fishery that are based on geography

<sup>2</sup> NMFS (National Marine Fisheries Service). 1993. Fishery management plan for sharks of the Atlantic Ocean, 287 p. [Available from [website](#), accessed December 2015.]

<sup>3</sup> NMFS (National Marine Fisheries Service). 2006. Final consolidated Atlantic highly migratory species fishery management plan, 1600 p. [Available from [website](#), accessed March 2016.]

<sup>4</sup> NMFS (National Marine Fisheries Service). 2015. Stock assessment and fishery evaluation (SAFE) report for Atlantic highly migratory species. 170 p. [Available from [website](#), accessed March 2016.]



**Figure 1**

The 11 geographic zones of the U.S. pelagic longline fishery that were analyzed for this study to determine the immediate mortality of blue sharks (*Prionace glauca*) and tiger sharks (*Galeocerdo cuvier*) for the period 1992–2008. The geographic zones are Caribbean (CAR), Florida east coast (FEC), Gulf of Mexico (GOM), Mid-Atlantic Bight (MAB), north central Atlantic (NCA), northeast coastal (NEC), northeast distant (NED), South Atlantic Bight (SAB), Sargasso Sea (SAR), tuna north (TUN), and tuna south (TUS).

(Cramer and Adams, 2000; Mandelman et al., 2008; Fig. 1). These geographic zones were Caribbean (CAR), Gulf of Mexico (GOM), Florida east coast (FEC), Mid-Atlantic Bight (MAB), north central Atlantic (NCA), northeast coastal (NEC), northeast distant (NED), South Atlantic Bight (SAB), Sargasso Sea (SAR), tuna north (TUN), and tuna south (TUS). Target catch and operating procedures for the pelagic longline fleet vary among geographic zones, with each described in detail in Hoey and Moore<sup>5</sup> and in the NMFS consolidated fishery management plan for highly migratory species (NMFS<sup>2</sup>).

Within the USPL, target catch was reported as swordfish, yellowfin tuna (*Thunnus albacares*), bigeye tuna (*Thunnus obesus*), mixed species of tunas, species of sharks, dolphinfish, or other. In accordance with previous studies, yellowfin tuna, bigeye tuna, and mixed species of tunas were grouped into a single category designated as targeting tunas during the mortality

analysis (Serafy et al., 2012; Gallagher et al., 2014). However, a large portion of the data reported targeting of multiple species (e.g., swordfish and species of tunas in longline sets). Accordingly, for a separate analysis of the immediate mortality of target catch, we used a reduced data set that excluded longline sets in which multiple species were targeted.

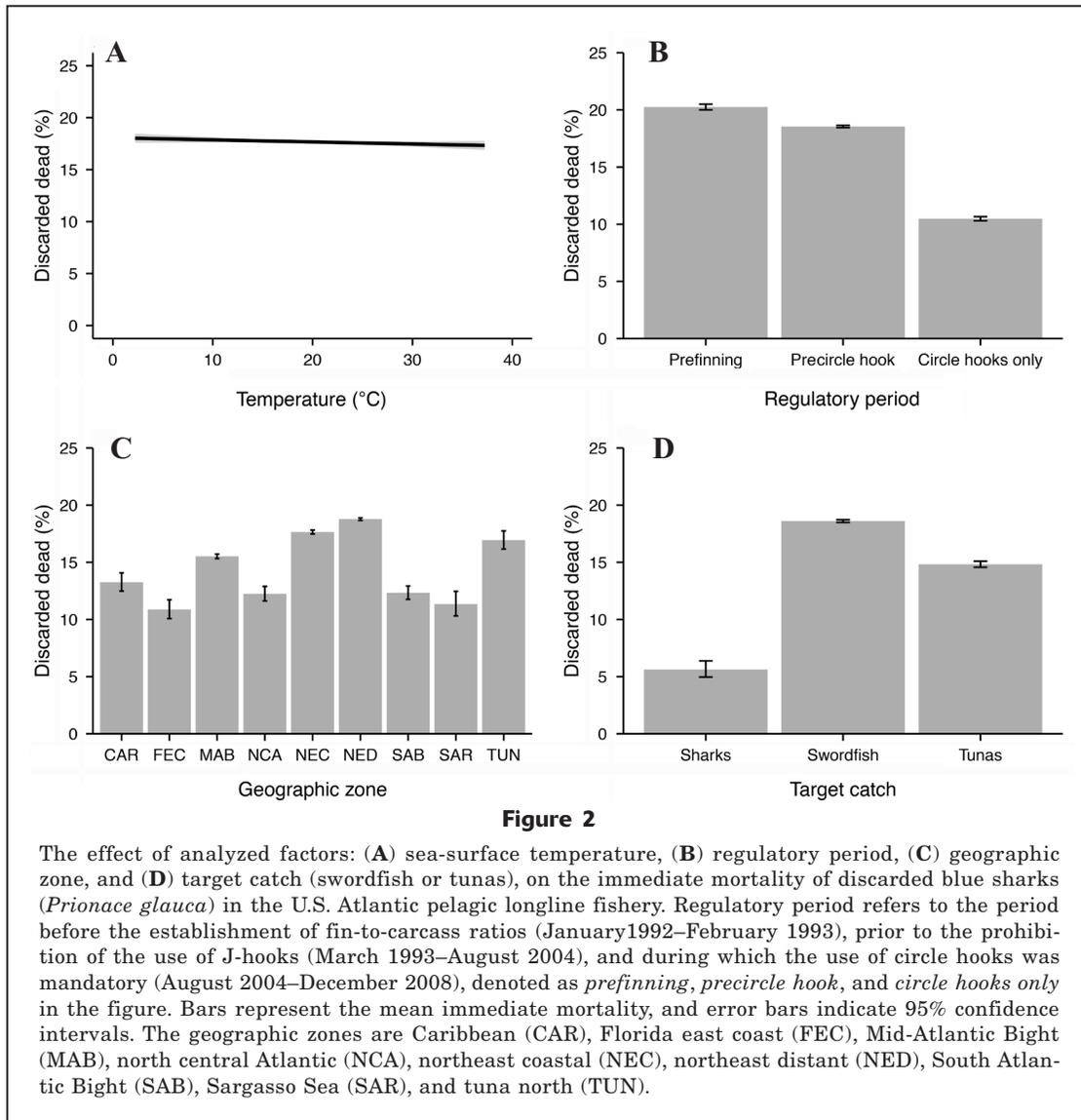
#### Statistical analysis

We used generalized linear models with a logit link function for each species. This statistical family was chosen because the dependent variable was binary, the data fitted model assumptions, and Pearson's  $\chi^2$  residual tests confirmed that logistic models fitted the data appropriately. The response variable (*immediate mortality*) was coded with a value of 0 or 1 according to whether an individual shark was discarded alive or dead, respectively. The final model used for blue sharks was

$$\begin{aligned} \text{Immediate mortality} = & SST + \text{Regulatory period} \\ & + \text{Geographic zone} + \text{Regulatory period} \\ & \times \text{Geographic zone.} \end{aligned} \quad (1)$$

An interaction effect was not examined during the

<sup>5</sup> Hoey, J. J., and N. Moore. 1999. Captain's report: multi-species catch characteristics for the U.S. Atlantic pelagic longline fishery. 78 p. National Fisheries Institute Inc., Arlington, VA. [Available from [website](#), accessed September 2015.]



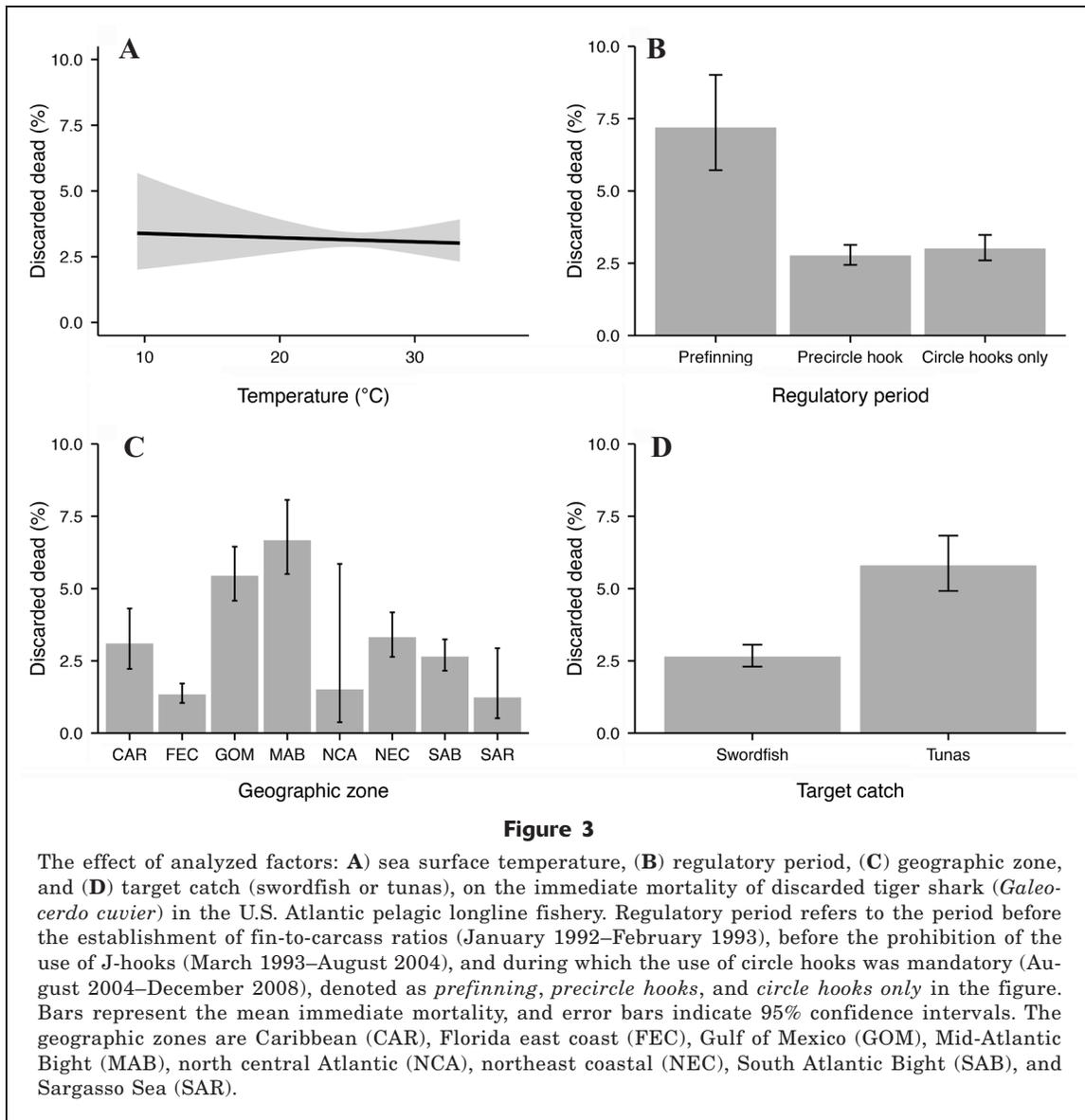
analysis of tiger shark because its examination required the use of a reduced data set. The model created by using the reduced data set that included the interaction explained less deviance (expressed as a percentage) in the model than did a model that used the full data set (Suppl. Table 3). The final model used for tiger sharks was

$$\text{Immediate mortality} = \text{SST} + \text{Regulatory period} + \text{Geographic zone.} \quad (2)$$

Predictor variables were *SST* (measured in degrees Celsius), *regulatory period* (January 1992–February 1993, March 1993–July 2004, August 2004–December 2008), and *geographic zone* (CAR, GOM, FEC, MAB, NCA, NEC, NED, SAR, SAB, TUN, TUS). Wald tests were used to determine whether the overall effect of each predictor variable on immediate mortality was statistically significant ( $P < 0.05$ ). To portray biological-

ly meaningful results, statistically significant predictor variables were examined in isolation in Figures 2, 3, and 4.

The variable *regulatory period* was defined according to changes in the management of the fisheries. During the first period (January 1992–February 1993), shark finning was legal and few regulations existed to protect shark populations. The implementation of the first fishery management plan for sharks of the Atlantic marked the beginning of the second regulatory period (March 1993–July 2004; NMFS<sup>2</sup>). This plan provided management for 39 species of sharks, establishing bag limits and a fin-to-carass weight ratio of 5% or less and requiring the release of sharks not retained under commercial quotas or bag limits. J-hooks were the predominant hook type used during this regulatory period (Hoey and Moore<sup>1</sup>; Watson et al., 2005). The final period examined (August 2004–



December 2008) was characterized by a new mandatory use of circle hooks for U.S. pelagic longline vessels (NMFS<sup>2</sup>). Although this rule was implemented to reduce bycatch mortality of species of turtles (NMFS<sup>2</sup>), circle hooks are less likely than traditionally used J-hooks to be swallowed by some species of shark. The use of these hooks, therefore, reduces occurrences of internal injuries and immediate mortality rates in some species (Kerstetter and Graves, 2006; Campana et al., 2009; Serafy et al., 2012; Gilman et al., 2016; but see Yokota et al., 2006).

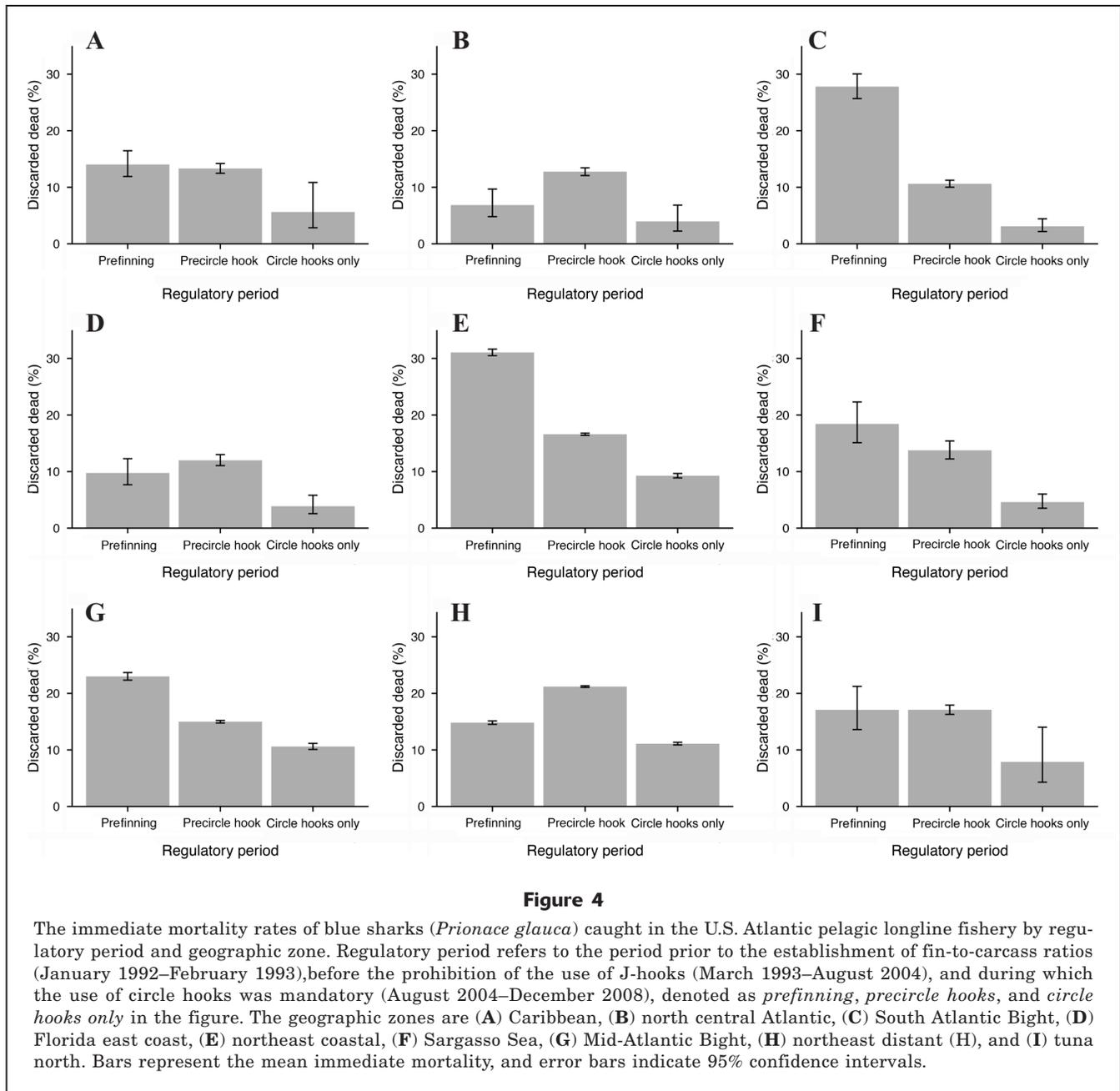
In accordance with the methods of Serafy et al. (2012), we considered only specific regulatory periods in our analysis. There were other measures enacted that were required for the use of longlines in commercial fisheries during the period examined, but they were not incorporated into models because they were

unlikely to have had a substantial effect on the immediate mortality of sharks. A few examples of regulatory measures enacted include the fishery management plan for Atlantic tunas, swordfish, and sharks (which was enacted in 1999 to prohibit the retention of several species of sharks and reduce commercial coastal quotas for sharks; these regulations did not affect our analysis because we examined discarded animals and species only) and time or area closures (e.g., the closing of the NED zone in 2002; NMFS<sup>2</sup>).

To determine how target catch influenced immediate mortality, the following generalized linear models with a logit link function were used:

$$\text{Immediate mortality} = \text{Target}. \quad (3)$$

*Target* = target catch and was defined as catch of tunas, swordfish, or sharks.



This variable was examined in isolation because records with multiple species had to be removed from the data set for the target catch analysis, resulting in a reduced data set. The reduced data sets, however, did not have the sample sizes necessary to examine all the geographic zones and regulatory periods.

All statistical analyses were conducted with R<sup>6</sup> statistical software, vers. 2.14.2 (R Core Team, 2012).

<sup>6</sup> Mention of trade names or commercial companies is for identification purposes only and does not imply endorsement by the National Marine Fisheries Service, NOAA.

## Results

### Shark retention and total numbers reported before data screening

There were 1,436,061 reported captures of sharks between 1992 and 2008 in the USPL data set (Table 1). Blue sharks accounted for approximately 60% of the total catch (Table 1). Numbers reported for other species caught are available in Table 1.

The percentage of animals retained varied considerably among species, with the blue shark having the lowest (1%; Table 1) and the porbeagle having the

**Table 1**

The numbers (and percentages) of sharks retained, discarded alive, and discarded dead on longline sets reported in the U.S. pelagic longline logbook data set from 1992 through 2008. Numbers reported are total numbers before data screening. An asterisk (\*) indicates species for which numbers reported are likely to be accurate. Numbers recorded for species other than blue sharks (*Prionace glauca*), tiger sharks (*Galeocerdo cuvier*), oceanic whitetip sharks (*Carcharhinus longimanus*), and porbeagle (*Lamna nasus*) should be interpreted with caution because it was likely that these species were consistently misidentified.

Species	Number	Retained	Discarded alive	Discarded dead
Blue shark*	863,153	9362 (1%)	702,955 (81%)	150,836 (17%)
Sandbar shark	167,887	157,261 (94%)	7973 (5%)	2653 (2%)
Blacktip shark	91,723	77,033 (84%)	9669 (11%)	5021 (5%)
Shortfin mako	66,750	51,710 (77%)	10,696 (16%)	4344 (7%)
Dusky shark	53,561	30,934 (58%)	16,376 (31%)	6251 (12%)
Silky shark	42,647	18,236 (43%)	14,472 (34%)	9939 (23%)
Tiger shark*	33,063	4975 (15%)	26,737 (81%)	1351 (4%)
Hammerhead (unidentified)	23,238	10,024 (43%)	8050 (35%)	5164 (22%)
Bigeye thresher	13,227	3675 (28%)	7255 (55%)	2297 (17%)
Scalloped hammerhead	13,062	5629 (43%)	4097 (31%)	3336 (25%)
Spinner shark	11,439	9340 (82%)	1560 (14%)	539 (5%)
Night shark	11,082	3084 (28%)	4432 (40%)	3566 (32%)
Oceanic whitetip shark*	10,847	2422 (22%)	7254 (67%)	1171 (11%)
Smooth hammerhead	9922	4433 (45%)	3646 (37%)	1843 (19%)
Porbeagle*	8113	3980 (49%)	3312 (41%)	821 (11%)
Longfin mako	7367	2523 (34%)	3887 (53%)	957 (13%)
Thresher (unidentified)	5248	2313 (44%)	2197 (42%)	738 (14%)
Bignose shark	2288	992 (43%)	940 (41%)	356 (16%)
White shark	1435	488 (34%)	879 (61%)	68 (5%)
All recorded sharks	1,436,061	398,415 (28%)	836,395 (58%)	201,251 (14%)

highest (49%; Table 1) rates of retention of the 4 species deemed to be accurately reported. When animals retained were included in our analyses, the porbeagle was the species least likely (41%) to be released alive by fishermen among the 4 species deemed to be accurately reported (Table 1). In contrast, tiger and blue sharks were the most likely species examined (both 81%; Table 1) to survive initial capture by the U.S. pelagic longline fleet.

#### Quantitative comparisons of mortality rates with rates from other published sources

The rates of immediate mortality reported for commonly discarded species, specifically the blue shark (1% retained after data screening completed) and the tiger shark (3% retained after data screening completed), in the USPL data set were similar to rates of immediate mortality reported for these species in other data sources. Rates of immediate mortality for the tiger shark were 3%, 3%, and 3% in the POP data set, in the USPL data set, and for the mean of 5 studies of immediate mortality, respectively (Table 2). For the blue shark, rates of immediate mortality were 15%, 18%, and 19% in the POP data set, in the USPL data set, and for the mean of 11 studies of immediate mortality, respectively (Table 2). In contrast,

rates of immediate mortality for occasionally retained species (i.e., oceanic whitetip sharks and porbeagles) deviated considerably from the rates in the POP data set (Table 2).

#### Immediate mortality analysis

Because rates of immediate mortality for blue and tiger sharks were comparable with estimates from other sources (Table 2), factors affecting mortality of these species were assessed. All factors tested had a statistically significant effect on immediate mortality of blue sharks (Table 3; Fig. 2). Similar factors affected immediate mortality of tiger sharks, including regulatory period, geographic zone, and target catch (Table 3, Fig. 3). Both models explained only a small percentage of the deviance within the data set: 1.6% for blue sharks and 4.5% for tiger sharks (Table 3).

In both species, rates of immediate mortality during examined regulatory periods were significantly different. Before March 1993, 7.2% (95% confidence interval [CI]: 5.7% to 9.0%) of tiger sharks were discarded dead; however, from March 1993 through August 2004, only 2.8% (95% CI: 2.4% to 3.1%) were discarded dead (Fig. 3). The percentage of discards of tiger sharks that were dead did not differ significantly between periods from March 1993 through August 2004 and periods after Au-

**Table 2**

The observed immediate mortality, calculated as the percentage of total discards that were dead discards, in the U.S. pelagic fishery logbook (USPL) data set for the period 1992–2008, after data screening was completed. Expected immediate mortality rate is given as a mean and range from existing sources that reported the immediate mortality rates of a species examined during longline capture. The expected immediate mortality rate column also provides the mean rate of immediate mortality recorded by the Pelagic Observer Program (POP), National Marine Fisheries Service, in Gallagher et al. (2014). Superscript <sup>1</sup> denotes that the observed immediate mortality rate is likely to be inaccurate because of the discrepancy between observed (USPL) and expected (POP) percentages.

Species	Number examined	Observed immediate mortality	Expected immediate mortality	Sources
Blue shark	806,598	17.7%	Range: 5–34% Mean: 19% POP: 15%	(Francis et al., 2001; Moyes et al., 2006; Hight et al., 2007; Petersen, 2008; Campana et al., 2009; Coelho et al. <sup>1</sup> ; Musyl et al., 2011; Bromhead et al., 2012; Coelho et al., 2012; Griggs and Baird, 2013; Gallagher et al., 2014)
Tiger shark	15,474	3.1%	Range: 0–7% Mean: 3% POP: 3%	(Morgan et al., 2009; Scott-Denton et al., 2011; Coelho et al., 2012; Afonso and Hazin, 2014; Gallagher et al., 2014)
Oceanic whitetip shark <sup>1</sup>	6348	15.8% <sup>1</sup>	Range: 5–34% Mean: 24% POP: 26%	(Musyl et al., 2011; Bromhead et al., 2012; Coelho et al., 2012; Gallagher et al., 2014)
Porbeagle <sup>1</sup>	2619	27.2% <sup>1</sup>	Range: 21–39% Mean: 32% POP: 21%	(Francis et al., 2001; Griggs and Baird, 2013; Gallagher et al., 2014)

<sup>1</sup>Coelho, R., P. G. Lino, and M. N. Santos. 2011. At-haulback mortality of elasmobranchs caught on the Portuguese longline swordfish fishery in the Indian Ocean. Indian Ocean Tuna Comm. IOTC-2011-WPEB07-31, 9 p. IOTC, Victoria Mahé, Seychelles. [Available from website, accessed March 2015.]

gust 2004, with a mean difference in percentages of 3.0% (95% CI: 2.6% to 3.5%; (Fig. 3).

The immediate mortality model for blue sharks had a statistically significant interaction effect between regulatory period and geographic zone. Rates of immediate mortality for blue sharks caught before March 1993 were lower in 2 zones (NCA and NED), higher in 3 zones (MAB, NEC, and SAB), and not significantly different in 4 zones (CAR, FEC, SAR, and TUN) than rates of immediate mortality for blue sharks caught between March 1993 and August 2004 (Figs. 1 and 4). However, after the implementation in August 2004 of regulations for the mandatory use of circle hooks, the immediate mortality of blue sharks had a statistically significant decrease in every geographic zone analyzed when compared with the regulatory period between March 1993 and August 2004 (Figs. 1 and 4). Between the period March 1993–August 2004 and the period August 2004–December 2008, the rate of immediate mortality in geographic zones decreased by a mean of 8.0% (standard error [SE] 0.5) and by a range of 4.4–10.1% for 9 geographic zones examined.

## Discussion

### Accuracy of logbook data

Despite being limited to blue and tiger sharks, our analysis with the USPL data set provided useful information about immediate mortality over a temporal and spatial scale not possible with other data sets. In previous studies, where USPL and POP data sets were compared, catch rates were determined to have been reported accurately for easily identifiable, commonly captured, and marketable species of sharks (blue, tiger, porbeagle, and oceanic whitetip sharks) (Mandelman et al., 2008; Baum and Blanchard, 2010). Our results show that the numbers of dead and live discards of bycatch species (i.e., blue and tiger sharks) recorded by commercial fishermen in the USPL data set are also similar to those recorded in the POP data set, indicating accuracy, and that the USPL is a useful, massive source of long-term data with value for management of sharks and fisheries, particularly in relation to shark bycatch over time. Given the large sample size of the

**Table 3**

The effect of sea surface temperature (SST), regulatory period, and geographic zone on the immediate mortality of blue and tiger sharks in the U.S. Atlantic pelagic longline fishery during the period 1992–2008. NS denotes a nonsignificant effect of the factor on mortality. An asterisk (\*) denotes significant results with  $P$ -values less than 0.05. An interaction effect was not examined in the model for immediate mortality of tiger shark (represented by N/A below).

Species	SST	Regulatory period	Geographic zone	Regulatory period × geographic zone	Deviance explained
Blue shark	* $\chi^2=15$ $P<0.05$ 1.6%	* $\chi^2=7$ $P<0.05$	* $\chi^2=2761$ $P<0.05$	* $\chi^2=4648$ $P<0.05$	1.6%
Tiger shark	NS	* $\chi^2=49$ $P<0.05$	* $\chi^2=137$ $P<0.05$	N/A	4.5%

data set and the mandatory collection of such data, the USPL data set will be a powerful and economical tool in future studies for analyzing shark mortality trends, but the current problem of reliable species identification needs to be addressed.

The rates of immediate mortality for 2 occasionally retained species deviated from the rates reported in the POP data set: 6% higher for porbeagles and 10% lower for oceanic whitetip sharks. Despite differences with the POP data set, the rates of immediate mortality for these species reported in the USPL data set were determined to be within the range of immediate mortality rates reported in other sources (Table 2). Although this comparability indicates that the reporting of immediate mortality in the USPL for these species may be accurate, we recommend interpreting these values with caution. During the screening of data, all longline sets that retained individuals of the species being examined were removed. This approach left only longline sets that had discarded sharks in the data set but it was assumed that the likelihood of retention was the same for dead and live sharks. This supposition is false because fishermen may be more likely to retain sharks that are dead or moribund than they are to keep live sharks (Gilman et al., 2008). Because of this limitation, for occasionally retained species, the factors that influence immediate mortality during capture cannot be accurately assessed by using the designated categories in the USPL data set. Therefore, it would be necessary for the USPL to include the number of live and dead or moribund animals retained in order for data to be reliable when some animals are kept as part of a catch.

#### Factors contributing to mortality in blue and tiger sharks

The establishment of fin-to-carcass weight ratios has afforded greater protection for tiger sharks than the

implementation of the mandatory use of circle hooks. The large number of sharks discarded dead before March 1993 may be attributable to the high value of the fins of tiger shark compared with that of the fins of other shark species because “finned sharks” (sharks whose fins were removed in the catch) were likely to be recorded as *discarded dead* rather than retained during this period (Clarke et al., 2006). The effect of circle hooks on immediate mortality is likely to be species-specific (Serafy et al., 2012), and immediate mortality of tiger sharks did not decrease after the start of regulations for the mandatory use of circle hooks.

In contrast with the effect on survival of tiger sharks, the prohibition of the use of J-style hooks had a more positive effect on the survival of blue sharks than the establishment of fin-to-carcass ratios (for zone-specific effects, see Fig. 4). We are unsure why differences in mortality rates varied according to geographic zones between the period before March 1993 and the period March 1993–August 2004. However, statistically significant decreases in rates of immediate mortality for blue sharks in every geographic zone analyzed after August 2004 have indicated that the mandated change in hook type has had a positive effect on the survival of blue shark caught as bycatch.

Several studies have reported that the use of circle hooks instead of J-style hooks can reduce immediate mortality of blue sharks (Campana et al., 2009; Caruthers et al., 2009; Afonso et al., 2011; Afonso et al., 2012; Epperly et al., 2012; Godin et al., 2012; Gilman et al., 2016; but see Kerstetter and Graves, 2006; Yokota et al., 2006; Curran and Bigelow, 2011; Serafy et al., 2012) because such hooks decrease the likelihood of hooking in the gut (gut-hooking) in this species (Watson et al., 2005; Afonso et al., 2011). We cannot determine the specific postrelease survival rate for released animals, but delayed death due to gut-hooking may have been a further significant cause of mortality that

has since been reduced or removed by the shift to circle hooks (Campana et al., 2009). Despite the decreases in rates of immediate mortality noted in this study, catch rates for species of sharks may increase when circle hooks are used and this increase may have contributed to a greater number of animals being captured (see meta-analysis by Gilman et al., 2016).

The reported effect of SST on immediate mortality of blue shark varies among studies. Clarke et al. (2013) and Gallagher et al. (2014) found a positive relation between the immediate mortality rate of blue sharks and SST. In contrast, Campana et al. (2009), Epperly et al. (2012), Serafy et al. (2012), and Coelho et al. (2013) reported that temperature had no effect on the rate of immediate mortality rate for blue sharks. Although we identified that the influence of SST on immediate mortality as statistically significant in blue sharks, immediate mortality rates were lower by only 0.5% at an SST of 30°C than at an SST of 10°C, indicating that other factors exert more influence on mortality of blue sharks. Statistical significance is more likely to be detected in studies with a very large sample size, as in our study, even when the effect that sample size has on mortality is minor (for more information on how sample sizes can influence *P*-values, see Sullivan and Feinn, 2012). Sea-surface temperature had no effect on immediate mortality of tiger shark (Fig. 3)—a finding that is consistent with the results of Gallagher et al. (2014). Although SST has been reported to have little influence on the immediate mortality rates of species we examined, higher SSTs are thought to increase physiological stress during fishery capture (Cicia et al., 2012; Hoffmayer et al., 2012; Guida et al., 2016) and the effect of SST on mortality is likely to be species specific.

Blue sharks caught on longline sets that targeted swordfish were more likely to be discarded dead than those caught on longline sets that targeted tunas or sharks (Fig. 2). However, the majority (83%) of blue shark caught on longline sets that targeted swordfish were caught in the NED zone, and blue sharks caught in the NED zone had higher mean rates of immediate mortality than those caught in other geographic zones (Fig. 2). It is unknown why blue shark caught in the NED zone had higher immediate mortality rates than those caught in other geographic zones. Tiger sharks exhibited the opposite trend; individuals caught on longline sets that targeted tunas were more likely to be discarded dead than those caught on longline sets that targeted swordfish. Several gear and operational strategies differ between longline sets that target tunas and those that target swordfish. For example, longline sets that target swordfish are typically left fishing nearer the water's surface and overnight, but longline sets that target tunas are typically set deeper and left from sunrise to sunset (NMFS<sup>2</sup>). Despite the identification of some operational differences, the exact causes of increased immediate mortality rates of tiger sharks during capture on longline sets that target tunas compared with mortality rates during sets that target

swordfish remain unclear and will require additional investigation.

Deviance in the data explained by our models was low (1.6% for blue sharks and 4.5% for tiger sharks), indicating that important factors that contributed to immediate mortality may not have been recorded in the USPL data set or included in our analysis. Factors that potentially contributed to immediate mortality during capture and that were not investigated include capture duration, body size, sex, differences between SST and air temperature, capture depth, degree of movement restriction, behavior during capture, hook size, individual crew handling practices, and bait used (Campana et al., 2009; Cicia et al., 2012; Serafy et al., 2012; Dapp et al., 2016a). These factors were not considered in our analysis because they were not recorded in the USPL. Despite the potential effect of unknown factors, models for immediate mortality of sharks typically explain a low percentage of the deviance in the data (e.g., 7% in Campana et al., 2009; 2–5% in Coelho et al., 2012; 3–6% in Clarke et al., 2013), and more research is necessary to evaluate the variety and extent of factors affecting immediate mortality of sharks.

One caveat concerning our analysis is that temporal differences in immediate mortality were attributed to regulatory measures, but explicit recordings of hook type and number of animals finned were not available. We assumed that before August 2004 longline fisheries had used J-hooks because J-hooks were the predominant hook type used by the U.S. Atlantic pelagic longline fishery during this time period (Hoey and Moore<sup>1</sup>; Watson et al., 2005). Before the requirement to use circle hooks was established in August 2004, circle hooks were not used with some vessels, but because hook type was not recorded within the USPL, we could not identify the vessels with which they were used. Despite this limitation, time period has been previously used as a proxy for hook type in the U.S. Atlantic pelagic longline fishery (Serafy et al., 2012). Additionally, we postulated that the number of dead discards of tiger sharks decreased after March 1993 because of the establishment of fin-to-carcass ratios that reduced the economic viability of retaining shark fins. Because the number of sharks that had been finned was not explicitly recorded, it is possible that other unknown variables could have decreased immediate mortality of tiger sharks after this time period. Despite this caveat, there were clear trends of decreasing immediate mortality after regulatory measures, and these management initiatives are likely to have positively affected the survival of blue sharks and tiger sharks.

One statistical limitation in our study was that target catch was examined by using a univariate model because of the need to use a reduced data set to examine this factor. A univariate approach ignores the effect of other potentially important factors and such effects should be considered when interpreting our results.

Another caveat concerning our study is that the USPL data set used is reported by fishermen. Inaccuracies may arise in the USPL data set as a result

of misidentification, over-reporting, or underreporting (Burgess et al., 2005). Screening data removed many records that were likely inaccurate; however, some inaccuracies are not possible to readily identify and may have passed through the data screening process. Regardless of these concerns, immediate mortality and catch rates for the 2 species examined, blue and tiger sharks, closely match the rates reported in observer records and by other sources. Accordingly, the inaccurate records that could not be identified were unlikely to have had a substantial effect on our results.

## Recommendations

Although the USPL originally was designed to examine catch per unit of effort, if several additional variables were recorded in it, improved estimates of immediate mortality could be derived from this data set. Two additional categories, *at-vessel alive* and *at-vessel dead*, could be used to determine the number of animals that survive initial capture, and these categories would be required to determine factors that contribute to immediate mortality. An understanding of factors contributing to immediate mortality (Frick et al., 2010a; Frick et al., 2010b; Dapp et al., 2016b) could help fisheries managers to make well-informed management decisions. This information can also be used by commercial fishermen to improve the quality of their catch by avoiding environmental or operational conditions that result in increased likelihood of death of sharks in catches before the sharks are landed.

Other changes to recording variables or to presenting data in the USPL data set can be made to contribute to our understanding of fisheries-induced mortality and catch rates in future studies. Some variables (e.g., soak time and other targeted species) that were recorded in the USPL during the period examined were not made publicly available; a greater availability of these data would allow examination of additional, potentially important factors. Average gangion length was reported in the USPL, but we did not incorporate this factor into our analysis because lengths consistently were reported inaccurately (e.g., average gangion lengths >46 m were reported in 50% of longline sets). We are unsure why gangion length was often recorded inaccurately by fishermen, but a greater awareness of proper recording techniques for this variable could result in its use in future studies of immediate mortality. We recommend that 2 additional variables that can influence mortality or catch rates, namely air temperature during hauling and estimated set depth, should be added to future USPL reporting forms. In addition, several other variables that were not examined in our study but could influence catch and mortality rates have been included in recent iterations of the reporting form for the USPL (2015 form available from [website](#); 2003 form available from [website](#)). These variables—bait used, hook type, hook size, and hook offset—should be incorporated into future analyses in which the USPL data set is used.

There were 19 categories (species or groupings) of sharks that were recorded by fishermen in the USPL data set (Table 1). Only 4 of these categories were considered for analysis because of problems with identification and uncertainty about the accuracy of the recordings. The International Plan of Action for the Conservation and Management of Sharks outlined improved shark identification as one of its primary objectives and as a critical step to acquiring data to assess shark stocks (FAO<sup>7</sup>). We recommend that fishermen use shark identification guides or undertake shark identification training (or both) to improve the accuracy of entries in the USPL data set for cryptic species and species that are similar in appearance to other species.

We are the first to use the USPL data set to assess immediate mortality rates of longline-caught tiger and blue sharks. Rates of immediate mortality for these species closely match results from previous studies, and this similarity indicates accurate recording by commercial fishermen (Table 2). Because the USPL data set covers the entirety of the U.S. Atlantic commercial longline fishery, it can be used to determine long-term changes in mortality over a wide geographic scale that may not be achievable with other data sets. If additional variables are recorded by commercial fishermen, the USPL data set can be used to accurately discern causes of mortality during fishery capture in a wide range of species. Although our analysis was restricted to examining bycatch of sharks, the inclusion of additional variables could allow for mortality examinations of targeted teleosts and targeted sharks over a vast temporal and spatial scale.

The results of our study indicate the value of logbook data for scientific studies. In addition to providing immediate mortality rates, logbook data can be used to analyze catch rates, spatiotemporal catch trends, and species distributions (Cheng et al., 2001; Mandelman et al., 2008). The accessibility of the USPL data set to the general public promotes its use and advances our knowledge of fisheries science. Many other long-term government data sets have been collected, but they are not publicly available for analysis. Although we recognize the legal requirements for the protection of a fisherman's personal information, greater availability of governmental logbook and observer data would allow for the examination of fishery trends on a worldwide scale and will be necessary to implement effective global strategies for species management.

Our results indicate that fisheries management regulations have had a positive effect on the survival of the 2 shark species examined. The establishment of fin-to-carass ratios has reduced the number of tiger shark discarded dead in the U.S. commercial long-

<sup>7</sup> FAO (Food and Agriculture Organization of the United Nations). 1999. International plan of action for reducing incidental catch of seabirds in longline fisheries. International plan of action for conservation and management of sharks. International plan of action for the management of fishing capacity, 26 p. FAO, Rome. [Available from [website](#).]

line fishery. Additionally, fin-to-carcass ratios have not increased retention rates for tiger sharks (the mean percentages retained were 16% in 1992–1993 and 14% in 1993–2008) because these sharks are large-bodied animals, boats often have limited deck space, and their meat has a low commercial value (Mandelman et al., 2008; Simpfendorfer, 2009). Similarly, regulations that require the use of circle hooks during commercial longline operations have decreased the rate of immediate mortality for blue shark by 8.0%. Our study adds support to the assumption that fisheries regulations have been beneficial to some species, and results from recent studies indicate that species of sharks caught in the U.S. longline fishery are stable or increasing in abundance (Carlson et al., 2012).

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