Longline-caught blue shark (*Prionace glauca*): factors affecting the numbers available for live release*

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The blue shark (*Prionace glauca*) is an oceanic species that occurs in temperate and tropical waters around the globe (Robins and Ray, 1986). This species is a major bycatch of pelagic longline fleets that operate to supply the world's growing demand for tunas and swordfish (*Xiphias gladius*) (Stevens, 1992; Bailey et al., 1996; Francis, 1998; Francis et al., 2001; Macias and de la Serna, 2002); numerically, the blue shark is the top nontarget species captured by the U.S. longline pelagic Atlantic fleet (Beerkircher et al.[1]).

Ward et al. (2004) examined the effect of longline soak time (set duration) on the catch rate of several target and bycatch species, including the blue shark. However, they did not investigate the effects of fish size, set duration, and water temperature on shark survival, and, therefore, numbers potentially available for live release (Francis et al., 2001; Campana et al.[2]). Knowledge of such relationships may be of value: 1) for minimizing bycatch mortality on this and other highly vulnerable pelagic species through modification of fishing strategy; and 2) for blue shark stock assessments that are based on commercial longline catch data.

Materials and methods

Data analyses were conducted on a portion of the U.S. Atlantic Pelagic Observers Program (POP) database. The POP places trained observers aboard commercial fishing vessels to record detailed information about each fishing set, the catch and the bycatch that would not otherwise be collected. Recorded information includes individual fish size (measured or estimated) and disposition (alive or dead), surface water temperature (°C) at gear deployment and at haulback, and set location (latitude and longitude). The duration of each set (soak time, in hours) can be obtained because time at start of gear deployment and at end of gear retrieval is also recorded. In the present study, we restricted our analyses to observed sets made from 1992 to 2002 by U.S. flag vessels north of 35°N latitude (Fig. 1). This area includes much of the U.S. exclusive economic zone north of Chesapeake Bay but also includes waters overlying the Grand Banks. Data resulting from experimental fishing conducted from 2001 to 2004 over the Grand Banks area (i.e., north of 35°N latitude and west of 60°W longitude) were not included because they did not reflect typical fishing operations.

For analysis purposes, blue shark were placed in 25-cm fork length (FL) size classes and water temperatures (means) and set durations into 2°C and 2-hour intervals, respectively.

Size intervals were set at 25 cm FL to increase the number of observations in each size category and to reduce the bias that results from estimating lengths versus actually measuring them (e.g., observed increase in the frequency of the estimated lengths in 5- or 10-cm intervals). For each combination of size, temperature, set duration, season, and area (i.e., Grand Banks and U.S. Atlantic east coast), the proportion of blue shark released alive (P_{DA}) was calculated.

Only sharks explicitly recorded as "discarded alive" or "discarded dead" were used and only proportions derived from at least 20 observations (i.e., captured sharks) were analyzed. The influence of the fish size, water temperature, set duration, area, and season (and all possible interactions) on P_{DA} was assessed by using the linear model

$$P_i = \beta_0 + \beta_1 T_i + \beta 2\, D_i + \beta 3\, S_i + \beta 4\, L_i + \beta 5\, A_i + \epsilon_i,$$

where P_i = to the proportion of blue shark discarded alive;
T = the temperature;
D = set duration;
S = season;
L = length;
A = set area,
ϵ = the residual term of the i^{th} observation; and
$\beta_0 - \beta 5$ are model parameters.

Prior to regression, proportions were arcsine-transformed according to the methods of Sokal and Rohlf (1981). In

[1] Beerkircher, L. R., C. J. Brown, and D. W. Lee. 2002. SEFSC pelagic observer program data summary for 1992–2000. NOAA Tech. Memo. NMFS-SEFSC-486, 23 p. Southeast Fisheries Science Center, Miami, FL 33149.

[2] Campana S., P. Gonzalez, W. Joyce, and L. Marks. 2002. Catch, bycatch and landings of blue shark (*Prionace glauca*) in the Canadian Atlantic. Canadian Science Advisory Secretariat, Research Document 2002/101, 41 p. Marine Fish Division, Bedford Institute of Oceanography. Dartmouth, Nova Scotia, B2Y 4A2, Canada.

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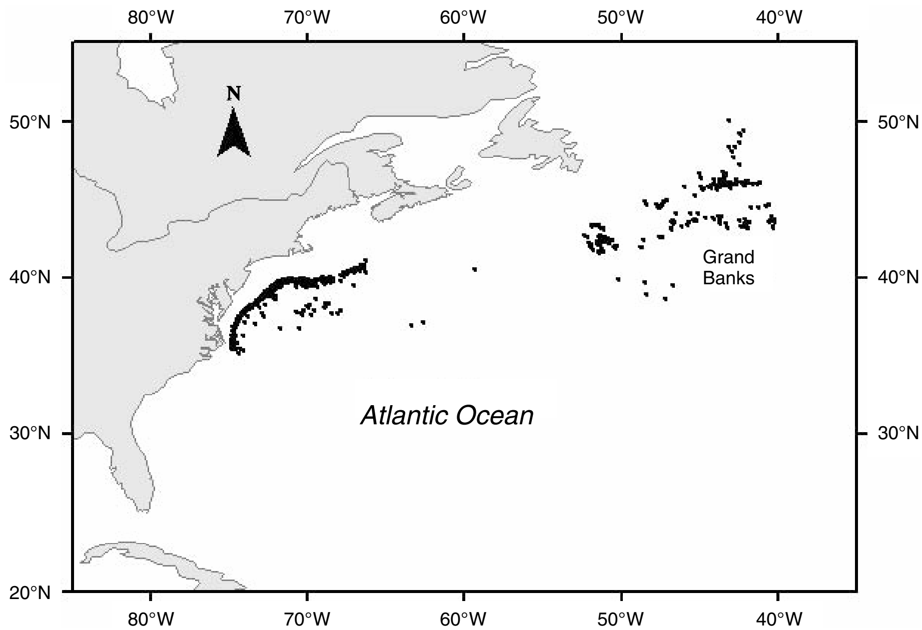

Figure 1
Locations of observed longline sets (1992–2002) recorded in the U.S. Pelagic Observers Program database and analyzed in the present study.

the event that a factor was found to be nonsignificant (P>0.05), it was removed and a regression was rerun until all highest order model terms were significant (Hocking, 1976; Draper and Smith, 1981). We assumed maturity (both sexes) occurred at 185 cm FL (Pratt, 1979). The average P_{DA} and the ratio of immature-to-mature individuals discarded in each 0.5-degree cell were estimated and plotted in order to visually examine the spatial distribution of these two variables.

Results

Data from 702 longline sets were used in analyses and resulted in size and condition (i.e., live or dead) information on 4290 individual blue shark. From these data, a total of 37 proportions (i.e., P_{DA} values) were calculated and used in regression analyses.

Most of the sets targeted swordfish (39%) or swordfish and tuna (36%), or unspecified tuna species (14%). Bigeye tuna and yellowfin tuna were the target of 8% and 3% of the sets, respectively. About 88% of the sets included in the analysis were characterized as "night sets" and the remaining were "day sets."

Overall, more blue shark were released alive (69%) than dead. Shark sizes, water temperatures, and set durations used in the multiple linear regression ranged from 75 to 300 cm FL (median=175 cm), 8 to 29°C (median=19°C), and 6 to 14 hours (median=12), respectively. About 68% of all released animals measured less than the size of sexual maturity (i.e., <185 cm FL).

Multiple linear regression indicated that no interaction terms were statistically significant and that only shark size and set duration had significant effects on P_{DA} (r^2=0.86, n=37, P<0.00001; Table 1). Plots of the observed proportions and the predicted response surface illustrate how the proportion of live releases increases with shark size and decreases with duration of set (Fig. 2, A and B). Whereas set duration has a moderate impact on the largest size classes, the proportion of live sharks <185 FL (i.e., immature stages) is considerably reduced even at relatively short set durations. For example, predicted P_{DA} for the smallest sharks (i.e., FL=75 cm) was 0.67 and 0.47 for set durations of 6 and 14 hours, respectively; for those animals measuring 250 cm FL, it was 0.94 and 0.80 for the same set durations. Maps of mean P_{DA} values and of the proportion of immature sharks caught indicated conspicuous differences off the U.S. east coast versus over the Grand Banks (Fig. 3, A and B). Specifically, the proportion of live releases

Table 1

Regression coefficients and associated standard error values (SE) for the estimation of proportion of blue shark released alive (P_{DA}) (n=37), where β_0 corresponds to the intercept, and β_1 and β_2 are coefficients associated with blue shark fork length and set duration, respectively.

Parameters	Estimate	SE	$P>\|t\|$
β_0	0.967	0.0500	<0.0001
β_1	0.0021	0.0002	<0.0001
β_2	−0.0269	0.0037	<0.0001

tended to be lower over the Grand Banks than off the U.S. east coast and the mean ratio of immature blue shark tended to be higher.

Discussion

Our results indicate that blue shark tolerance to the stresses associated with longline capture decreases with animal size at levels that vary with set duration. These results are consistent with the findings of Neilson et al. (1989) and Milliken et al. (1999) who observed greater discard mortality among the smallest sizes classes of longline-caught Atlantic halibut (*Hippoglossus hippoglossus*) and cod (*Gadus morhua*), respectively. In our study, set duration represented the maximum possible time a given fish was "on-hook," and thus was only the coarsest of measures of the magnitude and duration of stress experienced by hooked fishes. Nevertheless, this crude measure appears to have captured enough of the cumulative stress effects on fish survival to emerge as a significant factor. In contrast, water temperature did not emerge as important in our analysis. However, we suspect this resulted because surface water temperatures (the only temperature measurements available) are poor indicators of the levels and changes in temperature actually experienced by captured sharks. Presumably, better predictions of condition at boat-side (and thus live discard quantities) could be made with knowledge of time-on-hook, depth, and temperature of capture, rate of gear retrieval, sea conditions, etc. Unfortunately, many of the measurements that are likely most relevant to recording shark condition at boat-side can only be made by distributing and retrieving large quantities of electronic instruments (i.e., temperature-depth recorders and hook-timers, see Boggs, 1992) near the hooks, and for each set. Such an approach is not only costly, but also difficult to implement without a research team dedicated for this purpose. Similarly, only by directed research can questions of postrelease mortality be addressed. Clearly, the proportions of living blue shark considered in our study are minimum estimates of fishing impacts because they do not account for delayed mortality of individuals released injured or otherwise impaired. For gauging postrelease mortality of longline-caught blue shark, tagging studies are warranted (Neilson et al., 1989; Kohler et al., 2002).

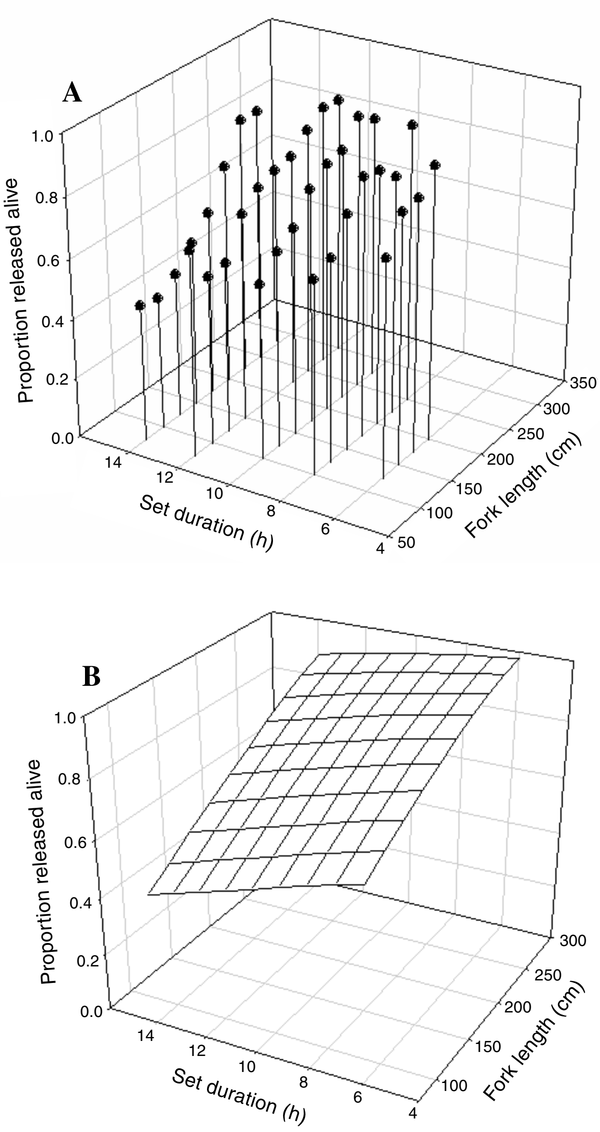

Figure 2

(**A**) Observed proportions of blue shark discarded alive (n=37) for each fork-length set duration combination; and (**B**) predicted response surface.

Evident in the maps is that the proportion of blue sharks available for live release was not homogeneous throughout the spatial range examined. Overall the proportion of blue shark released alive was higher (0.78) along the U.S. Atlantic east coast and decreased over the Grand Banks (0.67) (Fig. 3A). The maps also indicated that overall the proportion of immature blue sharks was highest over the Grand Banks (0.93) compared to the U.S. Atlantic east coast (0.63) (Fig. 3B). In their examination of U.S. Atlantic east coast longline catches south of the present study (i.e., between 35° and 22°N latitude), Beerkircher et al. (2004) found that 0.87 of blue shark caught were alive at boat-side. It seems likely, therefore, that contributing to the relatively higher survival observed by Beerkircher et al. (2004) was that only about half of the blue shark in their analysis were immature (as inferred from size). Blue shark interactions over the Grand Banks deserve special attention because most individuals discarded by the U.S. pelagic longline fleet are captured in that area. In 2002, for example, two thirds of the estimated 4335 blue shark mortalities attributed to U.S. Atlantic pelagic longline fleet were captured in this area (Diaz, unpubl. data[3]).

[3] Diaz, G. A. 2005. NMFS Pelagic longline logbook program. NMFS/SEFSC Miami, FL 33149.

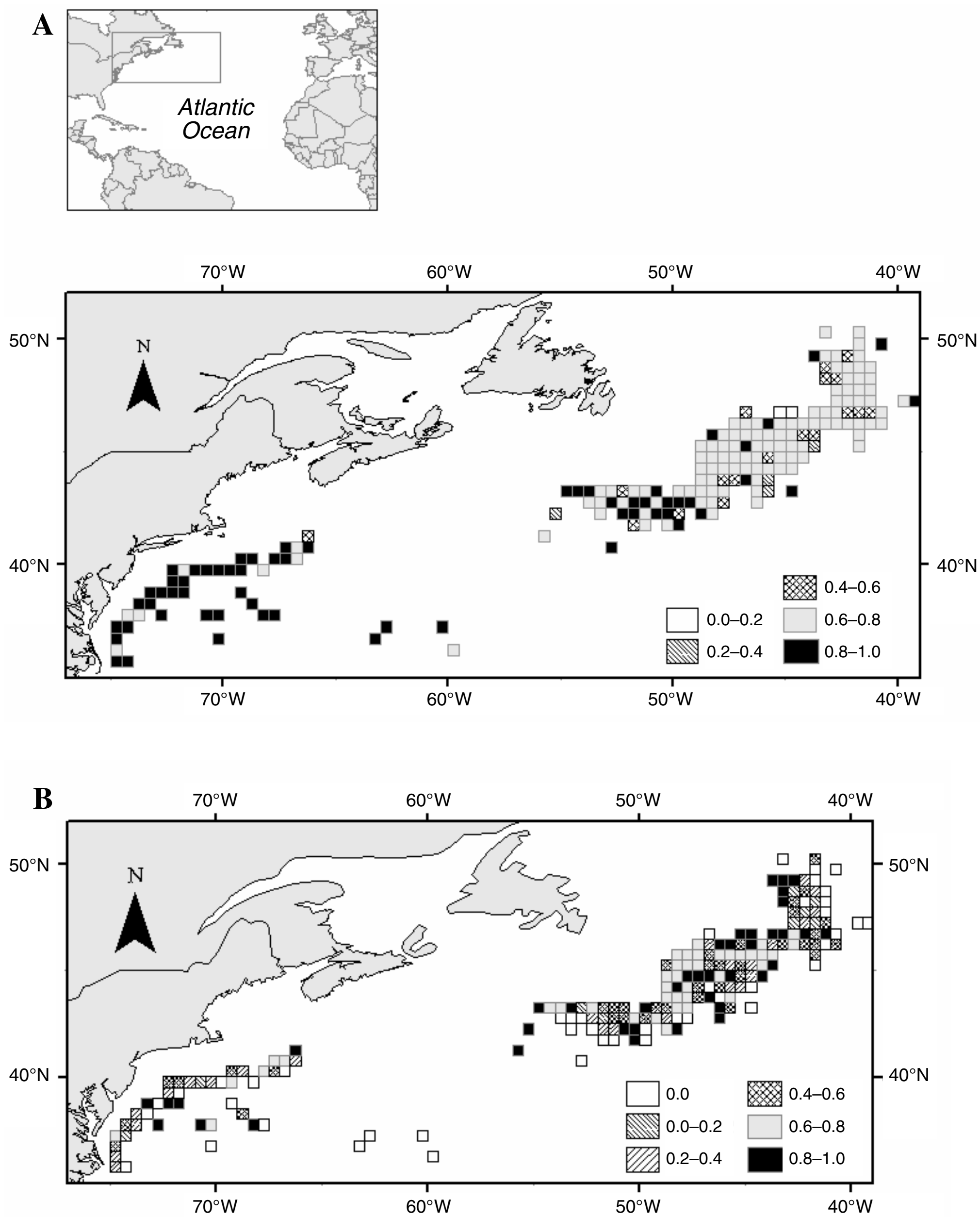

Figure 3

(**A**) Average proportion of blue shark released alive and (**B**) average proportion of immature blue shark released in pelagic longline sets. Proportions were estimated for 0.5-degree cells where at least one longline set was deployed in the period 1992–2002.

Ward et al. (2004) modeled the effect of set duration on pelagic longline catches and found that blue shark catch rates increased with set duration. According to our results, the increase in set durations also leads to increases in the number retrieved dead. In concept, a possible management measure to achieve reductions in blue shark mortality may include shortening longline set durations. However, a regulation of this nature would be difficult to implement (let alone enforce) because swordfish catch rates are also lowered when set durations are shortened (Ward et al., 2004) and therefore result in negative economic impacts that would likely be unacceptable to the industry.

Results of this analysis also have implications for blue shark stock assessment. Stock assessments based on longline fisheries data often use a hook selectivity function of a logistic form, whereby hook retention is 100% for fish larger than a certain size. In the particular case of blue shark, where most individuals caught are released (dead or alive), fishing mortality is best estimated from the number of animals released dead, rather than from all animals caught. Because larger animals have a higher probability of being released alive, a logistic selectivity function without size or age survival adjustment, could lead to overestimation of impacts on the stock. Thus, a dome-shaped selectivity function that incorporates the size-based survival information presented in the present study may represent an improvement over current techniques.

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