Abstract—Gillnet mesh selectivity parameters were estimated for juvenile blacktip sharks (*Carcharhinus limbatus*) by using length data from an experimental fishery-independent gillnet survey in the northeastern Gulf of Mexico. Length data for 1720 blacktip sharks were collected over 17 years (1994–2010) with seven mesh sizes ranging from 7.6 to 20.3 cm. Four selectivity models, a normal model assuming fixed spread, a normal model assuming that spread is proportional to mesh size, a lognormal model, and a gamma model were fitted to the data by using the SELECT (share each length's catch total) method. Each model was run twice under separate assumptions of 1) equal fishing intensity; and 2) fishing intensity proportional to mesh size. The normal, fixed-spread selectivity curve where fishing intensity is assumed to be proportional to mesh size provided the best fit to the data according to model deviance estimates and was chosen as the best model. Results indicate that juvenile blacktip sharks are susceptible as bycatch in some commercial gillnet fisheries.

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Gillnet selectivity for juvenile blacktip sharks (*Carcharhinus limbatus*)

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In the late 1980s, a gillnet fishery for sharks developed in the Atlantic Ocean off the coasts of Florida and Georgia (Trent et al., 1997). Fishing area varied with seasons, and shark drift gillnet vessels operated in nearshore waters between 4.8 and 14.4 km offshore, ranging from West Palm Beach, Florida (~26°46′N), to Altamaha Sound, Georgia (~31°45′N). A variety of methods were used to deploy gillnets, including drifting the net on the surface (Trent et al., 1997), striking around a school of sharks (Carlson and Baremore[1]), and anchoring the net to the bottom (Carlson and Bethea, 2007). Fishermen targeted a variety of coastal species of sharks, from blacktip sharks (*Carcharhinus limbatus*) to Atlantic sharpnose sharks (*Rhizoprionodon terraenovae*) depending on market conditions and fishery closures. Over the last 10 years, the size and scope of the commercial shark gillnet fishery has decreased primarily owing to regulations that restrict gear, fishing areas, and trip limits for sharks. In 2008, Amendment 2 to the Consolidated Atlantic Highly Migratory Species Fishery Management Plan (NMFS, 2008) limited landings of large coastal sharks to 33 sharks per trip. The high cost of fuel and low market value for shark meat, in conjunction with these regulations, caused most commercial fishermen in the U.S. south Atlantic Ocean to abandon the gillnet fishery for sharks.

Although shark-targeted gillnet trips are currently rare in the U.S. Atlantic Ocean, blacktip sharks are still caught as bycatch in other gillnet fisheries that target species such as Spanish mackerel (*Scomberomorus maculatus*) and king mackerel (*S. cavalla*) (Passerotti et al., 2010; Thorpe and Frierson, 2009). These coastal teleost gillnet fisheries are expansive, and had more than 65 active fishing vessels in 2010.[2] The fishing locations of these vessels span the U.S. east coast throughout the range of the blacktip shark.

The blacktip shark is a cosmopolitan species, ranging from Massachu-

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[1] Carlson, J. K., and I. E. Baremore. 2003. The directed shark gillnet fishery: catch and bycatch 2003, NOAA Sustainable Fisheries Division Contribution PCB-03/07, 8 p. Panama City Laboratory, National Marine Fisheries Service, Panama City, Florida. [Available from http://www.sefsc.noaa.gov/labs/panama/documents/observer_documents/gillnet/SDG2003.pdf, accessed December 2011.]

[2] Southeast Fisheries Science Center Coastal Fisheries Logbook, available at http://www.sefsc.noaa.gov/fisheries/reporting.htm, accessed March 2011.

setts throughout the Gulf of Mexico in U.S. coastal waters (McEachran and Fechhelm, 1998). Juvenile blacktip sharks use nursery areas such as bays and nearshore habitats during spring and summer months (Castro, 1993; Heupel and Hueter, 2002). Because of their range and life history characteristics, juvenile blacktip sharks are likely to encounter commercial gillnets.

Gillnet selection curves are a useful way to represent the retention probabilities of different mesh sizes for a given species of fish. Retention probability by gillnets is usually considered to be dome-shaped and can be described by the equation

$$r_j\left(l_i\right) = \exp\left(-\frac{\left(1-\mu_j\right)^2}{2\sigma_j^2}\right),$$

where $r_j(l_i)$ is the retention probability that a fish of length l in size class i is caught by mesh size j, and μ and σ represent the mean and spread of the curve (Millar and Fryer, 1999). However, the selection curve may be skewed because of snagging, rolling, or entangling of animals, and can result in a gamma or lognormal curve (Millar and Fryer, 1999).

Generally, selectivity can be measured in two ways: directly and indirectly (Millar and Fryer, 1999). Direct experiments are performed on a population for which the size distribution is known, and size selection is calculated by comparison of the population with the catch distributions. Indirect, or comparative, experiments are more common and usually involve simultaneously fishing gillnets of differing mesh sizes with equal effort.

Commercial fishing gear selectivity curves are incorporated into modern stock assessment models, and changes in the parameters have the potential to impact the assessed status of the stock (Maunder, 2002). Size selectivity is used in the estimation of the length-frequency of a stock, estimation of fishing-induced mortality, and in age-based assessment models (Millar and Fryer, 1999). Although important for the stock assessment models, fishery-independent selectivity models are rare for many large shark species (McAuley et al., 2007). Selectivity for bycatch species is also becoming an important issue in stock assessment, but direct estimates are likewise rare for most fisheries. The goal of this study is to determine the relationship between gillnet mesh size and selectivity for juvenile blacktip sharks using fishery-independent data.

Materials and methods

Sampling

Data necessary for indirect calculation of gillnet mesh selectivities were obtained from the Gulf of Mexico Shark Pupping and Nursery (GULFSPAN) survey, which is a fishery-independent gillnet survey of coastal shark populations in the northeastern Gulf of Mexico (Carlson and Brusher, 1999). Catch data for *C. limbatus* were collated over 17 years (1994–2010) from five bay systems in northwest Florida: St. Andrew Bay, Crooked Island Sound, St. Joseph Bay, the gulf side of St. Vincent Island, and Apalachicola Bay (Fig. 1).

Six gillnet panels of differing stretched mesh sizes were strung together in increasing mesh size, anchored, and fished concurrently as a single gillnet. Each panel was 30.1 m long and 3.4 m deep (Table 1). From 1994 through 2005, stretched mesh sizes ranged from 8.9 cm to 14.0 cm, increasing by 1.3-cm (0.5-in) intervals, with an additional panel of 20.3 cm. In 2006, the 20.3-cm panel was removed and a 7.6-cm panel was added *ad hoc*. The largest mesh panel was removed because of its historically low catch of juvenile small coastal shark species, and the 7.6-cm panel was added to increase catch of small neonatal sharks. Unless otherwise indicated, all mesh sizes reported in the present study are stretched mesh sizes.

Sampling occurred each year from late March through October. Net set locations within bay systems were randomly chosen over a variety of habitat and depth combinations. The majority of sets were short (<1 hr) as a means of reducing mortality, especially when water temperatures were above 25°C. However, some nets were soaked for longer periods of time, depending on the research priorities at the time. Captured sharks were removed from the net, their sex was determined, and they were measured for fork length (FL) on a rigid measuring board in a straight line from the tip of the nose to the fork in the tail. Sharks in poor condition were sacrificed for research projects and those in good condition were tagged and released. Maturity state was determined by clasper calcification for males, internal examination for sacrificed female sharks, and released females were considered to be mature when greater than 115 cm FL (Carlson et al., 2006). Sexes were combined for data analyses.

Data analysis

Catch data were pooled by mesh size into 5-cm-FL size bins, and the midpoint of each size class (l_i) was used to calculate a selectivity curve for each mesh size (Millar and Holst, 1997). Four gillnet selectivity models were fitted to the l_i for each mesh size (m_j) (Millar and Holst, 1997), by using the SELECT (share each length's catch total) method (Millar and Holst, 1997; Millar and Fryer, 1999; Millar, 2003, 2010). The selection curves were fitted to the data by using the "gillnetfunctions" package in R statistical software (Millar, 2003, 2010; R Development Core Team, 2009). The SELECT method applies the method of maximum likelihood, which estimates selectivity parameters from a general log-linear model. The expected catch of sharks of length class i in gillnet j is described by

$$v_{ij} = p_j \lambda_i r_j, \tag{1}$$

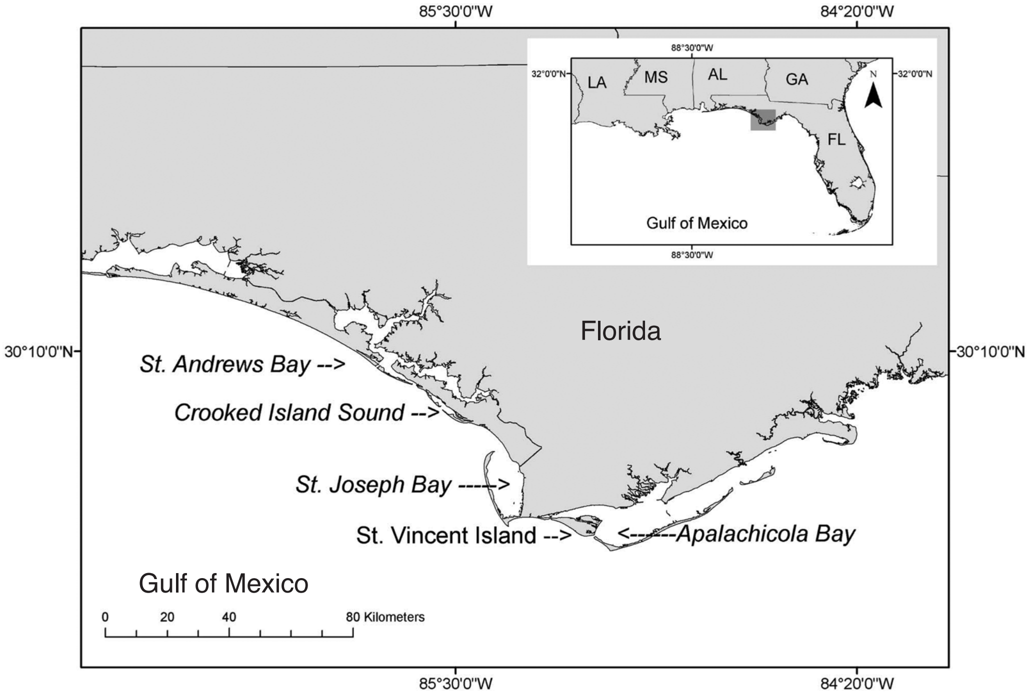

Figure 1

Location of the Gulf of Mexico Shark Pupping and Nursery (GULFSPAN) survey in northwest Florida. Sampling sites were located in St. Andrew Bay, Crooked Island Sound, St. Joseph Bay, the gulf side of St. Vincent Island, and Apalachicola Bay. Sampling occurred from 1994 through 2010.

Table 1

Gillnet specifications used in the Gulf of Mexico Shark Pupping and Nursery (GULFSPAN) survey 1994–2010. For all net configurations, the hanging ratio (length to height ratio of the meshes) was 0.5, leadline weight was 4.5 kg, 2.3 kg of buoyancy was used, and each panel length was 30.1 m.

Stretch mesh size (in/cm)	Twine size no.	No. of meshes deep	Thickness of twine (mm)	Breaking strength (kg)	Years fished
3.0/7.6	208	45	0.52	11.8	2006–2010
3.5/8.9	208	40	0.52	11.8	1994–2010
4.0/10.2	208	35	0.52	11.8	1994–2010
4.5/11.4	208	35	0.52	11.8	1994–2010
5.0/12.7	277	30	0.62	18.2	1994–2010
5.5/14.0	277	25	0.62	18.2	1994–2010
8.0/20.3	24	20	1.00	115.9	1994–2005

where p_j = the relative fishing intensity of gillnet j:
λ_i = the abundance of sharks in length class i; and
r_j = the selection curve for each gillnet j.

Relative fishing intensity represents fishing effort and fishing intensity combined and is the conditional probability that a fish contacted gillnet panel j, with the assumption that it made single contact with the entire combined gillnet panel (Millar, 1992). The normal, gamma, and lognormal models observe geometric similarity (mean μ_j and spread σ_j proportional to mesh size), whereas the normal model with fixed spread is not geometrically similar (mean μ_j and spread σ_j equal across mesh sizes). When p_j is assumed to be equal among mesh sizes, the form of the log-linear model is as follows:

$$\log\left(v_{ij}\right) = factor\left(l_i\right) + \beta_1 \cdot f_1\left(m_j, j\right) + \beta_2 \cdot f_2\left(m_j, j\right), \qquad (2)$$

Table 2

Selectivity curves for normal, gamma, and lognormal models used to estimate gillnet selectivity for blacktip sharks (*Carcharhinus limbatus*): m_j is the mesh size for panel j (j=1–7 panels) and l_i is the midpoint of length class i (i=1–22 length classes). Relative fishing intensity is modeled separately. Equations in the right hand column are the last two terms in the log-linear model

$$\beta_1 = -\frac{a_1}{a_2}, \beta_2 = -\frac{1}{2a_2}, f_1\left(m_j, l_i\right) = \frac{l_i}{m_j}, f_2\left(m_j, l_i\right) = \frac{l_i^2}{m_j^2}.$$

Model	Selection curve	$\beta_1 \cdot f_1\left(m_j,l_i\right)+\beta_2 \cdot f_2\left(m_j,l_i\right)$
Normal: fixed spread	$\exp\left(-\frac{\left(l_i - k \cdot m_j\right)^2}{2\sigma^2}\right)$	$\left(\frac{k}{\sigma^2}\right)\cdot\left(l_i \cdot m_j\right)+\left(-\frac{k^2}{2\sigma^2}\right)\cdot m_j^2$
Normal: proportional spread	$\exp\left(-\frac{\left(l_i - a_1 \cdot m_j\right)^2}{2a_2 \cdot m_j^2}\right)$	$\left(\frac{a_1}{a_2}\right)\cdot\left(\frac{l_i}{m_j}\right)+\left(-\frac{1}{2a_2}\right)\cdot\left(\frac{l_i}{m_j}\right)^2$
Gamma: proportional spread	$\left(\frac{l_i}{(\alpha-1)\cdot k \cdot m_j}\right)^{\alpha-1}\exp\left(\alpha-1-\frac{l_i}{k \cdot m_j}\right)$	$[\alpha-1]\cdot\left(\log\left(\frac{l_i}{m_j}\right)\right)+\left(-\frac{1}{k}\right)\cdot\left(\frac{l_i}{m_j}\right)$
Lognormal: proportional spread	$\frac{1}{l_i}\exp\left(\mu_1+\log\left(\frac{m_j}{m_1}\right)-\left(\frac{\sigma^2}{2}\right)-\frac{\left(\log\left(l_i\right)-\mu_1-\log\left(\frac{m_j}{m_1}\right)\right)^2}{2\sigma^2}\right)$	$\frac{1}{\sigma^2}\cdot\left(\log\left(l_i\right)\cdot\log\left(\frac{m_j}{m_1}\right)-\frac{1}{2}\log^2\left(\frac{m_j}{m_1}\right)\right)+\left(1-\frac{\mu_1}{\sigma^2}\right)\cdot\left(\log\left(\frac{m_j}{m_1}\right)\right)$

Table 3

Equations used to estimate the modal length of blacktip sharks (*Carcharhinus limbatus*) caught with each gillnet mesh size (m_j) for all four gillnet selectivity models.

Model	Mode
Normal (fixed and proportional spread)	Mode $(m_j)=k \cdot m_j$
Gamma	Mode $(m_j)=(\alpha-1) \cdot k \cdot m_j$
Lognormal	Mode $(m_j)=\exp(\mu-\sigma^2) \cdot \left(\frac{m_j}{m_1}\right)$

where *factor*(l_i) indicates that length class is fitted as a factor of the model, and $f_1(m_i, j)$ and $f_2(m_j, j)$ are the selectivity functions of m_j and j (right hand column of Table 2). When p_j is assumed to be proportional to mesh size ($\log p_j=\log m_j$), the form of the log-linear model is as follows:

$$\log\left(v_{ij}\right)=\log\left(m_j\right)+\mathit{factor}\left(l_i\right)+ \\ \beta_1 \cdot f_1\left(m_j, j\right)+\beta_2 \cdot f_2\left(m_j, j\right). \qquad (3)$$

The parameters β_1 and β_2 are related to the form of the selectivity curve and are defined in Table 2. The following assumptions were made for all models: 1) catches were independent; and 2) gillnet panels were fished with equal effort. The mode, or maximum selected size for each panel, was calculated according to equations listed in Table 3. All models were fitted to the data twice, once under the assumption of equal fishing intensity and again under the assumption of fishing intensity proportional to mesh size. Overdispersion, or lack of fit, was tested by calculating the dispersion parameter, which is the model deviance divided by the degrees of freedom. When the dispersion parameter is >1, data are considered to be overdispersed.

Results

A total of 1720 blacktip sharks were measured from 1994 through 2010 (Table 4). Blacktip sharks were collected during 14 of the 17 years of the survey. Average net soak time was 2.67 hr (range: 0.17–23.83 hr) over 1573 sets. Some outliers were excluded when sampling protocol was considered to be out of the ordinary procedure. The majority (97%) of blacktip sharks caught in all panels were immature and less than 110 cm FL (mode=65 cm FL, Fig. 2). There was a general increase in the mean size of blacktip sharks with increasing mesh size. For the panels that were fished concurrently for all years (8.9–14.0 cm mesh), the total sample sizes of measured sharks were similar (Table 4).

Table 4

Length distribution for all blacktip sharks (*Carcharhinus limbatus*) caught in each gillnet mesh panel in the Gulf of Mexico Shark Pupping and Nursery (GULFSPAN) Survey in northwest Florida, 1994–2010.

Fork length (cm)	Mesh sizes (cm)						
	7.6	8.9	10.2	11.4	12.7	14.0	20.3
42.5	4	4	4	0	1	0	0
47.5	2	10	14	18	6	4	0
52.5	13	25	29	57	21	22	2
57.5	13	20	32	53	30	43	3
62.5	12	24	21	41	63	41	0
67.5	7	30	31	29	47	31	4
72.5	6	26	30	34	20	32	6
77.5	13	36	34	21	30	20	5
82.5	8	15	20	22	17	28	7
87.5	4	29	24	34	25	16	9
92.5	7	15	17	20	14	15	9
97.5	0	14	12	15	13	14	18
102.5	2	4	16	15	9	8	17
107.5	0	10	5	1	5	4	12
112.5	0	1	0	2	4	0	6
117.5	0	2	0	4	3	0	8
122.5	0	2	1	1	0	0	4
127.5	0	0	0	1	0	0	2
132.5	0	0	0	0	0	0	0
137.5	0	0	0	0	0	0	2
142.5	0	0	0	1	0	0	1
147.5	1	0	1	0	0	0	0
Totals	92	267	291	369	308	278	115

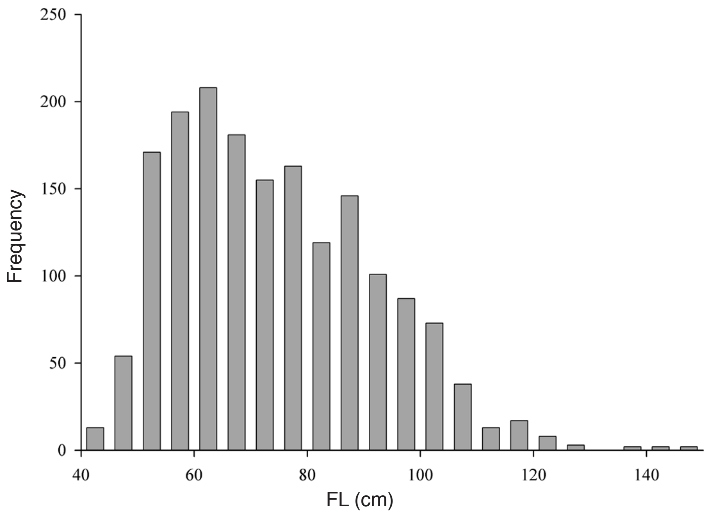

Figure 2

Length frequency of blacktip sharks (*Carcharhinus limbatus*) in fork length (FL) for all years combined caught in the Gulf of Mexico Shark Pupping and Nursery (GULFSPAN) survey in northwest Florida, 1994–2010.

The normal, fixed-spread models had the lowest model deviance overall, with the model incorporating fishing intensity proportional to mesh size having the lowest total model deviance (Fig. 3, Table 5). The ratio of model deviance to degrees of freedom was higher than 1 (2.9), indicating overdispersion of the data. This result indicates that blacktip sharks may not have behaved independently (e.g., with schooling behavior), violating the first assumption of independent catches. Residual plots showed a similar degree of bias for all models (Fig. 3), with none demonstrating markedly different fits to the data. The biggest difference among models was for the largest mesh (20.3 cm) for which the normal (proportional spread), lognormal, and gamma curves under-represented some of the smaller length classes. The highest number of positive residuals was seen for the smaller length classes (50–70 cm FL) in mesh sizes 11.4 cm and 12.7 cm and, to a lesser degree, the 14.0 cm panel for all models (Fig. 3). The plots indicated that more of the smaller individuals were caught in these panels than predicted by the models. The largest and smallest mesh sizes (20.3 and 7.6 cm) caught fewer of the smallest sharks than predicted by the models. The residuals did not indicate systematic bias in any of the models aside from the lack of fit to the smallest size classes (Fig. 3). Predicted selectivity curves for the normal, fixed-spread model assuming proportional fishing intensity plotted with observed length-frequencies for each mesh size (Fig. 4) showed that the model fitted the observed data well.

Discussion

In previous gillnet selectivity studies on sharks, a gamma-shaped distribution has been assumed (Carlson and Cortes, 2003; Kirkwood and Walker, 1986; McLoughlin and Stevens, 1994; Simpfendorfer and Unsworth, 1998), based on the specialized SELECT method described by Kirkwood and Walker (1986). However, a more recent study on the gillnet selectivity for sandbar sharks *C. plumbeus* (McAuley et al., 2007) found that all four models estimated by the Millar and Holst (1997) method provided better fits than the Kirkwood and Walker (1986) gamma model. Our study on blacktip sharks indicated that the normal, fixed spread models provided the best fit. A more limited study in North Carolina (Thorpe and Frierson, 2009) found that the normal model with spread proportional to mesh size generally provided the best fit for blacknose (*C. acronotus*), bonnethead (*Sphyrna tiburo*), and blacktip sharks. Although the method of Kirkwood and Walker (1986) was not employed in this study, the gamma curve estimated by the Millar and Holst (1997) SELECT method provided a poorer fit than the normal and lognormal models. Therefore, it

Table 5

Gillnet selectivity parameter estimates for each model for blacktip sharks (*Carcharhinus limbatus*) in northwest Florida, 1994–2010. All four models were run twice: first assuming fishing intensity to be equal across mesh sizes and again assuming that fishing intensity was proportional to mesh size. Model deviance is the likelihood ratio goodness of fit, with 130 degrees of freedom for each model.

	Equal fishing intensity		Proportional fishing intensity	
Model	Parameters	Model deviance	Parameters	Model deviance
Normal (fixed spread)	(k, σ)=(5.98, 30.98)	411.79	(k, σ)=(6.94, 34.91)	371.36
Normal (prop. spread)	(a_1, a_2)=(6.80, 10.11)	536.33	(a_1, a_2)=(8.11, 8.20)	553.73
Lognormal	(μ_1, σ)=(4.00, 0.41)	440.33	(μ_1, σ)=(4.17, 0.41)	440.33
Gamma	(α, k)=(6.39, 1.17)	469.68	(α, k)=(7.39, 1.17)	469.68

was not necessary to test a separate method to estimate a gamma selectivity curve.

Residual plots from all selectivity models showed some degree of bias for the smaller (50–70 cm FL) size classes in the 11.4-, 12.7-, and 14.0-cm mesh sizes. This finding indicated that all models underestimated the numbers of small blacktip sharks caught in these mesh sizes, and these underestimates could be an artifact of the sampling design of the GULFSPAN juvenile shark survey (Carlson and Brusher, 1999). In this survey gillnet panels were arranged in increasing order by mesh size, and the order of panels was not randomized. Randomization of gillnet panels is common in selectivity experiments because it is thought to reduce the potential preference of fish for any one area of the net. However, because fixed stations were not used, and the nets were fished at a variety of depths, habitats, and seasons, sampling design was probably not a factor in the model's lack of fit to the data. The overdispersion of the data could be a result of the pooling of the data into 5-cm bins, or could indicate schooling behavior by some size classes of blacktip sharks. Shark species are known to segregate by size and sex; therefore the capture of a cluster of similar-size blacktip sharks is likely. Overdispersion does not necessarily affect parameter estimation (Millar and Fryer, 1999), although an initial model assumption may have been violated.

Although the assumption of equal catches may have been violated, the second assumption of equal fishing effort among gillnet panels was most likely met. The shallow bays and estuaries sampled, along with the length of the net (~600 m), decreased the probability of different panels fishing in different habitats and depth zones. Commercial gear can be several kilometers in length, and sagging can cause the middle part of the gear to fish in different depth strata than those at the ends. Blacktip sharks were therefore equally likely to encounter each panel of the GULFSPAN survey gillnet.

On occasion, adult blacktip sharks (>130 cm FL) have been captured in the survey areas on longlines (Bethea and Carlson[3]). However, larger sharks are less likely to be caught in gillnets with mesh sizes smaller than 20 cm, and those few large sharks captured in the smaller mesh sizes were generally entangled by rolling in the gear—a phenomenon that was also noted for finetooth sharks (*C. isodon*) (Carlson and Cortes, 2003). All gillnet panels, except the 20.3 cm panel, were monofilament, and large sharks were able to break the monofilament and escape the gear. Such cases where larger sharks were entangled in smaller mesh sizes or where they broke free of the net could also have affected the lack of fit because the assumption of geometric similarity would not stand. The occurrence of larger sharks in small mesh sizes may have been reflected by the high model deviances for the models (normal proportional spread, lognormal, and gamma) where geometric similarity of the data was assumed. However, other than the lack of fit to the smallest size classes, the models described the data very well, with residuals showing mostly equal error distribution and little systematic bias.

Because of the change in the gear from 2005 through 2006, several attempts were made to account for a year effect within the SELECT method. Because of low sample sizes within years, especially for the 7.6- and 20.3-cm panels, it was not possible to incorporate year as a factor. For instance, a total of 92 and 115 blacktip sharks were captured by the 7.6- and 20.3-cm panels, respectively. Although these sample sizes were adequate for the overall model, when broken down by year the sample sizes were in the single digits for most size classes. The data were also separated into two time periods (1994–2005 and 2006–10), and the SELECT method was used to estimate selectivity models for each time period. The first time period produced reasonable results; however, no realistic solution was found for the second time period. This could also be due to sample sizes in the second time period. Although

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[3] Dana M. Bethea and John. K. Carlson. 2011. Unpubl. data. Panama City Laboratory, Southeast Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 3500 Delwood Beach Rd., Panama City, Florida 32408.

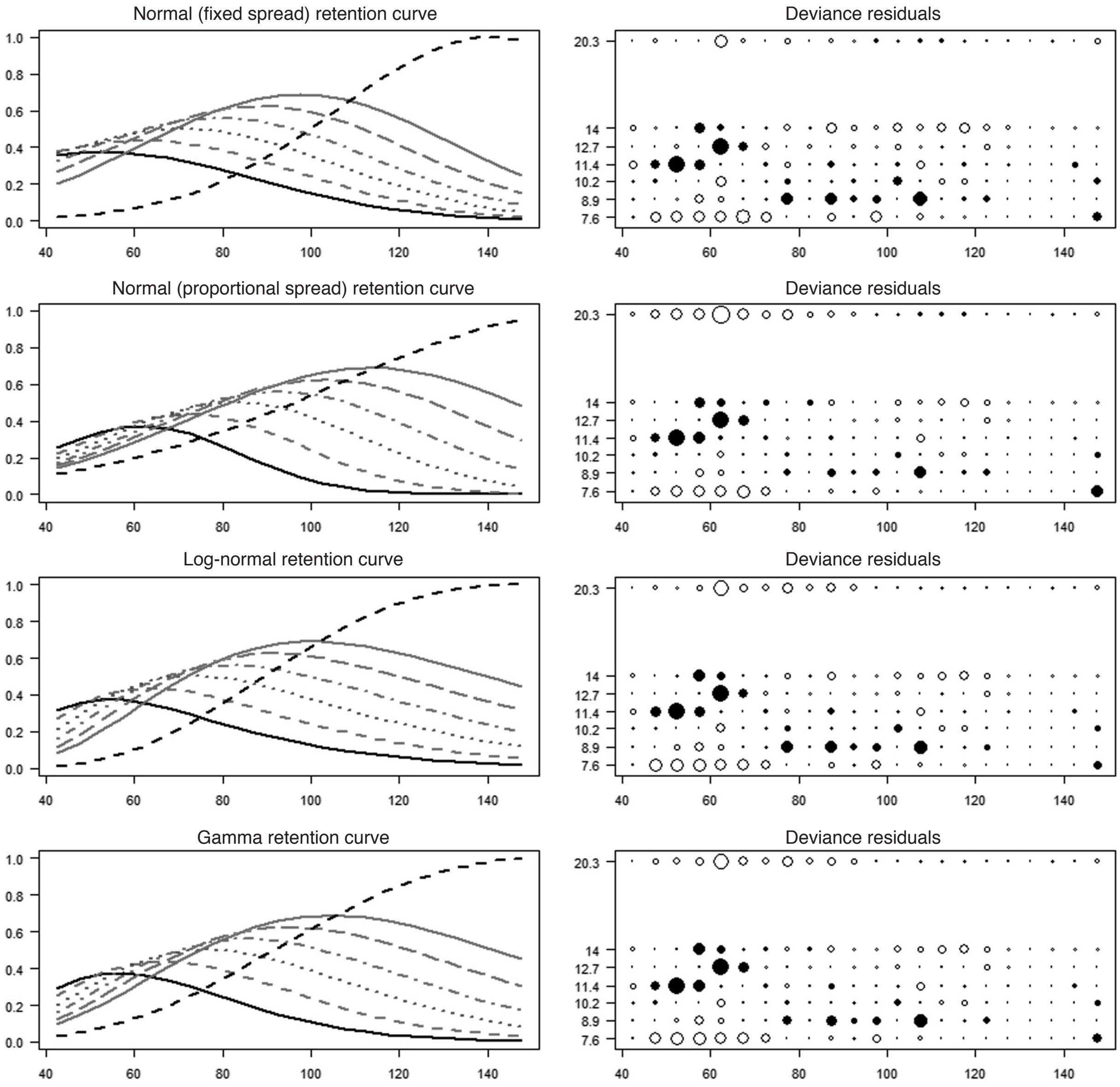

Figure 3

Gillnet selectivity curves and residuals estimated for blacktip sharks (*Carcharhinus limbatus*) in the Gulf of Mexico Shark Pupping and Nursery (GULFSPAN) survey in northwest Florida calculated from the normal (fixed spread), normal (proportional spread), lognormal, and gamma distributions. The plots on the left are the estimated gillnet selectivity curves with relative retention probability on the *y* axis. Increasing height of the curves indicates increasing mesh sizes. The plots on the right show the residuals of the models and mesh size on the *y* axis increases from bottom to top. Filled circles represent positive residuals and open circles represent negative residuals. The area of the circle is proportional to the square of the residual.

there may have been a year effect that we were unable to account for, this is unlikely because of the nature of the survey and the species studied. Generally, year-to-year variability in recruitment is lower in sharks than in teleosts because of the production of large, well-developed young and low natural mortality (Smith et al., 1998; Walker, 1998). The GULFSPAN survey primarily targets juvenile sharks in nursery areas, and the majority of the blacktip sharks captured were juveniles. Therefore it is probable that interannual size variability was low in the survey area for blacktip sharks. Although this is an important factor that could be applied to other selectivity studies with more robust sample sizes, current stock assessment models

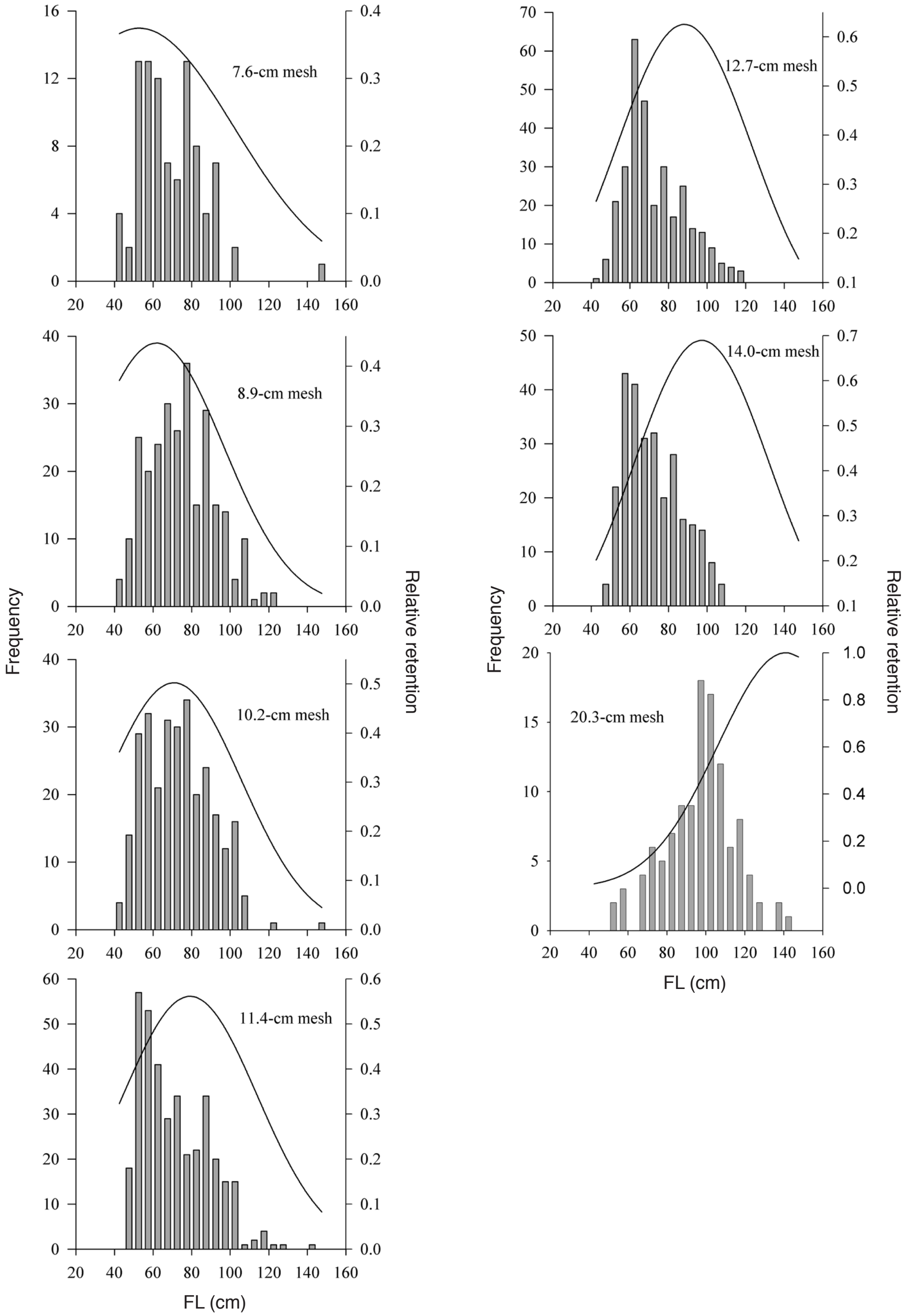

Figure 4

Selectivity curves for the normal proportional spread model where fishing intensity is assumed to be proportional to mesh size. Curves were plotted with observed data on frequency of fork lengths (FL) for blacktip sharks (*Carcharhinus limbatus*) caught in the Gulf of Mexico Shark Pupping and Nursery (GULFSPAN) survey. Selectivity curves and length frequencies are plotted separately by mesh size. Relative retention is the probability that a fish of a given length class that comes into contact with that mesh size is captured.

Table 6

Mode estimates (maximum selectivity) for blacktip sharks (*Carcharhinus limbatus*) (FL cm) caught in gillnets in northwest Florida for each mesh size fished and selectivity model. All four models were run twice: first assuming fishing intensity to be equal across mesh sizes and again assuming that fishing intensity was proportional to mesh size. Numbers in parentheses represent standard deviations, calculated for each mesh size when applicable. The normal, fixed spread and lognormal standard deviations are constant for all mesh sizes.

	Modes of selectivity curves						
Mesh size (cm)	7.6	8.9	10.2	11.4	12.7	14.0	20.3
Equal fishing intensity							
Normal: fixed spread	45.44 (30.98)	53.22	60.99	68.16	75.94	83.71	121.38
Normal: prop. spread	51.65 (24.16)	60.49 (28.30)	69.32 (32.43)	77.48 (36.24)	86.31 (40.38)	95.15 (44.51)	137.96 (64.54)
Gamma	47.86 (22.44)	56.05 (26.28)	64.24 (30.11)	71.79 (33.66)	79.98 (37.49)	88.17 (41.33)	127.84 (59.93)
Lognormal	45.88 (25.59)	53.73	61.58	68.83	76.68	84.52	122.56
Proportional fishing intensity							
Normal: fixed spread	52.78 (34.91)	61.81	70.84	79.18	88.21	97.23	140.99
Normal: prop. spread	61.64 (21.76)	72.18 (25.48)	82.73 (29.20)	92.46 (32.64)	103.00 (36.36)	113.55 (40.08)	164.65 (58.12)
Gamma	56.74 (24.13)	66.44 (28.26)	76.15 (32.38)	85.10 (36.19)	94.81 (40.32)	104.51 (44.45)	151.54 (64.45)
Lognormal	54.43 (30.36)	63.74	73.06	81.65	90.96	100.27	145.40

for sharks do not include year-specific selectivity functions (SEDAR, 2006).

Gillnet selectivity is more highly influenced by morphological features such as girth and the presence or absence of hard structures than it is by the length of a fish (Reis and Pawson, 1999; Carol and García Berthou, 2007). Nevertheless, straight-line measured length can often be used as a proxy for girth in selectivity studies because of the close direct relationship between the two parameters (Reis and Pawson, 1999), with exceptions for cases of unusual morphological features (e.g., in hammerheads [Thorpe and Frierson, 2009]) or behavioral response to entanglement (e.g., finetooth sharks [Carlson and Cortes, 2003]). Many sharks in the family Carcharhinidae share similar body shape and structure (Compagno and Niem, 1998), with girth and the rigidity of fins acting as a limiting factor for capture by gillnets (Carlson and Cortes, 2003; McAuley et al., 2007). Girth-to-length relationships have been found to be similar among related species of sharks (McLoughlin and Stevens, 1994). It is therefore possible that selectivity curves could be family-specific rather than species-specific for sharks. The most recent data have shown that the normal selectivity curves may provide the best fit for sharks in the family Carcharhinidae (McAuley et al., 2007; Thorpe and Frierson, 2009), indicating that the results for blacktip sharks could be useful for other carcharhinids of similar size. Selectivity parameters estimated for the blacktip shark could be used as a proxy for other species in the same family when species-specific selectivity estimates are unavailable. This theory could be tested by applying this method to other similar-size shark species for which a gillnet selectivity curve has been estimated, and should be pursued further as more data become available.

Thorpe and Frierson (2009) found length modes of 97 and 88 cm FL for blacktip sharks caught in mesh sizes 7.6 and 10.2 cm, respectively, whereas we estimated modes of 46 and 62 cm FL for the same mesh sizes (Table 6). However, Thorpe and Frierson (2009) failed to fit a selectivity curve to the individual mesh sizes because of the wide spread of the sparse length data. Their study was based on a small number of samples (n=76) and the modes for only two mesh sizes were estimated. The low sample size reported by Thorpe and Frierson (2009) was likely due to the relatively short duration of sampling, which was conducted over a period of eight months. Additionally, Thorpe and Frierson (2009) conducted their survey more than 1 km from shore, where the likelihood of small juveniles coming in contact with the gear was low. Total effort was not reported; however, catch rates were low in all gillnet panels (<0.15 blacktip sharks caught per hour of fishing). It is also possible that the size classes sampled in both studies were not reflective of the true size structure of the population because localized concentrations of sharks in each area that were available to the gear probably differed. The true availability of blacktip sharks to gillnets in different regions cannot be known; therefore applying selectivity functions should be done with a proper context and with supporting length-frequency data when possible.

Based on data from fisheries observers, the average mesh size used from 2005 through 2010 in the commercial anchored gillnet fishery in the U.S. Atlantic Ocean was 11.1 cm, with a range of 8.5–16.0 cm (Passerotti[4]). The modal length calculated by using the equation in Table 3 for normal models indicates that blacktip sharks approximately 77 cm FL should be most vulnerable to the average mesh size in the commercial gillnet fishery. When calculated by using the full range of mesh sizes, the predicted modes range from 59 to 111 cm FL. Average lengths of blacktip sharks measured by observers captured by commercial anchored gillnets from 2005–2010 ranged from 79 to 107 cm FL (Baremore et al., 2007; Passerotti and Carlson, 2009, 2010; Passerotti et al., 2010, 2011). The observed lengths are consistent with the selectivity model estimated for blacktip sharks. Blacktip sharks are born at approximately 40 cm FL and mature between 120 and 130 cm FL (5–7 yr) in the U.S. Atlantic Ocean (Carlson et al., 2006), suggesting that the blacktip sharks most vulnerable to commercial gear are juveniles. Juvenile blacktip sharks use inshore nursery areas during spring and summer months, but migrate into deeper waters in the fall and winter (Castro, 1993; Heupel et al., 2007). Commercial gillnet fishermen operating in states with gillnet bans are required to fish at least 4.8 km from shore (federal waters) in the U.S. Atlantic Ocean; therefore the smallest juvenile blacktip sharks may not be as vulnerable to bycatch in these areas, especially during summer months. However, in states such as North Carolina, which allow commercial gillnet fishing in state waters, the potential for gear interaction with juvenile blacktip sharks year-round is higher. Observer data show that blacktip sharks <120 cm FL are captured in commercial gillnet fisheries and therefore juvenile blacktip sharks are likely affected by both offshore and inshore gillnet fisheries.

Thorpe and Frierson (2009) reported a mortality rate of 90.5% for blacktip sharks captured in experimental gillnets. Although soak time was not reported, the gillnets and sampling protocol in their study were designed to mimic those commonly used by commercial gillnet fishermen in North Carolina; therefore it is probable that juvenile blacktip sharks interacting with commercial gillnets may also experience high bycatch mortality. Demographic evidence suggests that population growth rates are more sensitive to survival of juvenile life stages of sharks than adults (Cortés, 2002). Therefore, modeling of the gear selectivity of gillnet fisheries, and particularly modeling bycatch from fisheries that have the potential to impact juveniles, is especially important.

Blacktip sharks are a commercially exploited species in U.S. waters, and the stock status in the Atlantic Ocean and Gulf of Mexico is assessed by the National Marine Fisheries Service on a regular basis (NMFS, 2002; SEDAR, 2006). Bycatch estimates for blacktip sharks are available from observer data (Passerotti et al., 2010), and fishing intensity of the Spanish and king mackerel gillnet fisheries has been previously estimated (SEDAR 2008; 2009). These fishery-dependent data, along with selectivity curves provided by this study, can be used by assessment scientists to estimate the selectivity of blacktip sharks caught as bycatch by commercial gillnet fisheries in the U.S. Atlantic Ocean. Bycatch data are equally as important as primary catch data for stock assessment models (NMFS[5]; SEDAR, 2006), though often more difficult to attain because bycatch is generally discarded at sea. This study provides valuable information for assessment scientists and managers tasked with estimating the size structure of blacktip sharks caught by commercial gillnet fisheries.

Conclusions

Juvenile blacktip sharks are caught as bycatch in commercial gillnet fisheries in the U.S. Atlantic Ocean, although the impact on the population has not been assessed. The results from this study showed that gillnet selectivity for juvenile blacktip sharks caught in the fishery-independent survey was best described by a normal selectivity curve with fixed spread and with fishing intensity proportional to mesh size. Because many commercial gillnet fisheries use mesh sizes similar to those used to produce these results, it may be possible to estimate the length frequencies of juvenile blacktip sharks influenced by these coastal fisheries. Selectivity estimates may also be applicable to other sharks of similar size for which species-specific information is unavailable. Future studies should focus on fishery-dependent gillnet selectivity estimates to determine if selectivity changes with gear, location, or target species.

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[4] Passerotti, M. 2011. Personal commun. Panama City Laboratory, Southeast Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 3500 Delwood Beach Rd., Panama City, Florida 32408.

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information on commercial gillnet fisheries. The comments of three anonymous reviewers also added to the overall quality of the article. Sharks were collected under Florida Fish & Wildlife Conservation Commission special activity licenses 02R-075, 03SR-075A, 04SR-075 and 08SR-075.

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