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ARTICLE

# Effects of Turtle Excluder Devices (TEDs) on the Bycatch of Three Small Coastal Sharks in the Gulf of Mexico Penaeid Shrimp Fishery

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***Abstract***
**The stock of blacknose sharks *Carcharhinus acronotus* in the U.S. South Atlantic and the Gulf of Mexico is overfished, and according to the 2007 stock assessment conducted by the National Marine Fisheries Service overfishing continues to occur. Penaeid shrimp trawl bycatch rates in the Gulf of Mexico were modeled for this species as well as for the Atlantic sharpnose shark *Rhizoprionodon terraenovae* and bonnethead shark *Sphyrna tiburo* using a combination of research trawl and observer data. Research trawls have never used turtle excluder devices (TEDs), which are expected to exclude larger specimens of blacknose sharks. Most of the observer data that contain blacknose shark occurrences were collected during the pre-TED era when the two data sets tracked one another. Minimum observer data were available for the post-TED period (1990–present). As a consequence, the pre-TED (1972–1989) relationship between observer and research trawl catch per unit effort (CPUE) is driving the observer CPUE estimates from 1990 to the present, a period characterized by increased blacknose shark abundance. We suspected that the increase in predicted observer CPUE in the post-TED era is an artifact of application of the pre-TED observer and research trawl relationship to the post-TED era. This suspicion led us to question whether the bycatch of these species was altered due to the use of TEDs. We used negative binomial regression in a before-after-control-impact setting to test the effects of TEDs on the bycatch rates of these small coastal sharks. The TED effect was found to substantially reduce the bycatch of blacknose sharks (by 94%) and to do so moderately for bonnethead sharks (31%); the results were inconclusive for Atlantic sharpnose sharks. The management implication of our findings is that the existing small coastal shark–penaeid shrimp fishery bycatch model needs to be modified or replaced with a model that explicitly incorporates the potential for a TED effect.**

Of the four species comprising the small coastal shark complex (SCS), only the stock of blacknose sharks *Carcharhinus acronotus* off the southeastern USA and Gulf of Mexico (GOM) has been determined to be overfished (overfishing occurring; SEDAR13 2007). On average 86,381 individual blacknose sharks were estimated to have been killed each year between 1999 and 2005, for all fisheries combined. Of these, roughly half (43,492) were estimated to have been taken as bycatch in the penaeid shrimp trawl fisheries. Most (38,626) of this bycatch occurs in the GOM shrimp fishery rather than the U.S. South Atlantic fishery (4,866). Comparatively, the Atlantic sharpnose sharks *Rhizoprionodon terraenovae* (an average

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of 330,253 caught annually in the GOM shrimp fishery), bonnethead sharks *Sphyrna tiburo* (223,491), and finetooth sharks *Carcharhinus isodon* (0) were not overfished (nor was overfishing occurring). In the current study, we examine the modeling techniques used to estimate these bycatch estimates in the GOM penaeid shrimp fishery. We included only the three species found in the bycatch of this fishery.

The historical estimates of blacknose shark bycatch in the GOM by year, beginning in 1972, suggested fairly stable bycatch levels (mostly between 10,000 and 20,000 individuals) from 1972 to 1988, followed by a pronounced increase in the late 1980s and early 1990s (Figure 1). From that time forward to the most recent years, the estimates have been high as compared with the early years, ranging up to 65,546 blacknose sharks in 2004. Bycatch of Atlantic sharpnose and bonnethead sharks remained relatively stable with the exception of a spike for these species during the early 1980s.

The cause for the increase in the blacknose shark bycatch estimates was not clear, and we argue that patterns presented in Figure 1 were erroneous. In essence, bycatch of a given species is estimated by multiplying shrimping effort and the bycatch catch rate of that species using data from observers on shrimp vessels and research vessel surveys (Nichols 2004). Penaeid shrimp trawling effort in the GOM increased markedly following passage of the Magnuson–Stevens Fisheries Conservation and Management Act in 1976, and remained uniformly high (~200,000 nominal days fished per year) through about 2002 (Gallaway et al. 2003). After 2002, GOM shrimp fishing effort declined dramatically, reaching 63,075 nominal days fished in 2008 (Nance, personal communication).

Overall, the observed penaeid shrimp fishing effort pattern exhibited little or no resemblance to the pattern of blacknose shark bycatch, especially when the respective time series was broken into pre- and post-1990 periods, which corresponded to the introduction of turtle excluder devices (TEDs; Figure 1). By 1990, TEDs (first required in 1987) were finally in widespread use throughout the offshore penaeid shrimp fishery of the southeastern USA and GOM (Crowder et al. 1995). A TED generally consists of a metal grid that is installed in the trawl to enable endangered sea turtles Chelonidae and Dermochelydae spp. to pass safely out of the net through a trap door without losing a large fraction of the shrimp catch. Because the spacing of the bars comprising the grid cannot exceed 100 mm, other animals wider than this spacing can also be excluded, including small coastal sharks. Prior to 1990, penaeid shrimp fishing effort exhibited an increasing trend while blacknose shark bycatch was low and stable. For the post-1990 period, shrimping effort trended downward while blacknose shark bycatch increased.

Bycatch catch rate estimates were modeled using research trawl survey data (Southeast Area Monitoring and Assessment Program [SEAMAP]) in conjunction with the shrimp trawl observer data (SEDAR13 2007). This was necessary because the historical observer programs have been relatively small, have not been conducted in many years, and in recent years were not required to identify sharks to the species level. For these reasons, there are large gaps in the observer data set (from 1983 to 1991 and from 1995 to 2008, albeit a few trawls were observed in 2001 and 2002 in one area; Table 1). In contrast, the research trawl surveys are more numerous, are conducted every year, and all species are identified. The observed relationship between observer and research trawl catch data for years in which both surveys were conducted were used to predict bycatch catch rates for all years and was particularly useful for years in which observer data were missing (Nichols 2007). In other words, an attempt was made to "rehabilitate" the spotty observer data by using the more-thorough research data.

Before 2009, most of the data available for defining this relationship were from the pre-TED years when neither the research survey nets nor the commercial shrimp trawls used TEDs. We believed that the use of TEDs had the potential to change the relationship between research and observer catch rates. If such changes occurred, they would impact the bycatch estimates for 1990 to present. However, any change to the research–observer relationship was not reflected in the bycatch estimates (at least before the 2009 data were used) because there was little observer data in the post-TED period to parameterize it. Even with the inclusion of the 2009 data, an explicit TED effect should be included in the model to more correctly estimate bycatch since 1990.

This paper provides the results of a cooperative research venture involving NMFS and industry scientists that was conducted to address the question of whether there were TED effects on small coastal shark catch rates in shrimp trawls. Our objective was to quantify the evidence for and magnitude of a TED effect on the bycatch of these species in the GOM. Surely the respective abundance levels for these three species were reflected in their bycatch rates, but we also suspected that morphological differences affected the efficiency with which TEDs excluded each species as well. Atlantic sharpnose sharks are smaller at birth and do not grow as large as blacknose sharks (Branstetter 1990), and bonnethead sharks possess a cephalofoil (though it is not as pronounced as for other species with this feature). We believed that results obtained for these species might provide insight into how differences in species morphology and growth may have influenced the TED effect.

## METHODS

*Data sources*.—Data for this analysis were collected by NMFS and came from (1) a fisheries-independent sampling program using standard 12.2-m (40-ft) commercial shrimp trawls (SEAMAP), henceforth referred to as "research data" (Nichols 2005a); and (2) several fishery-dependent observer programs, henceforth referred to as "observer data" (Scott-Denton 2005). The information associated with each trawl tow that was germane to this analysis included count of sharks caught (by species and total) and towing time. Each tow was categorized into temporal and spatial strata consistent with that used by Nichols

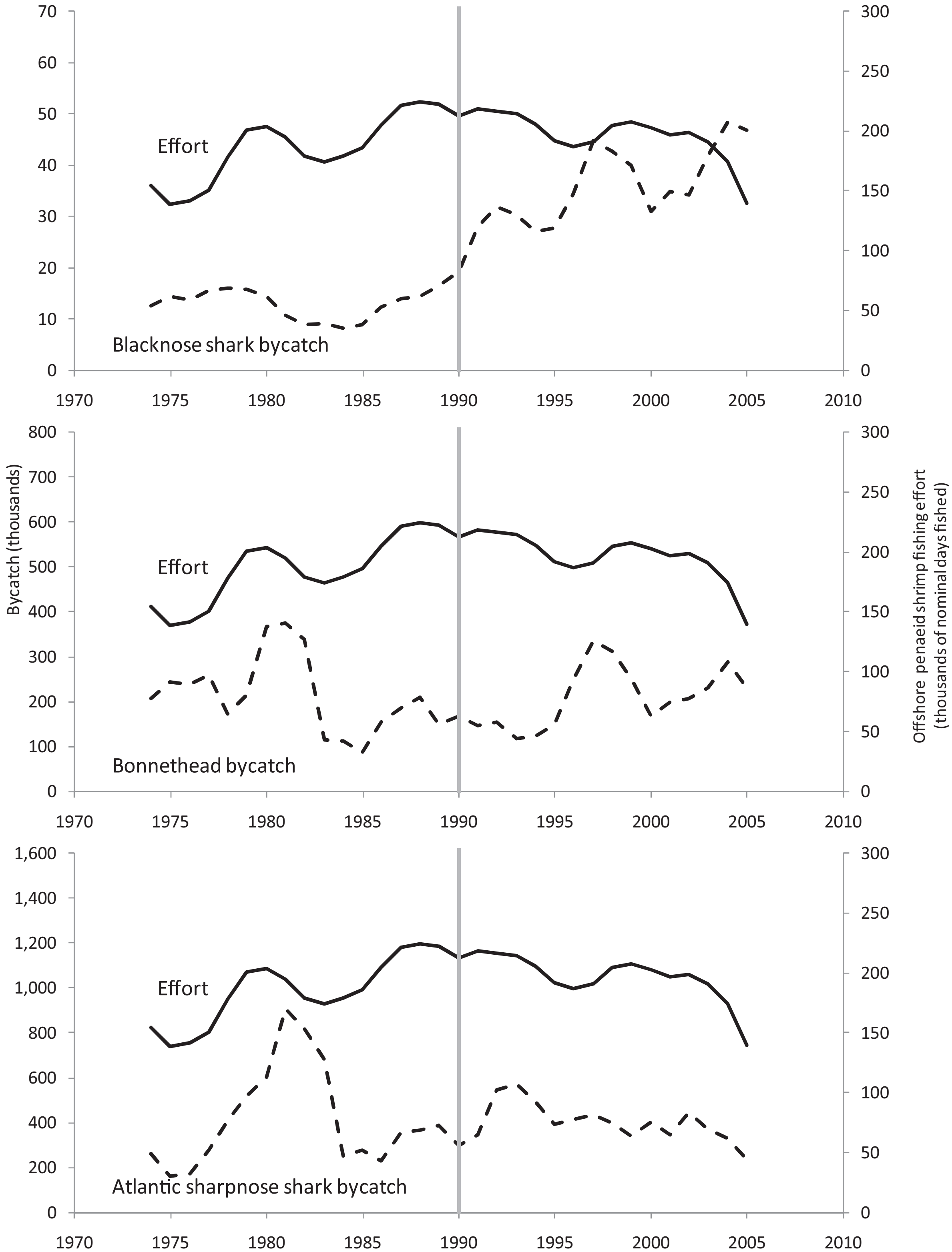


FIGURE 1. Estimates of blacknose shark bycatch (SEDAR13 2007) and GOM offshore penaeid shrimp fishing effort (J. Nance, National Marine Fisheries Service [NMFS], personal communication) from 1972 to 2005. Solid lines represent the trends for fishing effort, and dashed lines represent trends for bycatch (both lines were smoothed with a 3-year moving average). The vertical gray line separates before and after TEDs were in widespread use in the commercial fishery.

TABLE 1. Sum of effort (net hours) for combinations of factors for tows where sharks were identified to species. The factors depth zone (DZ) and trimester (tri) were not included to conserve space but were tested as independent variables. See Methods for factor definitions. Statistical area 1 begins in the Florida Keys, and statistical area 4 ends in south Texas.

| | Research data set Statistical area | | | | | Observer data set Statistical area | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Year | 1 | 2 | 3 | 4 | Research total | 1 | 2 | 3 | 4 | Observer total |
| **Before TEDs** | | | | | | | | | | |
| 1972 | | 58 | 67 | | 125 | | 2 | 4 | | 6 |
| 1973 | 9 | 87 | 101 | | 197 | | 4 | 77 | 64 | 145 |
| 1974 | | 146 | 241 | | 387 | 31 | 22 | 28 | 51 | 132 |
| 1975 | | 138 | 259 | | 397 | 34 | 593 | 280 | 4 | 910 |
| 1976 | | 92 | 185 | 3 | 279 | 27 | 18 | 227 | 1,223 | 1,494 |
| 1977 | | 53 | 124 | 52 | 229 | 264 | 143 | 257 | 1,024 | 1,688 |
| 1978 | 52 | 60 | 73 | | 185 | 566 | 169 | 157 | 849 | 1,741 |
| 1979 | | 54 | 71 | | 125 | | 1 | | | 1 |
| 1980 | 0 | 151 | 115 | 21 | 288 | 269 | 669 | 927 | 1,432 | 3,296 |
| 1981 | | 91 | 167 | 61 | 318 | 144 | 319 | 1,092 | 474 | 2,029 |
| 1982 | | 106 | 162 | 23 | 291 | 13 | 106 | 3 | 62 | 184 |
| 1983 | 5 | 104 | 99 | 16 | 225 | | | | | |
| 1984 | | 92 | 155 | 31 | 278 | | | | | |
| 1985 | | 51 | 73 | 38 | 162 | | | | | |
| 1986 | 9 | 24 | 49 | 42 | 124 | | | | | |
| 1987 | | 22 | 102 | 80 | 204 | | | | | |
| 1988 | | 22 | 95 | 106 | 224 | | | | | |
| 1989 | | 22 | 86 | 105 | 212 | | | | | |
| Total | 76 | 1,375 | 2,222 | 578 | 4,250 | 1,348 | 2,045 | 3,052 | 5,183 | 11,627 |
| **After TEDs** | | | | | | | | | | |
| 1990 | | 37 | 115 | 104 | 256 | | | | | |
| 1991 | | 33 | 131 | 121 | 284 | | | | | |
| 1992 | | 18 | 127 | 109 | 253 | | 102 | 1,297 | 1,127 | 2,525 |
| 1993 | | 36 | 126 | 120 | 281 | 593 | 160 | 1,532 | 1,107 | 3,391 |
| 1994 | | 35 | 127 | 111 | 274 | 1,059 | 48 | 118 | 225 | 1,450 |
| 1995 | | 18 | 123 | 118 | 258 | | | | | |
| 1996 | | 19 | 135 | 128 | 282 | | | | | |
| 1997 | | 14 | 135 | 126 | 275 | | | | | |
| 1998 | | 12 | 114 | 123 | 248 | | | | | |
| 1999 | | 27 | 132 | 124 | 282 | | | | | |
| 2000 | | 18 | 140 | 122 | 280 | | | | | |
| 2001 | | 29 | 74 | 103 | 206 | 41 | | | | 41 |
| 2002 | | 15 | 126 | 127 | 268 | 1,126 | 5 | | | 1,132 |
| 2003 | | 29 | 85 | 122 | 236 | | | | | |
| 2004 | | 6 | 128 | 123 | 256 | | | | | |
| 2005 | | 12 | 62 | 53 | 127 | | | | | |
| 2006 | | 9 | 96 | 127 | 232 | | | | | |
| 2007 | | 11 | 128 | 125 | 265 | | | | | |
| 2008 | | 32 | 160 | 134 | 327 | | | | | |
| 2009 | 3 | 35 | 136 | 146 | 320 | 3,961 | 1,223 | 6,481 | 10,149 | 21,814 |
| 2010 | | | | | | 199 | | 218 | 166 | 582 |
| After total | 3 | 445 | 2,400 | 2,364 | 5,212 | 6,980 | 1,538 | 9,645 | 12,774 | 30,936 |
| Overall total | 79 | 1,820 | 4,621 | 2,942 | 9,462 | 8,327 | 3,582 | 12,697 | 17,956 | 42,563 |

(2005b); namely, four areas (*A*; statistical reporting areas 1–9, 10–12, 13–17, and 18–21), two DZs (inside 10 fathoms, outside 10 fathoms), three tri periods (January–April, May–August, and September–December), and 39 years (1972–2010).

The sampling designs varied among and within the data sets. The SEAMAP trawl survey incorporated a random sampling design, sampling being stratified by depth (see Nichols 2005a for a detailed description of this sampling program). Prior to 1998, the penaeid shrimp fishery observers were not deployed on randomly selected vessels but were placed on vessels which had volunteered to participate in the program (Renaud et al. 1990; Renaud et al. 1991). Following 1998, a government mandate required that all vessels participate in the observer program and random vessel selection was possible (see Scott-Denton 2005, 2007). However, the number of vessels and trips sampled remained small.

*Statistical modeling of catch*.—As noted above, TEDs were not in widespread use by the offshore commercial penaeid shrimping fleet of the southeastern USA until about 1990, and they have never been used on SEAMAP research vessels. Thus, the observer data are conducive to a before-after-control-impact (BACI) design (Smith 2002) to test the effect of TEDs on shrimp trawl bycatch. The two main effects in the model were (1) research versus observer data, and (2) the before period (1972–1989) versus the after period (1990–2010) TEDs were required. Evidence for a TED effect would be present if there was an interaction of the two main effects (i.e., instances where the statistical evidence showed that the relationship between the research and observer data were different between the before- and after-TED periods).

The negative binomial is a discrete probability distribution that is recognized as a suitable descriptor of net catch count data (Power and Moser 1999). We portrayed the predicted catch rate through a global linear log link function to the negative binomial distribution, given as

$$\log_e(\lambda_i) = \mu + P + \text{DS} + A + \text{DZ} + \text{tri} + \text{year} + T + (P\cdot\text{DS}) + (P\cdot\text{DS}\cdot T), \quad (1)$$

where all factors are without the strata identifier subscripts and represent their respective levels for the *i*th sample, and where $\lambda_i$ is predicted catch rate for the *i*th sample tow; $\mu$ is overall mean; *P* is period before versus after TEDs (coded as 0 = before, 1 = after); DS is data set for research tows versus observer tows (0 = research, 1 = observer); *A* is 1, 2, 3, or 4 (see earlier description); DZ is 1 or 2 (see earlier description); tri is 1, 2, or 3; year is 1972–2010; *T* is time (decimal year); $P\cdot DS$ is the interaction of *P* and DS; and $P\cdot\text{DS}\cdot T$ is the interaction of *P*, DS, and *T*. All independent variables entered the model as categorical data with the exception of time as a continuous variable, which was formatted in decimal years (i.e., observed year plus the month divided by 12). The $P\cdot\text{DS}$ and $P\cdot\text{DS}\cdot T$ terms allow the intercept and slope (with respect to time) of the model, respectively, to differ across the four BACI cells, both of which allow for a TED effect.

All computations were conducted using the GENMOD procedure in SAS version 9.2 (SAS Institute 2008). The GENMOD procedure estimates the regression parameters to maximize the negative binomial log-likelihood, which is the sum of the log-likelihoods for each tow ($l_i$) ignoring constant terms, expressed as

$$l_i = r\log_e(r) - \log_e[\Gamma(r)] + \log_e[\Gamma(\tilde{C}_i + r)] + \log_e(\theta_i) - (r + \tilde{C}_i)\cdot\log_e(\tilde{C}_i + \theta_i), \quad (2)$$

where *r* is the negative binomial dispersal coefficient (an additional parameter that allows for inflated variance and requires estimation), $\log_e\Gamma(r)$ is the log-gamma function, $\tilde{C}_i$ is the observed catch of sharks in tow *i*, and $\theta_i$ equals $\lambda_i\tilde{w}_i$ ($\tilde{w}_i$ being the duration of tow *i*) and is the predicted catch in tow *i*. Note that the predicted catch rate ($\lambda_i$) comes from equation (1) and the tow duration defines the element size (also called weight or offset) of the negative binomial distribution.

In addition to the global model, all nested combinations of variables were compared using the information-theoretic approach as recommended by Burnham and Anderson (2002). Typically, the number of models (including the null model) given the number of predictor variables (*k*) is $2^k$. The nine terms (including the interactions $P\cdot\text{DS}$ and $P\cdot\text{DS}\cdot T$) in this study would equate to $2^9$ (or 512) possible models. However, models with categorical interaction terms yield the same predictions and model fit with and without main effects included. Including an interaction term without main effects is referred to as a "cell means model," where combinations of factors are treated as levels in a one-way treatment layout (SAS Institute 2008). In this study, fewer than 512 models were tested because no main effects were included in models with their interactions. Furthermore, the slope interaction term, $P\cdot\text{DS}\cdot T$, was never entered without the intercept interaction term, $P\cdot\text{DS}$, but the intercept interaction was tested without the slope interaction. Time was modeled as a categorical variable with year and as a continuous variable with *T*; as these two variables would be redundant in the same model, year was never included in a model with *T* (even when *T* was entered as an interaction). The resulting total number of models tested was 127.

Weights were assigned to each model based upon their Akaike information criterion (AIC) values. These AIC values were modified to QAIC (the Q stands for quasilikelihood) values by first dividing the log-likelihood for each model by the variance inflation factor from the global model as recommended by Burnham and Anderson (2002) to account for overdispersion. Of the suite of models investigated, Akaike weights sum to 1 and indicate how probable one model is compared with all others considered.

Model diagnostics were carried out according to the recommendations by Lin et al. (2002) for assessing model fit of generalized linear models, whereby the observed cumulative residuals across the range of the predicted responses is compared with randomized realizations. A poor fit is indicated by a low *P*-value (estimated from the Kolmogorov-type supremum test) and visual deviation of the observed fit from the randomized realizations. These plots and tests are now part of the routine output by the GENMOD procedure (SAS Institute 2008) and were performed on the best model for each species, as indicated by the lowest QAIC value.

*Quantifying effect size*.—The TED effect is changing through time as the research and observer data sets change, but we can calculate a single average effect for the defined before and after periods. We compared the change in the difference between data sets from the before period (1972–1989) to the after period (1990–2010) as follows:

$$TEDEffect = \frac{\left(\frac{RB}{RA} \times OA\right) - OB}{OB} \times 100, \qquad (3)$$

where RB is marginal mean catch per unit effort (CPUE) across the researcher data set before period, RA is researcher after, OA is observer after, and OB is observer before. This formulation compares data sets based on their respective proportional changes, not on their absolute changes. By using the marginal means from each period and data set, all other factors are held constant and differences among cells are strictly due to the TED effect. These means are standardized for effort in the model output and thus represent predicted CPUE. Furthermore, the output from all 127 Akaike-weighted models were averaged and used in the calculation of this effect.

*Modeling threshold girth for exclusion by turtle excluder devices*.—In the methods described earlier, we are testing the hypothesis (among others) that TEDs reduced the bycatch of sharks. The mechanism by which this occurs would be physical exclusion of sharks too large to pass through the spacing between TED bars. We used morphometric equations published in the literature to postulate the lengths and ages at which each study species might be excluded. The NMFS regulation allows for a maximum spacing of 100 mm between TED bars. The most common width between bars in GOM penaeid shrimp trawls is 95 mm (G. Graham, Texas A&M Sea Grant, personal communication) because most shrimpers prefer a spacing 5 mm narrower than required to hedge against a bar getting bent enough to cause noncompliance with the regulation.

Based on girth size as a percentage of fork length (FL; Carlson and Cortés 2003), total length (TL) to FL relationships (SEDAR13 2007), and the assumption that shark girth is more or less circular, we estimated body diameter for each species as a function of age and length. We recognize that our assumption of shark girth being circular is not strictly true. The idea is that the growth parameters developed for small coastal sharks may suggest at what age or length each species reaches the threshold body diameter enabling exclusion and indicate relative differences among species with respect to TED effectiveness at reducing their respective bycatch rates.

## RESULTS

Sharks were identified to species in 28,852 research trawl tows, representing 9,462 h of trawl time (Table 1). A total of 192 blacknose sharks were encountered in 131 of these tows, 805 bonnetheads were taken in 495 tows, and 4,022 Atlantic sharpnose sharks were represented in 1,867 tows. During the observer program, 6,825 tows accounted for 42,563 h of trawl time in studies where sharks were identified to species. A total of 146 blacknose sharks were encountered in 37 tows, 1,449 bonnetheads were taken in 146 tows, and 4,427 Atlantic sharpnose sharks were represented in 403 tows.

### Blacknose Sharks

The model diagnostics for blacknose sharks showed that the best negative binomial model fit the data well (Figure 2). Based upon visual inspection, the pattern in cumulative residuals was located at the center of the randomized realizations (indicating no abnormal deviations) and the *P*-value from the Kolmogorov-type supremum test was 0.58 (meaning 58% of the randomizations yielded higher absolute values than the observed pattern).

The dispersion parameter from the global model was estimated to be 1.27 (a value of 1.00 would indicate no overdispersion), which was used in the calculation of QAIC values for all of the 127 models tested. Given the negative binomial was a suitable model for the blacknose shark data, eight models accounted for 99% of the weight, the best approximating model receiving 31% of the total weight (Table 2). Important terms in this model included *A* (area), DZ (depth zone), and the two interactions terms ($P$·DS and $P$·DS·$T$). There was a greater than 99% chance that the interaction terms were important and therefore that the TED effect was present (Table 3). Area and DZ were marginally important, as chances of being a true effect were 83% and 68%, respectively. For all other variables there was a less than 50% chance that they were important, year receiving very little weight (<1%). Evidence for and against the main effects by themselves—*P*, DS, and *T*—could not be interpreted due to the overwhelming evidence for their interaction.

The model-averaged prediction of blacknose shark CPUE resulted in an exponential decay for both research and observer data before TEDs were implemented (Figure 3). Following TEDs, the research CPUE increased while the observer CPUE remained low. Given the proportional changes in each data set across the before and after periods, we estimated that TEDs reduced the catch rate of blacknose sharks by 94% in the observed tows.

### Bonnethead Sharks

Model diagnostics for bonnethead sharks also revealed that the best negative binomial model to fit the data well (Figure 2; *P*-value = 0.61). The dispersion parameter for the global model was estimated to be 1.14. Two models accounted for

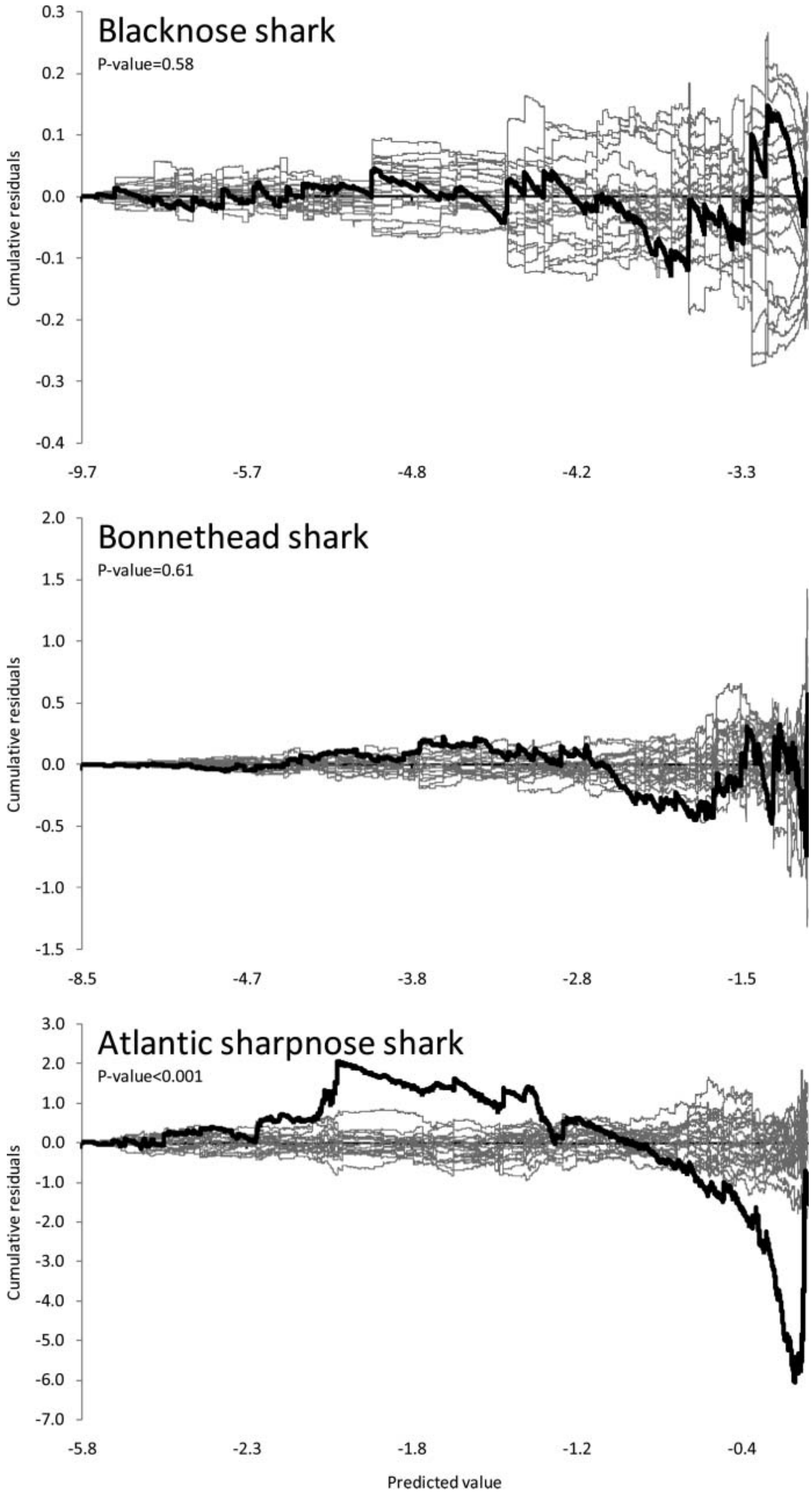


FIGURE 2. Cumulative residual plots using the best negative binomial regression model (i.e., lowest AIC; see Table 2) for each study species. The observed pattern is shown by the bold black line, and 20 simulated realizations are shown by the thinner gray lines. The *P*-value pertains to the suprenum test with 1,000 realizations (a poor fit is indicated by low values). (See Lin et al. 2002 for a thorough description of the diagnostic procedure.)

TABLE 2. Likelihood values and Akaike metrics for the negative binomial regression models that account for 99% of the weight (out of the 127 models). Abbreviations are as follows: $K$ = the number of model parameters, including the dispersion parameter; QAIC = the dispersion-corrected value of the Akaike information criterion (a lower value indicates a better fit); Delta = the QAIC value in question – the lowest QAIC value of all 127 models; $W_i$ = the Akaike weight, interpreted as the direct probability of that model being's true given the suite of models investigated. See Methods for factor definitions.

| Model term | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $P$·DS | $P$·DS·$T$ | $P$ | DS | $A$ | DZ | Tri | Year | $T$ | Log-likelihood | $K$ | QAIC | Delta | $W_i$ |
| | | | | | | | **Blacknose sharks** | | | | | | |
| X | X | | | X | X | | | | –951.5 | 13 | 1,524.8 | 0.00 | 0.31 |
| X | X | | | X | X | X | | | –949.1 | 15 | 1,525.0 | 0.20 | 0.28 |
| X | X | | | X | | | | | –953.7 | 12 | 1,526.2 | 1.36 | 0.16 |
| X | X | | | X | | X | | | –952.0 | 14 | 1,527.5 | 2.71 | 0.08 |
| X | X | | | | | | | | –958.7 | 9 | 1,528.1 | 3.33 | 0.06 |
| X | X | | | | X | | | | –957.6 | 10 | 1,528.3 | 3.51 | 0.05 |
| X | X | | | | X | X | | | –955.8 | 12 | 1,529.6 | 4.77 | 0.03 |
| X | X | | | | | X | | | –957.4 | 11 | 1,530.1 | 5.28 | 0.02 |
| | | | | | | | **Bonnethead sharks** | | | | | | |
| X | X | | | X | X | X | | | –705.2 | 15 | 1,272.2 | 0.00 | 0.87 |
| X | X | | | | X | X | | | –710.8 | 12 | 1,276.1 | 3.88 | 0.13 |

TABLE 3. Weight of evidence (Akaike weight, $W_i$) for negative binomial regression model terms given the suite of models investigated. $W_i$ was standardized for the number of models with each term versus the number of models without each term by using the mean $W_i$ to calculate the percent chance that each term was important. Evidence for and against the main effects ($P$, DS, and $T$) cannot be interpreted due to the overwhelming evidence for their interaction. See Methods for factor definitions.

| | $W_i$ of models | | Percent chance that term is | |
|---|---|---|---|---|
| Model term | With term | Without term | Important | Unimportant |
| | | **Blacknose sharks** | | |
| $P$·DS | 1.00 | 0.00 | 100 | 0 |
| $P$·DS·$T$ | 1.00 | 0.00 | 100 | 0 |
| $P$ | 0.00 | 1.00 | | |
| DS | 0.00 | 1.00 | | |
| $A$ | 0.84 | 0.16 | 83 | 17 |
| DZ | 0.68 | 0.32 | 68 | 32 |
| Tri | 0.42 | 0.59 | 41 | 59 |
| Year | 0.00 | 1.00 | 0 | 100 |
| $T$ | 0.00 | 1.00 | | |
| | | **Bonnethead sharks** | | |
| $P$·DS | 1.00 | 0.00 | 100 | 0 |
| $P$·DS·$T$ | 1.00 | 0.00 | 100 | 0 |
| $P$ | 0.00 | 1.00 | | |
| DS | 0.00 | 1.00 | | |
| $A$ | 0.88 | 0.13 | 87 | 13 |
| DZ | 1.00 | 0.00 | 100 | 0 |
| Tri | 1.00 | 0.00 | 100 | 0 |
| Year | 0.00 | 1.00 | 0 | 100 |
| $T$ | 0.00 | 1.00 | | |

99% of the weight for bonnethead sharks (Table 2). The best approximating model received 87% of the weight, and the most important terms included not only the two interaction terms, but also $A$, DZ, and tri. As with blacknose sharks, there was a high probability that the TED effect was real and in addition that DZ and tri were also important. Statistical area ($A$) was again marginally important (87%), and year received virtually no weight (Table 3). The research catch rates trended downward before TEDs and up afterwards, whereas observer data trended up before TEDs, dropped considerably immediately following TEDs, and then began a slow increase (Figure 3). We estimated TEDs to have reduced the catch rate of bonnetheads by 31% over the course of the study periods.

### Atlantic Sharpnose Sharks

The model diagnostics for Atlantic sharpnose sharks showed a very poor fit to the data (Figure 2). An aberrant pattern in cumulative residuals was obvious and $P$ was less than 0.0001, both indicative of model misspecification. This extremely poor fit could have resulted from using an incorrect link function (although no other link function exists for the negative binomial model) or an improper functional form of a covariate (Lin et al. 2002). In this instance, the only covariate was $T$ (time as a continuous variable), which was included in the interaction term $P$·DS·$T$. We ran the diagnostic routine for the model without this term (i.e., the third best model; Table 2) but achieved similar results ($P < 0.0001$). Inferences about model terms when the model is misspecified are invalid; consequently, we rejected the results obtained for Atlantic sharpnose sharks and cannot offer any evidence for or against TEDs affecting the bycatch of this species.

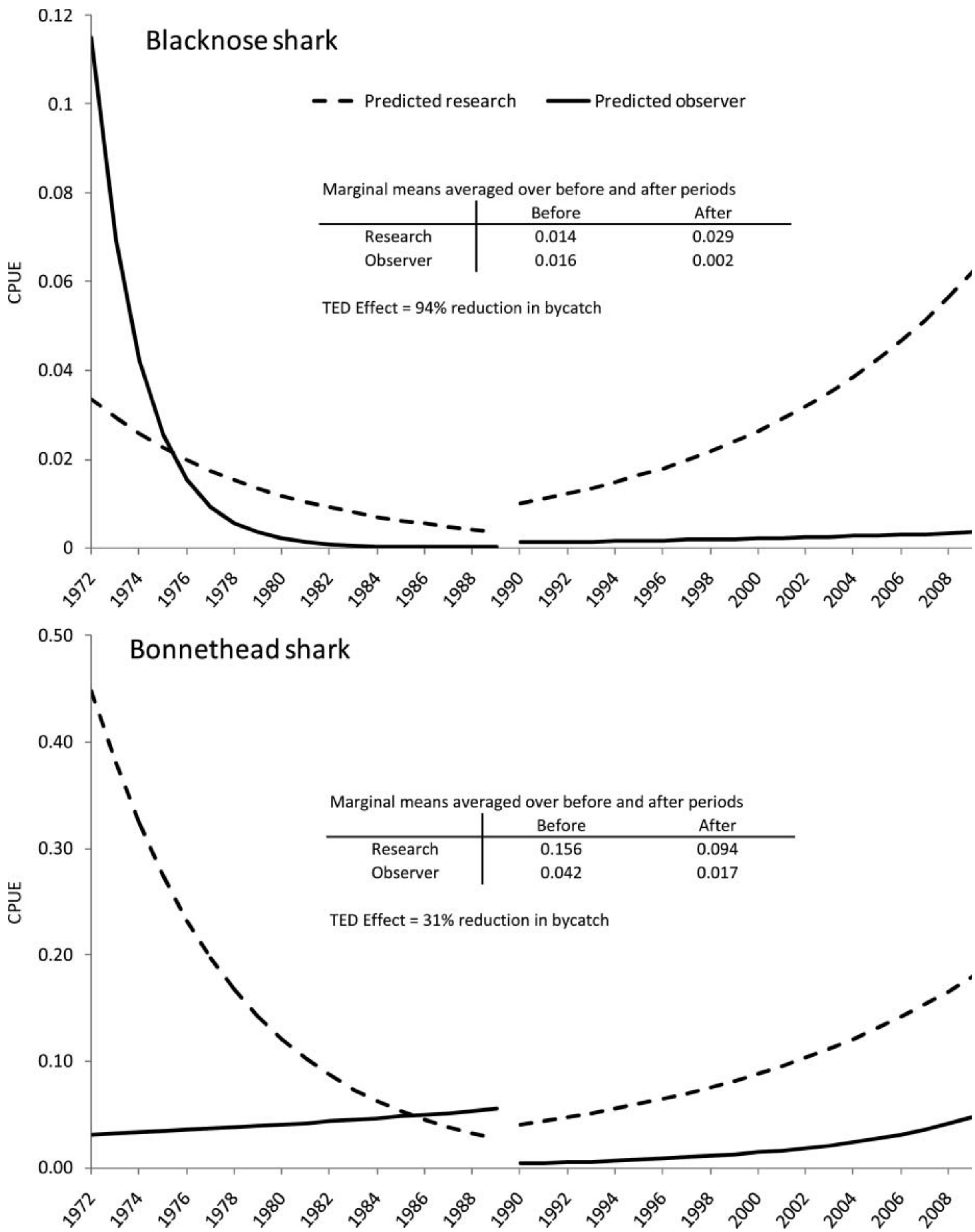


FIGURE 3. Predicted values of shark CPUE (catch/h/net) for research and observer trawl samples before and after TEDs were mandated on all commercial penaeid shrimping vessels. Lines represent the weighted predicted marginal means from all 127 negative binomial regression models, which were averaged based on their respective Akaike weights. All factors (DZ, *A*, and tri) were equally weighted. (See Methods for the formulation of the TED effect.)

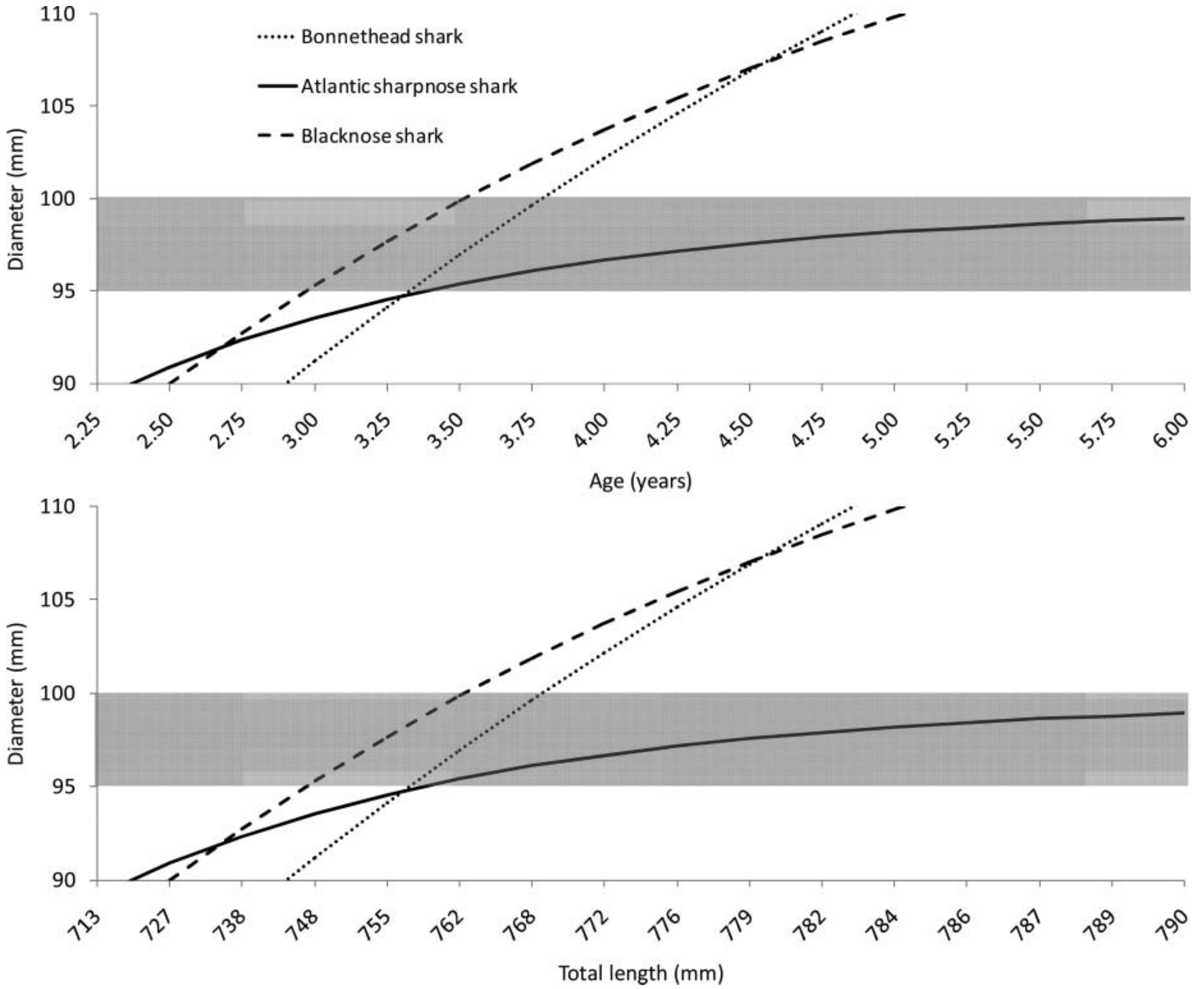


FIGURE 4. Diameter as a function of age and length for the three study species. Diameter, following Carlson and Cortés (2003), was calculated from girth (assumed to be a circle), which was estimated from FL estimated from TL. Diameter was regressed against age and length using equations published in the SEDAR13 (2007) literature. The space between bars in the GOM penaeid shrimp fishery is commonly about 95 mm; TED regulations require a maximum spacing of 100 mm (shaded areas reflect this range).



## Girth Modeling

We estimated that blacknose sharks reach a diameter of 95 mm at about age 3 when they are 785-mm TL; they reach 100 mm in diameter at age 3.5 and 821-mm TL (Figure 4). Bonnethead sharks reach 95 mm in diameter at age 3.3 and 730-mm TL, and 100 mm in diameter at age 3.8 and 768-mm TL. Atlantic sharpnose sharks reach 95 mm in diameter at age 3.4 and 759-mm TL but never reach 100 mm in diameter.

## DISCUSSION

Bycatch estimates of a variety of fishes in the penaeid shrimp trawl fishery have been calculated using the same Bayesian model since 2004 (Nichols 2007). It was first applied to the SCS in 2006 to provide bycatch estimates of age-0 and age-1 blacknose and bonnethead sharks. While the model allows for the inclusion of experimental data (paired tows, where one net is equipped with a bycatch reduction device (BRD) and one is not), the model does not explicitly account for a potential TED effect.

Larger specimens of shark species are subject to exclusion due to girth size relative to bar spacing, and this study provides evidence to support that fact. At birth, blacknose, bonnethead, and Atlantic sharpnose pups are about 380-, 350-, and 290-mm TL, respectively (SEDAR13 2007). Of the three small coastal species for which estimates were provided, the blacknose and bonnethead sharks are the largest, having $L_{\infty}$-values of 1,043-mm FL and 1,139 mm-TL, respectively (SEDAR13 2007). In comparison, the $TL_{\infty}$ for Atlantic sharpnose sharks is about 815 mm.

We found that TEDs reduced bycatch of blacknose and bonnethead sharks, but results were inconclusive for Atlantic sharpnose sharks. We expected that bonnethead sharks would be excluded at a greater rate than blacknose sharks due to their cephalofoil. Given comparable sizes among species, their wider heads should further restrict passage through the TED grid. However, their cephalofoils are not as pronounced (being not much wider than their bodies) as for other hammerhead species (family Sphyrnidae). Blacknose sharks reach a wider body diameter at an earlier age than bonnethead sharks, and our finding that TEDs resulted in a greater percent reduction in bycatch of blacknose sharks than for bonnetheads is consistent with these facts. Because most sizes of Atlantic sharpnose sharks would be physically capable of passing through the TED grid (Figure 4), we would not expect them to be as excluded by TEDs as the other two species; but again, due to poor model fits, we have no evidence for or against this expectation.

## Observed Exclusions

The initial studies of TED effects in the southeastern U.S. penaeid shrimp fishery focused on sea turtle exclusion, penaeid shrimp loss, total finfish reduction, or a combination thereof (Renaud et al. 1990; Renaud et al. 1991, 1993, 1997). Shark reduction per SE was not estimated but contributed to the overall finfish reduction. Total finfish reduction, however, was estimated to be low, ranging from about 5% to 13%. Most finfish in those studies were smaller or shaped very differently than young coastal sharks.

Empirical evidence for small shark exclusion in the U.S. penaeid shrimp fishery using TED grids with 95- to 100-mm bar spacing was available from Vendetti et al. (2009), who describe an analysis of a videotape compiled by the NOAA Highly Migratory Species Division. The footage was taken off the coast of Georgia from a research vessel (i.e., a converted shrimp trawler) pulling standard shrimp trawls equipped with TEDs having 100-mm or smaller bar spacing. This work was primarily conducted to test the TEDs for their ability to exclude sea turtles, therefore requiring an area with an abundance of sea turtles and clear water. The area sampled was certainly not representative of typical shrimping grounds, but the videotape nonetheless demonstrates the encounter of small sharks (average total length was estimated to be about 690 mm) with a standard TED grid. The species observed were mostly Atlantic sharpnose and bonnethead sharks. Overall, Vendetti et al. (2009) observed that there were 29 escapes within the 48 TED–shark encounters (i.e., about 60%). Qualitatively, their results support what we have determined quantitatively: TEDs tend to exclude sharks from shrimp trawl nets.

Brewer et al. (1998) reported results of commercial trials of three TED types used in Australia's Northern Prawn Fishery (families Penaeidae, Solenoceridae, Aristaeidae, Palaemonidae, and Pandalidae). All the TEDs utilized grates with 100-mm bar spacing. Turtle excluder devices reduced the catch of large sharks ($\geq$5 kg) by 63%. Brewer et al. (2006) observed the combination of TEDs and BRDs in this same fishery in 2001 reduced overall shark bycatch by about 18%, but for large sharks ($\geq$1 m long) the exclusion rate was 86%. The average bar spacing on these TED grids averaged 110 mm (95–120 mm). In the USA, TED bar spacing cannot exceed 100 mm. Smaller sharks may be excluded more effectively in the U.S. penaeid shrimp fishery than in the Australian prawn fishery due to the more closely spaced bars of the USA TED grid.

## Modeling Approach Considerations

In the 2007 stock assessment, the NMFS used a generalized linear model (more specifically, negative binomial regression) to estimate the bycatch of sharks in the penaeid shrimp fishery (SEDAR13 2007). We considered alternative models (including Poisson and logistic regression) but found that the negative binomial fit the data better than the Poisson and that the logistic model behaved poorly with respect to model diagnostics to where the results were unreliable (see diagnostics methods below). We also tried zero-inflated Poisson and zero-inflated negative binomial models (Minami et al. 2007; Arab et al. 2008), both of which failed to converge and provide parameter estimates using the GENMOD and COUNTREG procedures in SAS version 9.2 (SAS Institute 2008). This result makes sense when one considers that the zero-inflated models were designed for data generated from a combination of two processes: (1) a binary process separating zero from positive observations, and (2) the process controlling the magnitude of the positive observations. The zeroes in our data sets were likely due to the means (the parameter controlling the second process) just being very low. Because the samples occurred over an expansive geographic area, the data generated were likely from several Poisson distributions as densities varied. Data generated from such a compound Poisson process will typically be overdispersed and require a negative binomial to deal with the inflated variance.

The information-theoretic approach is more straightforward with respect to interpretation of results than classic hypothesis testing. The *P*-values rendered by the latter represent the percentage of times the data would be randomly selected given the null hypothesis is true (i.e., no difference among treatments). If this probability is larger than the a priori level of $\alpha$ (universally set to 0.05), then differences among treatments are deemed statistically insignificant. Further power analyses are required to move the interpretation beyond "failure to reject the null hypothesis" to the probability that the null would have been rejected had there been real differences of arbitrary levels. This approach is theoretically flawed, and many statisticians and quantitative biologists strongly oppose the use of post hoc power analyses (Goodman and Berlin 1994; Gerard et al. 1998; Anderson et al. 2001; Hoenig and Heisey 2001; Burnham and Anderson 2002). The information-theoretic approach directly estimates the probability of each hypothesis being true given the observed data and the suite of hypotheses being tested. Thus, the information-theoretic approach is more in keeping with the idea of multiple working hypotheses proffered by Chamberlin (1890) and Burnham and Anderson (2002).

Nonetheless, effect size remains quintessential, and differences among predicted responses were reported to facilitate interpretation of the results. We measured the effect size as percent change as opposed to absolute change in CPUE. This approach was selected because the research and observer CPUEs are inherently different with respect to magnitude; thus, we were interested in the relative change in each.

One may wonder why we did not measure the magnitude of bycatch reduction due to TEDs by comparing the predicted outputs from two models—one with a TED effect and one without. With respect to management concerns, it would be more appropriate to quantify differences in this way. Doing so would, of course, yield a difference in catch rates, but this difference would be due to a combination of the actual TED effect and the misspecification of the model without the TED term. The goal of this paper was to identify changes in the catch rate of blacknose sharks that were solely attributable to TEDs. Thus, we used the correctly specified models to estimate the magnitude of bycatch reduction as per equation (3). Having shown that TEDs impact the bycatch catch rates, the next logical step is to explicitly include a TED effect in the bycatch estimation model used by the NMFS.

The issue of autocorrelation was not addressed in our analysis of the time series of catch rate data because of the discreteness of the data. With these types of data sets, the researcher must choose between modeling the discrete nature of the data (as we did with negative binomial regression) versus assuming the data were continuous to add an autoregressive process (Heinen 2003). Time series modeling of discrete data are an area of current statistical research (e.g., Heinen 2003; Jung et al. 2006). Nevertheless, because autocorrelation causes bias in estimated confidence intervals around parameters and not the parameter estimates themselves, we argue that our conclusions based upon the current analysis were robust to ignoring autocorrelation as the level of observed effects was relatively large.

## MANAGEMENT IMPLICATIONS

The estimates presented in Figure 1 should be revised based on the more correctly specified model presented in the current study. The results of our analyses suggest that TEDs have reduced the catch rates of blacknose and bonnethead sharks in the southeastern U.S. penaeid shrimp fishery. Also, the negative binomial regression model applied to the SEAMAP research trawl survey data suggested the abundance of age-0 and age-1 blacknose and bonnethead sharks has followed an increasing trend since 1990. Prior to 1990, decreasing trends were observed for blacknose and bonnethead sharks.

It is unclear how our results will affect the stock status of these species. With the majority of blacknose shark catches coming from bycatch, one might anticipate that the effect may be large. This may or may not be the case because eight other stock abundance indices were used in the existing assessment. The status of the blacknose and bonnethead shark stocks will be assessed again in 2011; the new assessment model should incorporate the potential for TED effects as well as all other known effects on the population.

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