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

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Abstract. The blacknose shark stock in the U.S. south Atlantic and the Gulf of Mexico is overfished and overfishing is occurring according to the most recent stock assessment conducted by the National Marine Fisheries Service. Of the blacknose sharks estimated to be taken annually by the combined fisheries, about half were taken as penaeid shrimp fishery bycatch, predominantly in the Gulf. Shrimp trawl bycatch catch rates are modeled using a combination of research trawl data and observer data. Research trawls have never used Turtle Excluder Devices (TEDs) and most of the observer data that contain blacknose occurrences was collected during the pre-TED era. TED implementation was expected to exclude larger specimens of blacknose sharks, thereby reducing bycatch. The current modeling framework, which does not explicitly account for the effect of TEDs, predicted an increase of blacknose shark bycatch in the Gulf after 1990, a period when shrimp trawl effort was decreasing and TEDs had begun to be used. These inconsistent results led to the question, is there a TED effect? We used a negative binomial regression in a before-after-control-impact (BACI) setting to test the effects of TEDs on blacknose shark bycatch rates. The TED effect was found to reduce catch rates substantially. The management implication of our findings is that the existing blacknose shark penaeid shrimp fishery bycatch model needs to be modified or replaced with a model that explicitly incorporates the potential for a TED effect.

Introduction

The blacknose shark *Carcharhinus acronotus* stock off the southeastern United States and the Gulf of Mexico (Gulf) has been determined to be overfished with overfishing occurring (SEDAR13 2007). On average, 86,381 individual blacknose sharks were estimated to have been killed each year between 1999 and 2005, 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 of blacknose shark occurs in the Gulf shrimp fishery rather than the U.S. south Atlantic fishery (4,866).

The historical estimates of blacknose shark bycatch in the Gulf by year, beginning in 1950, suggested fairly stable bycatch levels (mostly between 10,000 and 20,000 individuals) from 1950 to 1988, followed by a pronounced increase in the late 1980's and early 1990's (Figure 1). From that time forward to the most recent years, the estimates have been high as compared to the early years, ranging up to 65,546 blacknose sharks in 2004.

The cause for the increase in the bycatch estimate was not clear. In essence, bycatch of a given species is estimated by multiplying shrimping effort and the bycatch catch rate of that species as determined by observers on shrimp vessels and research vessel surveys (Nichols 2004). Penaeid shrimp trawling effort in the Gulf 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, Gulf shrimp fishing effort declined dramatically, reaching 80,733 nominal days fished in 2007 (pers. comm., Jim Nance, National Marine Fisheries Service [NMFS], Galveston Laboratory).

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 are broken into pre- and post-1990 periods (Figure 1). 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.

By 1990, Turtle Excluder Devices (TEDs), first required in 1987, were finally in widespread use throughout the offshore penaeid shrimp fishery of the southeastern U.S. and Gulf of Mexico (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) 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 10 cm, other animals wider than this spacing can also be potentially excluded, including species like blacknose shark.

Research trawl survey data were used in conjunction with the shrimp trawl observer catch rates to estimate the bycatch catch rate. This was necessary because the historical observer programs have been relatively small, have not been conducted in many years, and, in most recent years, the observers have not been required to identify sharks to the species level. In contrast, the research trawl surveys are relatively large, 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 estimate bycatch catch rates for all years and was particularly useful for years in which observer data were missing (Nichols 2007). For blacknose sharks, 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.

Following the introduction of TEDs, we observed that the research trawl survey catch rates of blacknose shark increased. For example, the average research trawl survey catch rate for the 1985-1989 5-yr period immediately prior to TED use was 0.005 blacknose sharks per h fished. The corresponding post-TED average catch rates for 1990-1994, 1995-1999, and 2000-2006 were 0.012, 0.0-0.017, and 0.020 blacknose sharks per h fished, respectively. Observer catch rates would not be expected to increase much if TEDs effectively excluded blacknose sharks.

Unfortunately, there were only five years from the post-TED era in which observer programs were conducted that identified sharks to species (1992-1994, 2001-2002). Due to the absence of species-specific observer data and an absence of a TED effect term in the bycatch model, the recent increase in bycatch levels beginning in 1990 may have been due to the direct relationship between the research survey and observer catch rates observed pre-TED. We believed that this relationship had likely changed following the introduction of TEDs in the Gulf penaeid shrimp fishery.

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 bycatch of blacknose shark in the Gulf. Since the same bycatch model was also applied to the two other species of the small coastal shark complex, we also analyzed the data for Atlantic sharpnose *Rhizoprionodon terraenovae* and bonnethead shark *Sphyrna tiburo* as well. These species are more frequently encountered by shrimp trawls than blacknose sharks.

Because Atlantic sharpnose sharks are smaller at birth and do not grow as large as blacknose sharks (Branstetter 1990), and bonnethead sharks possess a cephalofoil, these species provided insight into how differences in species morphology and growth may have influenced the TED effect.

Lastly, many tow records were precluded from the analyses because sharks were not identified to species in most of the modern observer studies. In these studies, all sharks taken were counted and recorded in a "total shark" category. We created a "total shark" database using these data and the total shark count data from studies which had identified sharks to species. This provided a large sample size for evaluating the overall effects of TEDs on total shark catch.

Methods

Data Sources

Data for this analysis were collected by NMFS and came from (1) a fisheries independent sampling program using standard 40-ft commercial shrimp trawls (Southeast Area Monitoring and Assessment Program [SEAMAP]), henceforth referred to as "research data" (Nichols 2005a) and (2) several fishery dependent observer programs—"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 to that used by Nichols (2005b); namely, four areas (statistical reporting areas 1-9, 10-12, 13-17, 18-21) two depth zones (inside 10 fathoms, outside 10 fathoms), three trimesters (Jan-Apr, May-Aug, Sep-Dec), and 35 years (1972 – 2006).

As described previously, all records do not list bycatch at the species level. There are many more records listed as "sharks" than those listed to species. While we used these data to examine TED effects on total shark catch, there is no reliable way to parse these records into species using catch proportions from observer data.

The SEAMAP trawl survey incorporated a random sampling design with the sampling 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, 2008). However, sample size remained small.

Statistical Modeling

As noted above, TEDs were not in widespread use by the offshore commercial penaeid shrimping fleet of the southeastern U.S. 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 period before (1972-1989) versus the period after (1990-present) TEDs were required. Evidence for a TED effect is present when there is an interaction of the two main effects; i.e., instances where the statistical evidence showed that the relationship between the research and observer data was different between the before-and after-TED periods.

The negative binomial is a discreet 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, i.e.,

$$\log_e(\lambda_i) = \mu + P + DS + A + DZ + Tri + Yr + T + P \cdot DS + P \cdot DS \cdot T \,, \qquad (1)$$

where all factors are without the strata identifier subscripts and represent their respective levels for the i^{th} sample, and where,

λ_i = Predicted catch rate for the i'th sample tow.

μ = Overall mean.

P = Period before versus after TEDs (coded as 0 = before, 1 = after).
DS = Dataset for research tows versus observer tows (0 = research, 1 = observer).
A = Area (1, 2, 3, or 4, see description above).
DZ = Depth zone (1 or 2, see description above).
Tri = Trimester (1, 2, or 3).
Yr = Year (1972-2006).
T = Time (decimal year).
$P{\cdot}DS$ = interaction of P and DS.
$P{\cdot}DS{\cdot}T$ = interaction of P, DS, and T.

All variables entered the model as categorical with the exception of the overall mean, μ, and time as a regression variable, which was formatted in decimal years. The $P{\cdot}DS$ and $P{\cdot}DS{\cdot}T$ terms allow the intercept and slope 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 9.1.3 Software (SAS Institute Inc. 2003). 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, i.e.,

$$l_i = r\log_e(r) - \log_e\{\Gamma(r)\} + \log_e\left\{\Gamma(\tilde{C}_i + r)\right\} + \tilde{C}_i \log_e(\theta_i) - (r + \tilde{C}_i)\cdot\log_e\left\{\tilde{C}_i + \theta_i\right\} \qquad (2)$$

where

$$\theta_i = \lambda_i \tilde{w}_i,$$

and where $\log_e \Gamma(z)$ is the log-gamma function, $\tilde{C}_i$ is the observed catch of sharks in tow i, r is the negative binomial dispersal coefficient (an additional parameter that requires estimation), θ_i is the predicted catch in tow i and $\tilde{w}_i$ is the duration of tow i. Note that the predicted catch rate (λ_i) comes from equation (1) and the tow duration defines the element size (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). Because no observations occurred for some combinations of categorical variables, thus producing an incomplete factorial, main effects were not included by themselves when they entered the model as an interaction. This was because there were too few remaining degrees of freedom to test main effects in addition to the interaction. Additionally the null model was not tested, thus, the number of models totaled 127 instead of 512 for the nine terms tested.

Weights were assigned to each model based upon their Akaike Information Criterion (AIC) values. AIC values were modified to QAIC 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 one and indicate how probable one model is compared to all others considered.

Results

Sharks were identified to species in 27,096 research trawl tows representing 8,550 h of towing time. A total of 134 blacknose sharks were encountered in 97 of these tows, 673 bonnethead sharks were taken in 410 tows, and 3,707 Atlantic sharpnose sharks were represented in 1,731 tows. During the observer program 3,452 tows accounted for 20,625 h of towing time in studies where sharks were identified to species. A total of 85 blacknose sharks were encountered in 23 tows, 809 bonnethead sharks were taken in 60 tows, and 1,092 Atlantic sharpnose sharks were represented in 110 tows. For all sharks combined, there were 30,492 research trawl tows representing 9,870 h of towing time. A total of 5,304 sharks were encountered in 2,419 of the research trawl tows. Combining all sharks increased the observer program sample size to 12,574 tows representing 65,247 h of towing. A total of 13,371 sharks were encountered in 1,966 of the 12,574 total observer program tows.

For blacknose shark, 13 models accounted for 99% of the weight with the best approximating model receiving 44% of the total weight (Table1). Important terms in this model included the two interactions terms, *P·DS* and *P·DS·T*, and *A* (area). There was a greater than 99% chance that the interaction terms were important, and therefore that the TED effect was present (Table 2). *Area* was marginally important with an 88% chance of being a true effect. For all other variables there was less than a 50% chance that they were important with *yr* (year) receiving very little weight (<1%). The model-averaged prediction of blacknose shark CPUE resulted in an exponential decay for both research and observer data before TEDs were implemented (Figure 2, top panel). Following TEDs, the research CPUE increased, while the observer CPUE remained low.

Two models accounted for 99% of the weight for Bonnethead shark (Table 1). The best approximating model received 61% of the weight and the most important terms included not only the two interaction terms, but also *A*, *DZ* (depth zone), and *Tri* (trimester). As with blacknose shark, there was a high probability that the TED effect was real, and in addition that *DZ* and *Tri* were also important. *A* was again marginally important, 61%, and *yr* received little weight (Table 2). 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 2, bottom panel).

Thirteen models accounted for 99% of the weight for Atlantic sharpnose shark with the best approximating model receiving only 16% of the weight (Table 1). This model did not include either interaction as an important terms. There was only a 64% and 47% chance, respectively, that the *P·DS* and *P·DS·T* terms were real (Table 2). With the exception of *yr*, all other variables were at least marginally important. *A* and *DZ* were very important. Both intercepts (research and observer) dropped in the after-TED period, but the relationship between the slopes in the after-TED period was not substantially different from the relationship observed in the pre-TED period (Figure 2, top panel).

Only one model received weight when all sharks were combined and counted (Table 1). Both interaction terms were included in this model and were highly important along with *A*, *DZ* and *Tri* (Table 2). Trends for all sharks combined were similar to bonnethead shark, differing only in the magnitude of slopes. The research catch rates trended downward before TEDS and slowly increased thereafter. Observer catch rates increased exponentially before TEDS but then dropped to very low levels immediately following TED use. However, since that time catch rates of sharks, overall, are indicated to be slowly increasing (Figure 3, bottom panel).

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 2004). It was first applied to the small coastal shark complex in 2006 to provide bycatch estimates of age zeros and ones of blacknose and bonnethead shark. 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—but 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 solid evidence to 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_∞ values of 1,043 mm FL and 1,139 mm TL, respectively (SEDAR13 2007). In comparison, the FL_∞ for Atlantic sharpnose shark, as reported in SEDAR13 (2007), is about 802 mm. Maximum allowable spacing between TED bars in the Gulf penaeid shrimp fishery is 100 mm, as noted above. Based on girth size as a percentage of FL (Carlson and Cortez 2003), 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 time and length (Figure 4). Blacknose sharks reach a diameter of 95 mm at 3.0 yr of age when they are about 748 mm-TL (Figure 4). The most common width of the space between TED bars in Gulf penaeid shrimp trawls is 95 mm (Gary Graham, pers. comm., Texas A&M Sea Grant, College Station, Texas). Both bonnethead and Atlantic sharpnose reach 95-mm diameter at about 3.3 yr of age and 760 mm TL. We recognize that our assumption that shark girth is circular is not strictly true. The idea is that if the threshold body diameter for exclusion is ≥95 mm, the growth parameters developed for small coastal sharks suggest that a greater proportion of blacknose sharks would be excluded by TEDs than Atlantic sharpnose and bonnethead sharks.

Our results reflect solid evidence that TEDs reduced bycatch catch rates for blacknose shark and bonnethead shark, but TEDs did not appear to have much, if any, effect on the catch rates of Atlantic sharpnose sharks. Since virtually all sizes of Atlantic sharpnose sharks would be physically capable of passing through the TED bars, our results make common sense.

Observed Exclusions

The initial studies of TED effects in the southeastern U.S. penaeid shrimp fishery focused on sea turtle exclusion, penaeid shrimp loss and/or total finfish reduction (Renaud et al. 1990, Renaud et al. 1991, Renaud et al. 1993, Renaud et al. 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 from the small coastal sharks.

Empirical evidence for small shark exclusion in the U.S. penaeid shrimp fishery using TED grids with 9.5- to 10-cm bar spacing is available from the Vendetti et al. (2009) analysis of a videotape compiled by the NOAA Highly Migratory Species Division. The footage was shot off the coast of Georgia from a research vessel (a converted shrimp trawler) pulling standard shrimp trawls equipped with TEDs having ≤ 10-cm bar spacing. This work was primarily conducted to test the TEDs for their ability to exclude wild sea turtles, therefore requiring an area with an abundance of sea turtles and clear water. The area sampled was certainly not representative of the typical shrimp 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 having≤100-mm bar spacing. The species observed were mostly Atlantic sharpnose and bonnethead sharks. Overall, Vendetti et al. (2009) observed that there were 29 escapes (60%) within the 48 TED/shark encounters. Qualitatively, their results support what we have determined quantitatively: TEDs tend to exclude larger 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. All the TEDs utilized grates with 10-cm bar spacing. TEDs reduced the catch of large sharks (≥5 kg) by 62.5%. Brewer et al. (2006) observed the combination of TEDs and BRDs in this same fishery in 2001 reduced overall shark bycatch by about 17.7%; but for large sharks (≥1m long), the exclusion rate was 86%. The average bar spacing on these TED grids averaged 11.0 cm (9.5 to 12 cm). In the U.S., TED bar spacing cannot exceed 10 cm. 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 U.S. TED grid.

Modeling Approach Considerations

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 α (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. A statistically insignificant result coupled with high power is usually interpreted (incorrectly) as evidence for the null hypothesis. Our failure to detect a substantial TED effect for Atlantic sharpnose shark might suggest to some that a power analysis needs to be conducted. 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, Hoenig and Heisey 2001, Anderson et al. 2001, Burnham and Anderson 2002). Observed power, an *ad hoc* metric commonly used in the literature, will always diminish with increasing p-values, which is counterintuitive as larger p-values generally mean less evidence for the alternative hypothesis in favor of the null hypothesis (Hoenig and Heisey 2001).

Further, the information-theoretic approach directly estimates the probability of each hypothesis being true given the observed data and the suite of hypotheses being tested. The need for additional power analyses is obviated because hypotheses are directly compared and the probability of the null hypothesis being true is given explicitly. Thus, the information-theoretic approach is more in keeping with the idea of multiple working hypotheses proffered by Chamberlin (1965) (Anderson and Burnham 2002). Nonetheless, effect size remains quintessential and differences among predicted responses were reported to facilitate interpretation of the results.

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 datasets, 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 is an area of current statistical research (e.g., Heinen 2003, Jung et al. 2006). Nevertheless, we argue our conclusions based upon the current analysis are robust to ignoring autocorrelation as our sample size was large and the level of observed effects was relatively large. Also, our results are only a precursor to further modeling studies in this area. Having shown that TEDs impact the bycatch catch rates, our next step is to explicitly include a TED effect in the bycatch estimation model.

Management Implications

The results of our analyses suggest that TEDs have had an effect on blacknose and other small coastal shark catch rates in the southeastern U.S. penaeid shrimp fishery. However, the magnitude of the effect on bycatch has yet to be determined. Also, the negative binomial regression model applied to the SEAMAP research trawl survey data suggested the abundance of blacknose and bonnethead shark age zeros and ones has followed an increasing trend since 1990, while abundance of Atlantic sharpnose shark is relatively stable or slightly decreasing. Prior to 1990, trends of pronounced decrease were observed for blacknose and bonnethead sharks, while Atlantic sharpnose shark abundance was only moderately decreasing.

Thus, it is unclear how our results will affect blacknose shark stock status. With the majority of blacknose shark catches coming from bycatch, some anticipate that the effect may be large. This may or may not be the case because the magnitude of the TED effect has yet to be determined and eight other stock abundance indices were used in the existing assessment. The status of the blacknose shark stock will be assessed again in 2010 and it is important that the new assessment model incorporates the potential for TED effects as well as all other known effects on the population.

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Figure Legends

Figure 1. Estimates of blacknose shark bycatch (SEDAR13 2007) and Gulf of Mexico offshore penaeid shrimp fishing effort (James Nance, NMFS, pers. comm., Galveston Laboratory). Dashed lines represent the simple linear trends for fishing effort before and after TEDS were mandated. Solid lines represent trends for bycatch.

Figure 2. Observed and predicted values of blacknose shark (upper panel) and bonnethead shark (lower panel) catch per unit effort (catch/hr/net) for research and observer trawl samples. Lines represent the weighted predicted responses from all 127 models, which were averaged based on their respective Akaike weights. Observed values (circles and triangles) were averaged by dataset, year, area, trimester, and depth zone. Some observed values were omitted from the plot area to facilitate interpretation of the predicted responses (inclusion of these values lowered the height of the predicted lines to where they were unreadable).

Figure 3. Observed and predicted values of Atlantic sharpnose shark (upper panel) and all sharks (lower panel) combined catch per unit effort (catch/hr/net) for research and observer trawl samples. Lines represent the weighted predicted responses from all 127 models, which were averaged based on their respective Akaike weights. Observed values (circles and triangles) were averaged by dataset, year, area, trimester, and depth zone. Some observed values were omitted from the plot area to facilitate interpretation of the predicted responses (inclusion of these values lowered the height of the predicted lines to where they were unreadable).

Figure 4. Diameter as a function of age and length for the three study species. Diameter, following Carlson and Cortez (2003), was calculated from girth (assumed to be a circle), which was estimated from fork length estimated from total length. Diameter was regressed against time and length using equations published in the SEDAR13 (2007) literature. The space between bars in the Gulf penaeid shrimp fishery is commonly about 95 mm; TED regulations require a maximum spacing of 100 mm.

Table 1. Likelihood values and Akaike metrics for the models that account for 99% of the weight (out of the total 127 models). K=number of model parameters including the dispersion parameter, QAIC=dispersion corrected AIC value (a lower value indicates a better fit), Delta=QAIC-lowest QAIC of all 127 models, W_i=Akaike weight, interpreted as the direct probability of that model being true given the suite of models investigated. See Methods for term definitions.

Model term									Log				
P·DS	*P·DS·T*	*P*	*DS*	*A*	*DZ*	*Tri*	*Yr*	*T*	likelihood	K	QAIC	Delta	W_i
Blacknose shark													
X	X			X					-696.7	12	1273.3	0.00	0.44
X	X			X	X				-696.5	13	1275.1	1.77	0.18
X	X			X		X			-695.6	14	1275.5	2.16	0.15
X	X			X	X	X			-695.4	15	1277.1	3.76	0.07
X	X								-702.4	9	1277.6	4.29	0.05
X	X					X			-700.7	11	1278.6	5.31	0.03
X	X				X				-702.4	10	1279.6	6.29	0.02
X				X				X	-703.6	9	1279.8	6.49	0.02
X	X				X	X			-700.7	12	1280.6	7.29	0.01
X				X					-705.7	8	1281.5	8.17	0.01
X				X		X		X	-702.4	11	1281.7	8.33	0.01
X				X	X			X	-703.6	10	1281.8	8.44	0.01
Bonnethead shark													
X	X			X	X	X			-578.4	15	1023.1	0.00	0.61
X	X				X	X			-582.40	12	1023.9	0.86	0.39
Atlantic sharpnose shark													
		X	X	X	X	X		X	-4383.3	11	5289.3	0.00	0.16
		X	X	X	X	X			-4385.2	10	5289.6	0.31	0.14
			X	X	X	X		X	-4385.3	10	5289.6	0.34	0.14
X				X	X	X		X	-4382.2	12	5289.9	0.65	0.12
X				X	X	X			-4383.9	11	5290.0	0.68	0.12
		X	X	X	X			X	-4388.3	9	5291.2	1.92	0.06
		X	X	X	X				-4390.0	8	5291.3	2.04	0.06
			X	X	X			X	-4390.3	8	5291.6	2.36	0.05
X	X			X	X	X			-4378.9	15	5292.0	2.68	0.04
X				X	X				-4389.0	9	5292.0	2.77	0.04
X				X	X			X	-4387.4	10	5292.2	2.88	0.04
X	X			X	X				-4384.3	13	5294.4	5.13	0.01
			X	X	X	X	X		-4335.3	43	5295.5	6.24	0.01

Table 1 (continued

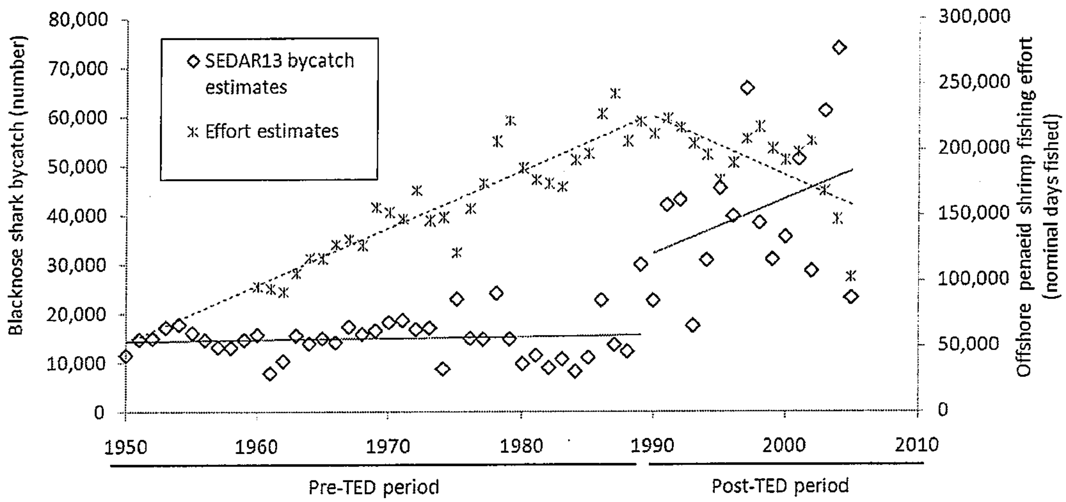
All shark species combined											
X	X		X	X	X		5667.6	15	-6321.57	0.00	1.00
		X	X	X	X	X	5699.6	45	-6297.43	24.14	0.00

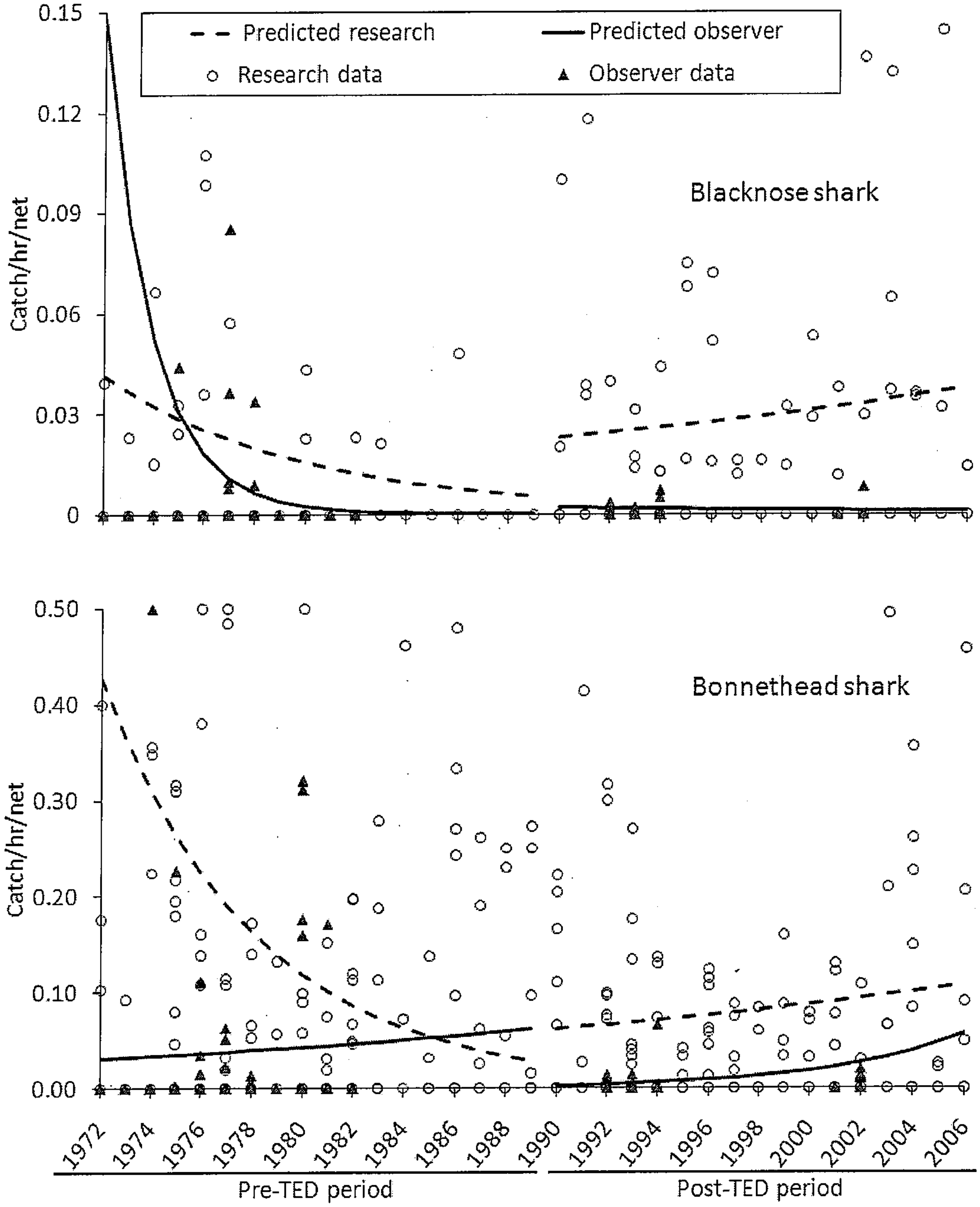
Table 2. Weight of evidence (Akaike weight, W_i) for model terms given the suite of models investigated. W_i was standardized for the number of models with each term versus the number of models without each term by using the Mean W_i to calculate the percent chance that each term was important. All sharks species combined includes species other than those listed in the table. See Methods for term definitions.

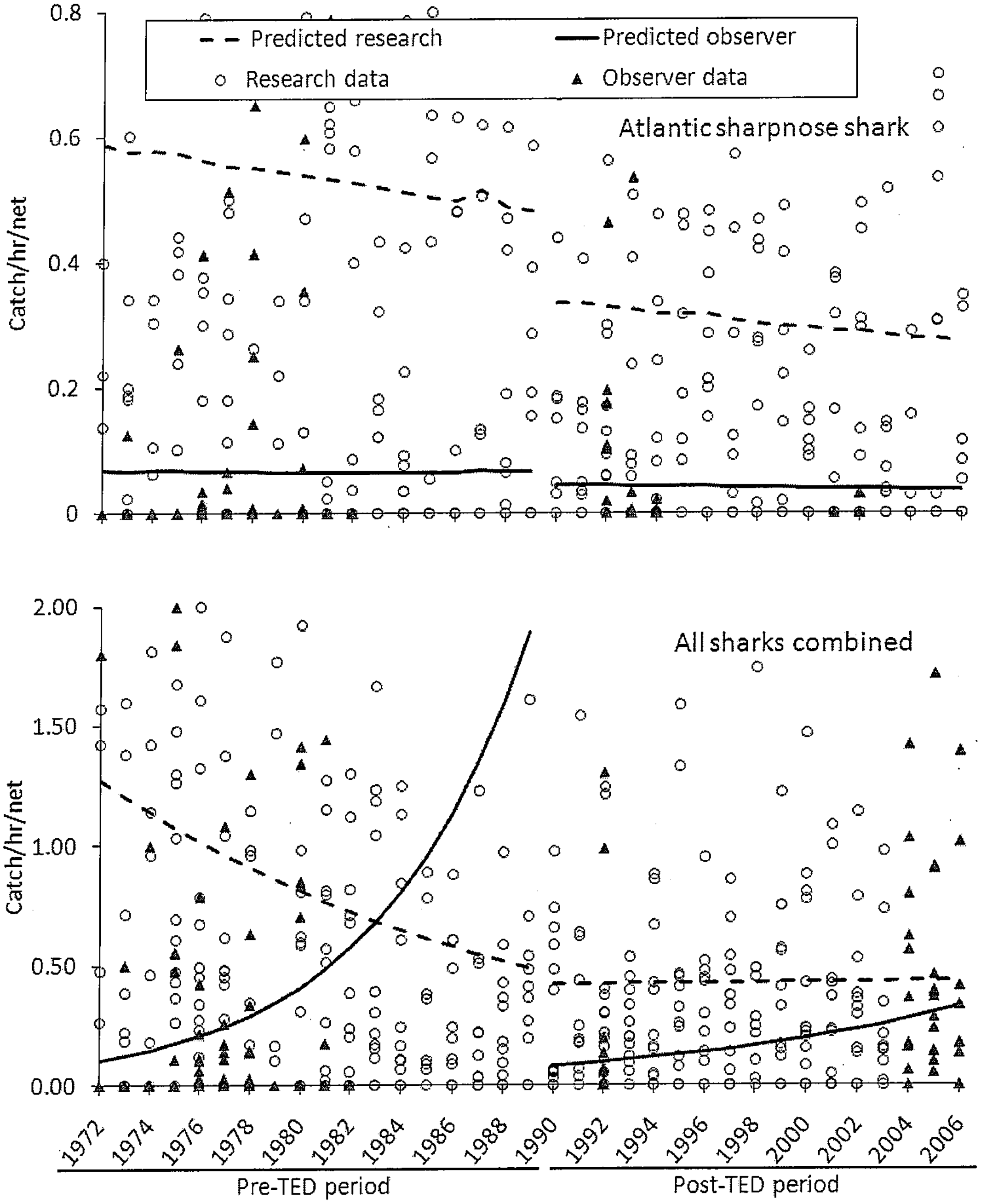
Model term	W_i of models with the term	No. of models w/ term	Mean W_i of models w/ term	Mean W_i of models w/out term	% chance for term being important
			Blacknose shark		
P·DS	0.997	32	0.031	0.000	100%
P·DS·T	0.947	8	0.118	0.000	100%
P	0.001	48	0.000	0.013	0%
DS	0.003	48	0.000	0.013	0%
A	0.884	64	0.014	0.002	88%
DZ	0.293	64	0.005	0.011	29%
Tri	0.273	64	0.004	0.012	27%
Yr	0.002	40	0.000	0.011	0%
T	0.036	40	0.001	0.011	8%
			Bonnethead shark		
P·DS	1.000	32	0.031	0.000	100%
P·DS·T	0.999	8	0.125	0.000	100%
P	0.000	48	0.000	0.013	0%
DS	0.000	48	0.000	0.013	0%
A	0.606	64	0.009	0.006	60%
DZ	1.000	64	0.016	0.000	100%
Tri	1.000	64	0.016	0.000	100%
Yr	0.001	40	0.000	0.011	0%
T	0.000	40	0.000	0.011	0%
			Atlantic sharpnose shark		
P·DS	0.372	32	0.012	0.007	64%
P·DS·T	0.055	8	0.007	0.008	47%
P	0.432	48	0.009	0.007	56%
DS	0.628	48	0.013	0.005	73%
A	1.000	64	0.016	0.000	100%
DZ	1.000	64	0.016	0.000	100%
Tri	0.734	64	0.011	0.004	73%
Yr	0.022	40	0.001	0.011	5%
T	0.568	40	0.014	0.005	74%

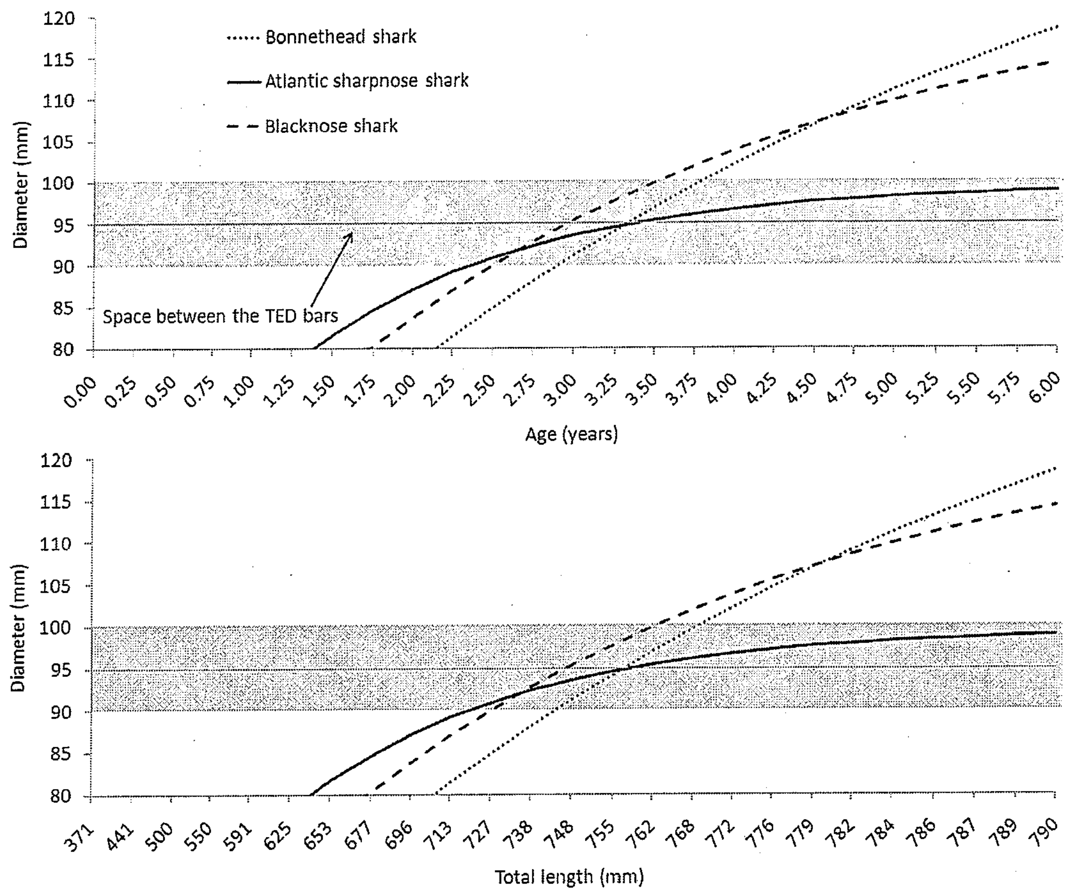
Table 2 (continued)

Model term	W_i of models with the term	No. of models w/ term	Mean W_i of models w/ term	Mean W_i of models w/out term	% chance for term being important
All shark species combined					
P·DS	1.000	32	0.031	0.000	100%
P·DS·T	1.000	8	0.125	0.000	100%
P	0.000	48	0.000	0.013	0%
DS	0.000	48	0.000	0.013	0%
A	1.000	64	0.016	0.000	100%
DZ	1.000	64	0.016	0.000	100%
Tri	1.000	64	0.016	0.000	100%
Yr	0.000	40	0.000	0.011	0%
T	0.000	40	0.000	0.011	0%


80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
Blacknose shark bycatch (number)
SEDAR13 bycatch estimates
Effort estimates
300,000
250,000
200,000
150,000
100,000
50,000
0
Offshore penaeid shrimp fishing effort (nominal days fished)
1950
1960
1970
1980
1990
2000
2010
Pre-TED period
Post-TED period


0.15
0.12
0.09
0.06
0.03
0
Catch/hr/net
Predicted research
Predicted observer
Research data
Observer data
Blacknose shark
0.50
0.40
0.30
0.20
0.10
0.00
Bonnethead shark
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
Pre-TED period
Post-TED period


Predicted research
Predicted observer
Research data
Observer data
Atlantic sharpnose shark
Catch/hr/net
0.8
0.6
0.4
0.2
0
All sharks combined
2.00
1.50
1.00
0.50
0.00
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
Pre-TED period
Post-TED period



120
115
110
105
100
95
90
85
80
Diameter (mm)
Bonnethead shark
Atlantic sharpnose shark
Blacknose shark
Space between the TED bars
0.00 0.25 0.50 0.75 1.00 1.25 1.50 1.75 2.00 2.25 2.50 2.75 3.00 3.25 3.50 3.75 4.00 4.25 4.50 4.75 5.00 5.25 5.50 5.75 6.00
Age (years)
371 441 500 550 591 625 653 677 696 713 727 738 748 755 762 768 772 776 779 782 784 786 787 789 790
Total length (mm)