Size composition and indices of relative abundance of the Atlantic blacktip shark (*Carcharhinus limbatus*) in coastal Virginia waters

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SEDAR65-DW-05

3 October 2019
Revised October 23, 2019

Please cite the document as:

Latour, R.J., J. Gartland, and C.F. Bonzek. 2019. Size composition and indices of relative abundance of the Atlantic blacktip shark (*Carcharhinus limbatus*) in coastal Virginia waters. SEDAR65-DW-05. SEDAR, North Charleston, SC. 17pp.

Size composition and indices of relative abundance of the Atlantic blacktip shark (*Carcharhinus limbatus*) in coastal Virginia waters

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Background

Virginia Shark Monitoring and Assessment Program (VASMAP)

The Virginia Shark Monitoring and Assessment Program (VASMAP), which is based out of the Virginia Institute of Marine Science (VIMS), has been sampling shark populations in the coastal waters of Virginia since 1974 using standardized fisheries-independent longline gear. The program provides detailed analyses of abundance, habitat utilization, age, growth, reproduction, trophic interactions, and demographics of dominant shark species in the Chesapeake Bay and coastal Virginia. VASMAP data are incorporated into stock assessments conducted by NOAA Fisheries for shark populations in the Atlantic, and are used by the Atlantic States Marine Fisheries Commission (ASMFC) and the Virginia Marine Resources Commission (VMRC) in their respective shark management policies.

This working paper summarizes the available VASMAP data for Atlantic blacktip shark (*Carcharhinus limbatus*) in support of the 2019 – 2020 peer-reviewed stock assessment (SEDAR 65). Information provided includes: overall, monthly, and regional length compositions of survey catches by sex, fork length (FL) to total length (TL) conversions by sex, percentages of survey catch immature/mature by sex, and annual indices of relative abundance spanning the years 1974 – 2018 derived from three different approaches (nominal time-series and two standardized time-series).

Methods

Field sampling

VASMAP utilizes a fisheries-independent bottom longline survey to sample large and small coastal sharks in the coastal waters of Virginia. The survey follows a fixed site design in which a 2400 m longline comprised of 4.8 mm diameter tarred, braided nylon mainline, with 100 equally spaced gangions (some longer sets in the early years had 200 hooks), is set for approximately four hours at six locations distributed evenly across three latitudinal regions (Figure 1). Each gangion is constructed of two meters of 4.8 mm diameter tarred, braided nylon mainline attached via an 8/0 barrel swivel to one meter of 1.6 mm diameter stainless steel leader, terminating with a 9/0 Mustad J hook (model 7698B DT). Gangions are fastened to the mainline via an 8/0 stainless steel longline snap. Norwegian buoys are placed between every 20 gangions and each end of the mainline is anchored. Atlantic menhaden (*Brevoortia tyrannus*) has been used as standard bait since 1995, before which bait was selected opportunistically. Soak time is calculated as the time elapsed from the start of each set to start of haul back. For each longline set, captured sharks are identified to the species level, sexed, enumerated, measured (0.5 cm), and released alive when possible.

Statistical analyses

Preliminary data exploration revealed that zero blacktip sharks were captured in several years thus limiting analyses to survey information from the following years: 1974 – 1975, 1980 – 1981, 1983, 1987 – 1988, 1990 – 1992, 1995 – 2002, 2004, and 2006 – 2018 (note, no sampling occurred in 1985 and 1994). From the data in those years, overall, monthly, and regional total length compositions of survey catches by sex were generated as barplots with bin widths of 5 cm. Carlson et al. (2006) provided FL values associated with 50% maturity of both sexes. Since more TL data were available than FL in the VASMAP data set, linear regression models were fitted for both sexes to provide conversions from FL to TL measurements which, in turn, allowed calculation of percent immature versus mature in terms of TL.

Yearly indices (I_y) of relative abundance were estimated using three approaches.

1. *Nominal*, defined as the arithmetic mean of catch-per-unit-effort (CPUE) with CPUE taken as N·(100-hook-hours)$^{-1}$, where N is the number of blacktip sharks captured. Standard errors (SE) were estimated as $\mathrm{SE}(I_y) = {sd(CPUE_y)}/{\sqrt{n_y}}$.
2. *Delta-LG*, defined as the mean from a generalized linear model (GLM; McCullagh and Nelder 1989) that assumed a delta-lognormal distribution for the CPUE data. Indices were computed as the product of the overall mean encounter proportion (modeled to include an offset variable defined as log([hook-hours-fished] ·[100-hook-hours]$^{-1}$)) and mean CPUE associated with only nonzero longline sets (again taken as N·(100-hook-hours)$^{-1}$). SEs associated with yearly mean encounter proportions (p_y) and mean CPUE from nonzero observations (c_y) were each estimated using the Delta method approximation (Seber 1982). SEs for the final, combined yearly indices were then estimated using Goodman's (1960) estimator for the variance of two independent random variables: $\mathrm{SE}(I_y) = \sqrt{(p_y^2)Var(c_y) + (c_y^2)Var(p_y) - Var(c_y)Var(p_y)}$.
3. *COUNT*, defined as the mean number of sharks captured using a GLM that assumed a discrete distribution designed for count data (modeled to include an offset variable defined as log([hook-hours-fished] ·[100-hook-hours]$^{-1}$)). SEs for the yearly indices were estimated using the Delta method approximation (Seber 1982).

The *Delta-LG* and *COUNT* indices were estimated using methods associated with the statistical modeling framework provided by the *gamlss* R package (Generalized Additive Models for Locations, Scale, and Shape; Rigby and Stasinopoulos 2005). The *gamlss* package is quite flexible in that it can accommodate probability distributions for the response variable beyond those in the exponential family, several zero-altered and zero-inflated mixture distributions, mixed effects, and an additive model structure to allow for nonlinearity among the response and explanatory variables.

As noted above, CPUE for *Delta-LG* was defined as a continuous random variable assumed to follow the delta-lognormal distribution. For a non-negative random variable Y taken to represent CPUE with $\Pr(Y > 0) = \pi$ and $X = \log(Y|Y > 0)$, where $X \sim \mathrm{N}(\mu_X, \sigma_X^2)$, it can be shown that the expected value of Y is given by (Aitchison 1955, Fletcher 2008):

$$\mu_Y = \pi \cdot \exp\left(\mu_X + \frac{\sigma_X^2}{2}\right). \tag{1}$$

The parameters π and μ_X were modeled as linear combinations of covariates assuming the binomial (logit link) and normal (log transformed nonzero CPUE, identity link) distributions, respectively. Given the fixed station, repeated measures design of the VASMAP survey, station was treated as a random effect in both the binomial and normal model components (random intercept model), however, preliminary modeling showed no appreciable improvement in fit when the mixed and fixed effects versions were compared. Therefore, only fixed-effects models were considered. Model validation was achieved by generating a binned residuals plot for the binomial model, which summarizes the average residual versus the average fitted value across categorically defined bins (Gelman et al. 2000). A normal QQ plot and a plot of residuals versus fitted values were used to validate the lognormal model component.

A total of 32 discrete distributions can be fitted to count data using the *gamlss* package. Thus, to guide the choice of the appropriate distribution for the Atlantic blacktip count data in developing *COUNT*, the *fitDist* function was used to fit all candidate distributions using maximum likelihood and AIC was used for comparison. Two distributions failed to converge (the logarithmic and zero-inflated Pareto distributions) and AIC selection favored consideration of the generalized Poisson, Delaporte, zero-altered logarithmic, Sichel, and the Poisson-inverse Gaussian distributions (ΔAIC < 2). Preliminary fits of those distributions along with evaluation of diagnostics supported the Sichel distribution (Sichel 1971), which is a compound Poisson distribution achieved by mixing the Poisson parameter using the generalized inverse Gaussian distribution (Stein et al. 1987). The mass function of the Sichel distribution implemented takes the form (Rigby et al. 2008):

$$P(Y = y|\mu, \sigma, \nu) = \frac{(\mu/c)^y K_{y+\nu}(\alpha)}{y!(\alpha\sigma)^{y+\nu} K_\nu\left(\frac{1}{\sigma}\right)} \tag{2}$$

for $y = 0,1,2,3, \ldots$ where $\mu > 0$, $\sigma > 0$, $-\infty < \nu < \infty$, $\alpha^2 = \sigma^{-2} + 2\mu(c\sigma)^{-1}$, $c = R_\nu(\frac{1}{\sigma})$, $R_\lambda(t) = K_{\lambda+1}(t)/K_\lambda(t)$, and $K_\lambda(t)$ is the modified Bessel function of the third kind. Again, mixed effects structures were explored but showed no improvement over fixed effects parameterizations. Model validation was achieved by generating a worm plot of the residuals, which is a detrended version of a normal QQ plot (van Buuren and Fredricks 2001) and by calculating the dispersion parameter (d) to evaluate overdispersion: $d = {\sum \varepsilon^2}/{residual\ df}$.

For both components of the *Delta-LG* and the *COUNT* GLMs, five combinations of the categorically defined covariates year, month, and region were fitted (Table 1) and AIC was used for model selection. Predictions of mean CPUE/count across the observed levels of the covariates retained in the most empirically supported model were computed as marginal means (Searle et al. 1980).

Results/Discussion

Survey summary

The VASMAP Atlantic blacktip shark dataset for the years 1974 – 1975, 1980 – 1981, 1983, 1987 – 1988, 1990 – 1992, 1995 – 2002, 2004, and 2006 – 2018 included 667 observations. Survey catches ranged from 0 to 17 animals with a mean of 0.48, hooks deployed per longline set ranged from 30 to 200 with a mean of 104.9, and soak time ranged from 0.5 to 17.9 hr with a mean of 4.6 hr. A total of 324 Atlantic blacktip sharks were captured over the sampling years, with slightly fewer females ($n_{Female} = 135; 42\%$) than males ($n_{Male} = 177; 55\%$). Sex data were not recorded for a small portion of the total catch ($n_{NoData} = 12; 4\%$).

Length composition

The total length ranges (R) and means ($\overline{TL}$) for captured female and male Atlantic blacktip sharks in Virginia waters were fairly similar (R_{Female}: 70 – 192.5 cm, $\overline{TL}_{Female}$= 138.4 cm; R_{Male}: 91.5 – 187 cm, $\overline{TL}_{Male}$ = 141.3 cm; Figure 2). Carlson et al. (2006) reported 50% maturity at 126.6 cm and 116.7 cm for female and male blacktip sharks in the South Atlantic Bight, respectively. Conversion of these sizes to TL from fitted regression models yielded respective values of 155.9 cm and 144.4 cm for females and males (Figure 3). Therefore, VASMAP samples a higher percentage of immature animals ($p_{I,Female} = 74.1\%$; $p_{I,Male} = 58.2\%$) when compared to mature animals. Patterns in monthly length compositions for both sexes indicated decreasing overall capture from Jun – Sep with generally similar values of monthly $\overline{TL}$ (Figure 4). Spatially, capture patterns of both sexes were comparable in that region 3 (south) showed the highest catches followed by region 1 (north) and region 2 (east). Although regional values of mean total length were similar, region 3 showed the lowest values of $\overline{TL}$ for both sexes (Figure 5).

Indices of relative abundance

Annual proportions of longline sets that captured at least one Atlantic blacktip shark were generally low and ranged from 0.04 (1996) to 0.46 (2008; Figure 6A). These results combined with a highly positively skewed distribution of nonzero longline catches (Figure 6B) generally supported application of the delta-lognormal GLM. Model selection among the five candidate parameterizations considered favored model M_1 (the fully saturated model) for the binomial component and model M_2 lognormal component (Table 2). The binned residuals plot showed good performance of the binomial model as virtually all of the binned residuals fell within ± two standard error bounds (Figure 7A). Diagnostics associated with the lognormal model component were also indicative of reasonable model performance (Figures 7B, C).

For the Sichel count GLM, model selection results favored model M_1 (Table 3). Diagnostics associated with the selected model suggested good model performance as all residuals were in the acceptance region inside the two elliptic curves of the worm plot (Figure 8), and the estimated dispersion parameters was 1.01. Typically, high frequencies of zero count observations can lead to overdispersion, however, the Sichel distribution accommodated the structure of the VASMAP Atlantic blacktip shark count data well and alleviated the need for zero–altered or zero–inflated mixture distributions.

The three versions of the annual indices of relative abundance scaled to their respective means overall showed comparable patterns, particularly in the most recent years (Figure 9A). However, the *COUNT* index differed from the other two indices notably in the early years. Specifically, *COUNT* was highest at the beginning of the time-series (1974) followed by fluctuations at lower levels later in time. In contrast, both the *nominal* and *Delta-LG* showed increasing trends in the beginning years (1974 – 1975) followed by declines to lower levels thereafter. The *COUNT* index also showed a sizable increase in the late 1980s (1987 – 1988) while the other two indices showed just a slight increase. These differences provide different signals about the relative scale and status of abundance of the Atlantic blacktip shark population historically (pre-1990) which could have important implications when used to tune the stock assessment model. Uncertainty in the indices, expressed as coefficients of variation (CV), was generally high regardless of the method used for estimation (several values greater than 0.8; Figure 9B). Among the standardized, GLM-based indices, CVs associated with the *COUNT* model were higher in the early years of the time-series (pre-1989), however, CVs associated with the *Delta-LG* model were higher more recently (2004-2018).

Acknowledgements

The authors wish to acknowledge the field efforts of past and present staff, students, and vessel crew working on the VASMAP survey at VIMS. Funding for VASMAP was provided by NOAA Fisheries, Silver Spring, MD.

Literature Cited

Aitchison, J. 1955. On the distribution of a positive random variable having a discrete probability mass at the origin. Journal of the American Statistical Association 50:901 – 908.

Akaike, H. 1973. Information theory as an extension of the maximum likelihood principle. In: Petrov, B.N., and F. Csaki (eds) Second International symposium on information theory. Akademiai Kiado, Budapest, pp. 267 – 281.

Burnham, K.P. and D.R. Anderson. 2002. Model selection and multimodel inference: a practical information-theoretic approach, 2nd ed. Springer – Verlag, New York.

Carlson, J.K., J.R. Sulikowski, and I.E. Baremore. 2006. Do differences in life history exist for blacktip sharks, *Carcharhinus limbatus*, from the United States South Atlantic Bight and Eastern Gulf of Mexico? Environmental Biology of Fishes 77:279 – 292.

Fletcher, D. 2008. Confidence intervals for the mean of the delta-lognormal distribution. Environmental and Ecological Statistics 15:175 – 189.

Gelman, A., Y. Goegebeur, F. Tuerlinckx, and I. Van Mechelen. 2000. Diagnostic checks for discrete data regression models using posterior predictive simulations. Applied Statistician 49:247 – 268.

Goodman, L.A. 1960. On the exact variance of products. Journal of the American Statistical Association 55:708-713.

McCullagh, P., and J.A. Nelder. 1989. Generalized Linear Models, 2nd ed. Chapman & Hall, London.

Rigby, R.A., and D.M. Stasinopoulos. 2005. Generalized additive models for location, scale and shape. Journal of the Royal Statistical Society: Series C (Applied Statistics) 54:507-554.

Rigby, R.A., D.M. Stasinopoulos, and C. Akantziliotou. 2008. A framework for modelling overdispersed count data, including the Poisson-shifted generalized inverse Gaussian distribution. Computational Statistics & Data Analysis 53:381 – 393.

Searle S.R., F.M. Speed, and G.A. Milliken. 1980. Population marginal means in the linear model: an alternative to least squares means. American Statistician 34:216 – 221.

Seber, G.A.F. 1982. The estimation of animal abundance and related parameters. 2nd ed. MacMillan, New York, New York.

Sichel, H.S. 1971. On a family of discrete distributions particularly suited to represent long-tailed frequency data. In: Laubscher, N.F. (ed) Proceedings of the Third Symposium on Mathematical Statistics. Pretoria, South Africa: Council for Scientific and Industrial Research, pp. 51 – 97.

Stein, G.Z., W. Zucchini, and J.M. Juritz. 1987. Estimation for the Sichel distribution and its multivariate extension. Journal of the American Statistical Association 82:938 – 944.

van Buuren, S., and M. Fredriks. 2001. Worm plot: simple diagnostic device for modelling growth reference curves. Statistics in Medicine 20:1259 – 1277.

Tables and Figures

Table 1. Model parameterizations considered for development of the two standardized time-series of annual indices of relative abundance for Atlantic blacktip shark (*Carcharhinus limbatus*) using generalized linear models. All covariates were treated as categorical.

Model	**Covariates**
M_1	Year, Month, Region, Month*Region
M_2	Year, Month, Region
M_3	Year, Month
M_4	Year
M_5	Year, Region

Table 2. Model selection statistics associated with the binomial and lognormal generalized linear model components fitted to presence/absence and catch-per-unit-effort data from the VASMAP survey for Atlantic blacktip shark (*Carcharhinus limbatus*) during years 1974-1975, 1980-1981, 1983, 1987-1988, 1990-1992, 1995-2002, 2004, 2006-2018 (missing years correspond to zero Atlantic blacktip shark catches; no sampling occurred in 1985 and 1994).

Model	**-2log(L)**	**Number parameters**	**AIC**	**∆AIC**
		Binomial model component		
M_1	493.4	43	579.4	0.0
M_2	507.9	37	581.9	2.5
M_3	557.7	35	627.7	48.3
M_4	585.3	32	649.3	69.9
M_5	537.6	34	605.6	26.2
		Lognormal model component		
M_1	250.3	44	338.3	10.4
M_2	251.9	38	327.9	0.0
M_3	258.9	36	330.9	3.0
M_4	266.8	33	332.8	4.9
M_5	261.6	35	331.6	3.7

Table 3. Model selection statistics associated with the Sichel generalized linear model components fitted to count data from the VASMAP survey for Atlantic blacktip shark (*Carcharhinus limbatus*) during years 1974-1975, 1980-1981, 1983, 1987-1988, 1990-1992, 1995-2002, 2004, 2006-2018 (missing years correspond to zero Atlantic blacktip shark catches; no sampling occurred in 1985 and 1994).

Model	**-2log(L)**	**Number parameters**	**AIC**	**ΔAIC**
M_1	897.3	45	987.3	0.0
M_2	911.6	39	989.6	2.3
M_3	961.4	37	1035.4	48.1
M_4	990.9	34	1058.9	71.6
M_5	943.0	36	1015.0	27.7

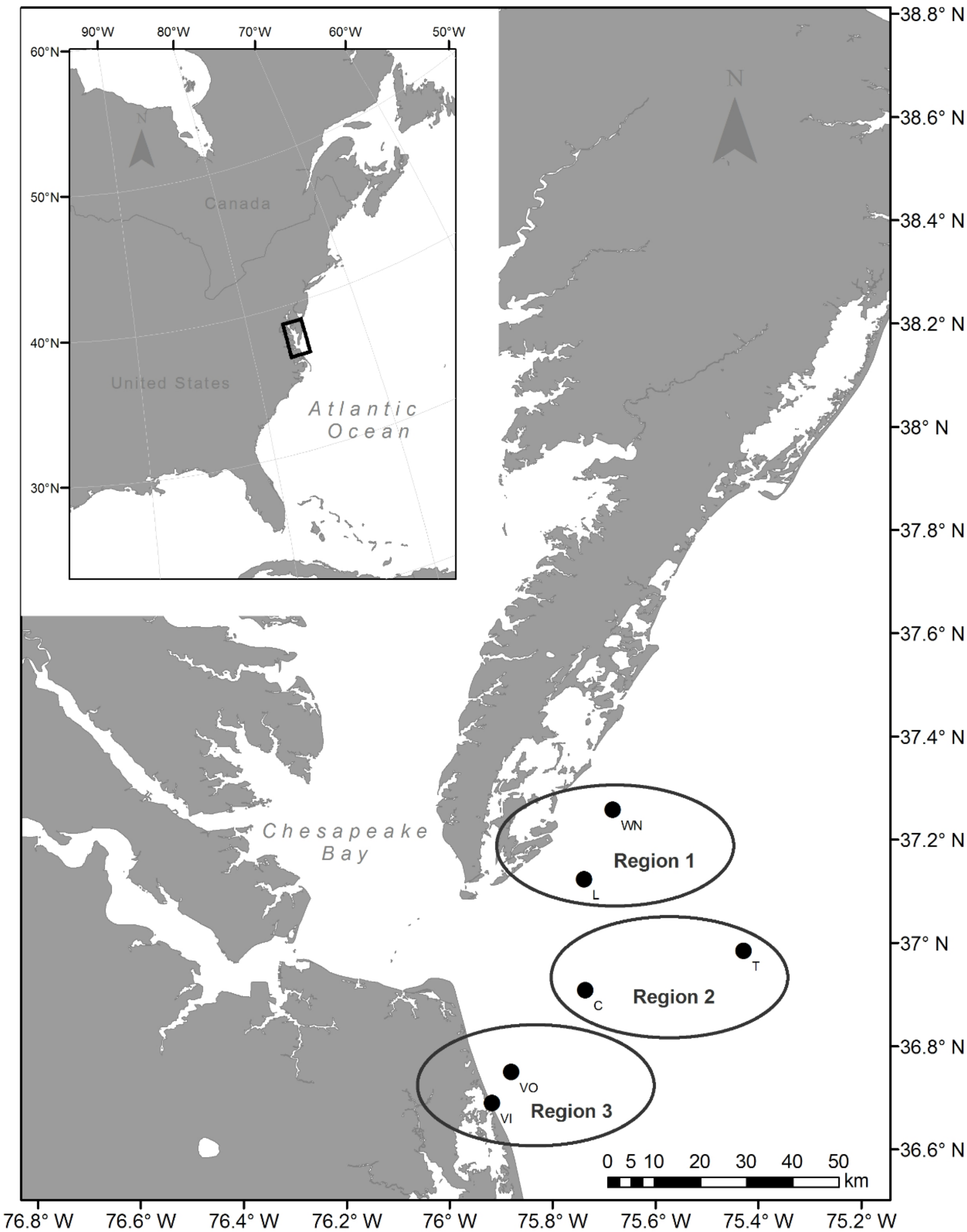

Figure 1. Standard VASMAP longline sampling sites within three latitudinal regions in the coastal waters of Virginia (WN – Sand Shoal New; L – Smith Island Shoal; T – Triangle Wreck; C – Chesapeake Light Tower; VO – Virginia Beach Offshore; VI – Virginia Beach Inshore).

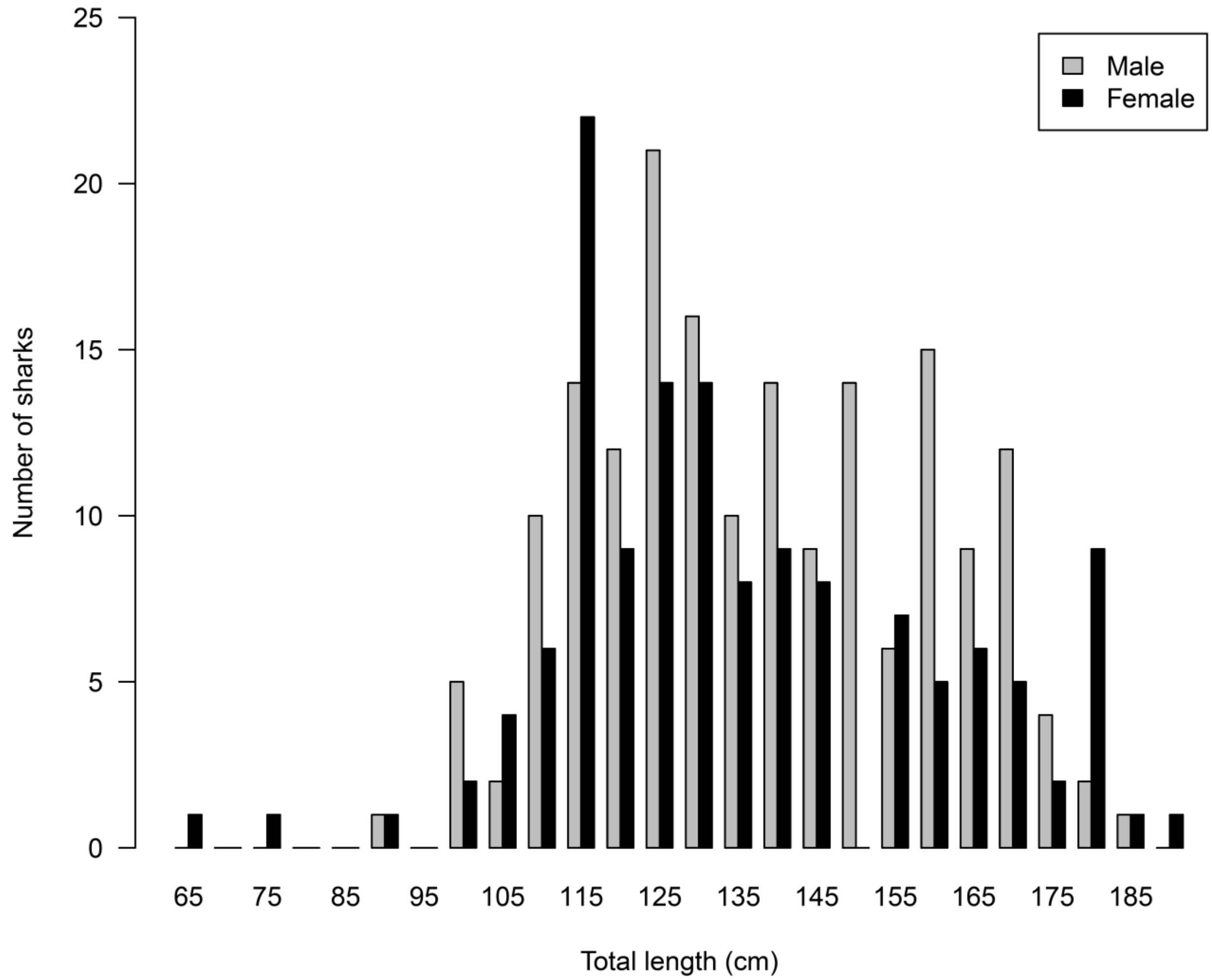

Figure 2. Length frequencies for male ($n_{Male} = 177$) and female ($n_{Female} = 135$) Atlantic blacktip sharks (*Carcharhinus limbatus*) collected at standard VASMAP sampling sites during years 1974-1975, 1980-1981, 1983, 1987-1988, 1990-1992, 1995-2002, 2004, 2006-2018 (missing years correspond to zero Atlantic blacktip shark catches; no sampling occurred in 1985 and 1994).

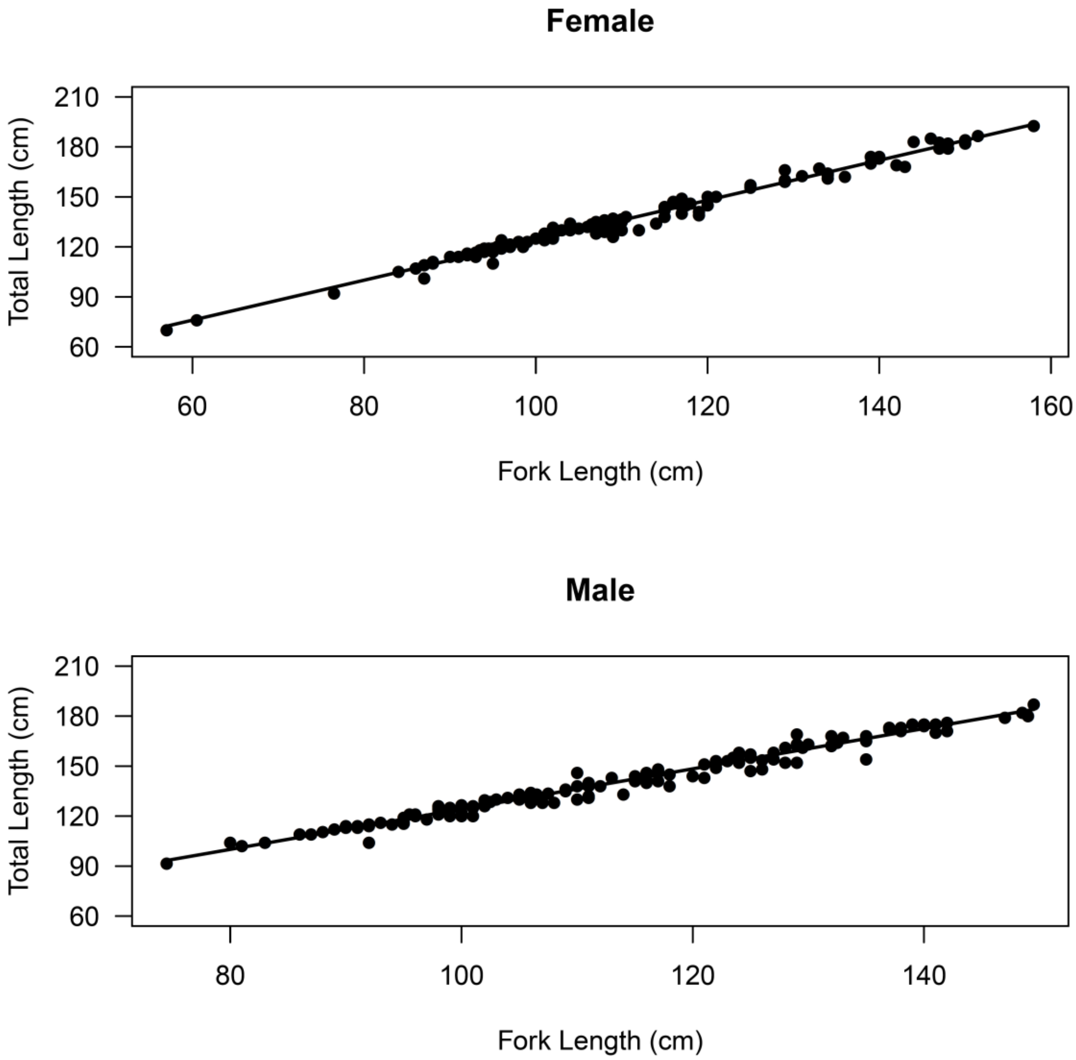

Figure 3. Fork length (FL) to total length (TL) linear regression model fits for female ($n_{Female} =$ 118) and male ($n_{Male} = 140$) Atlantic blacktip sharks based on available VASMAP data. Female model fit: $TL = 4.06 + 1.20 \cdot FL$, $r^2 = 0.98$; male model fit: $TL = 3.37 + 1.21 \cdot FL$, $r^2 = 0.97$.

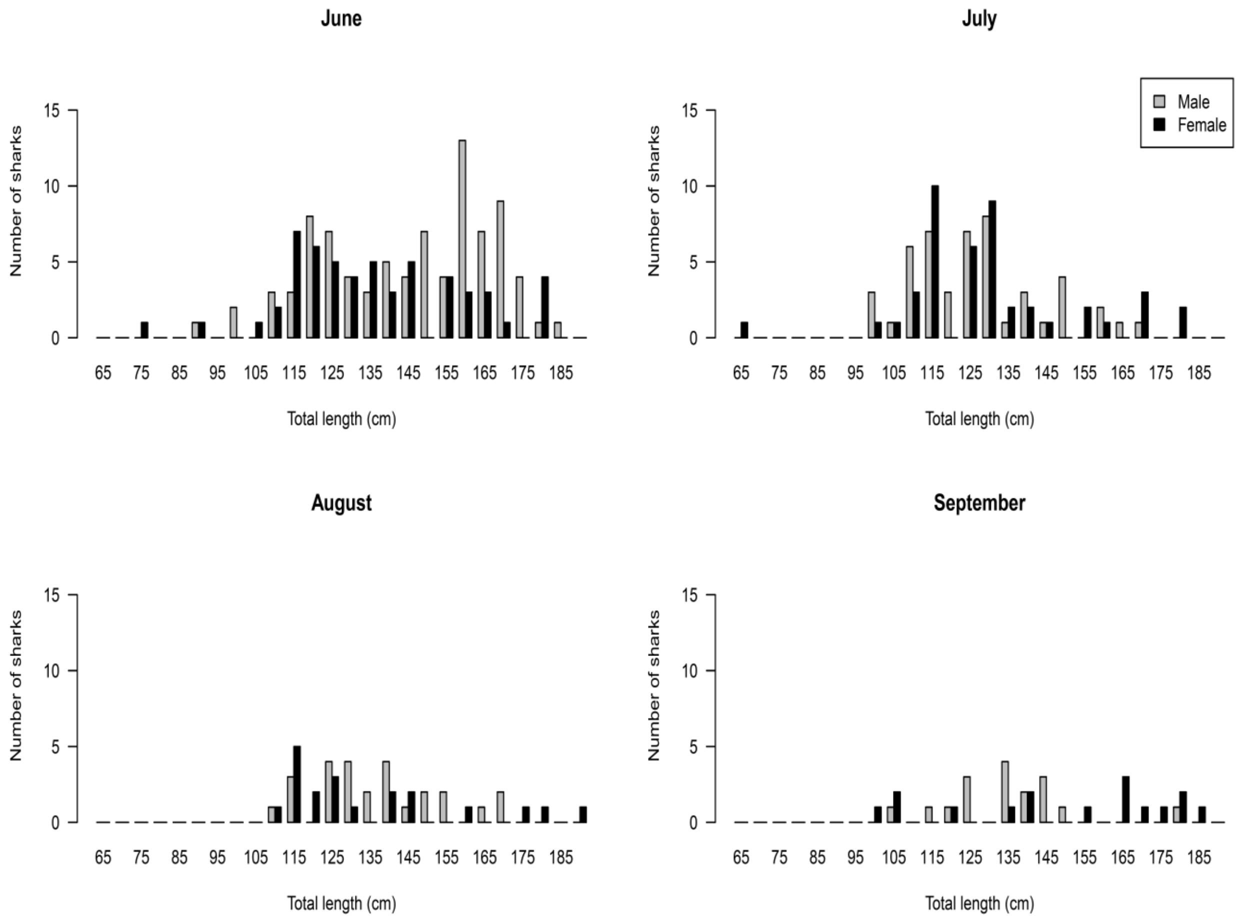

Figure 4. Monthly length frequencies for male and female Atlantic blacktip shark (*Carcharhinus limbatus*) collected by the VASMAP longline survey during years 1974-1975, 1980-1981, 1983, 1987-1988, 1990-1992, 1995-2002, 2004, 2006-2018 (missing years correspond to zero Atlantic blacktip shark catches; no sampling occurred in 1985 and 1994).

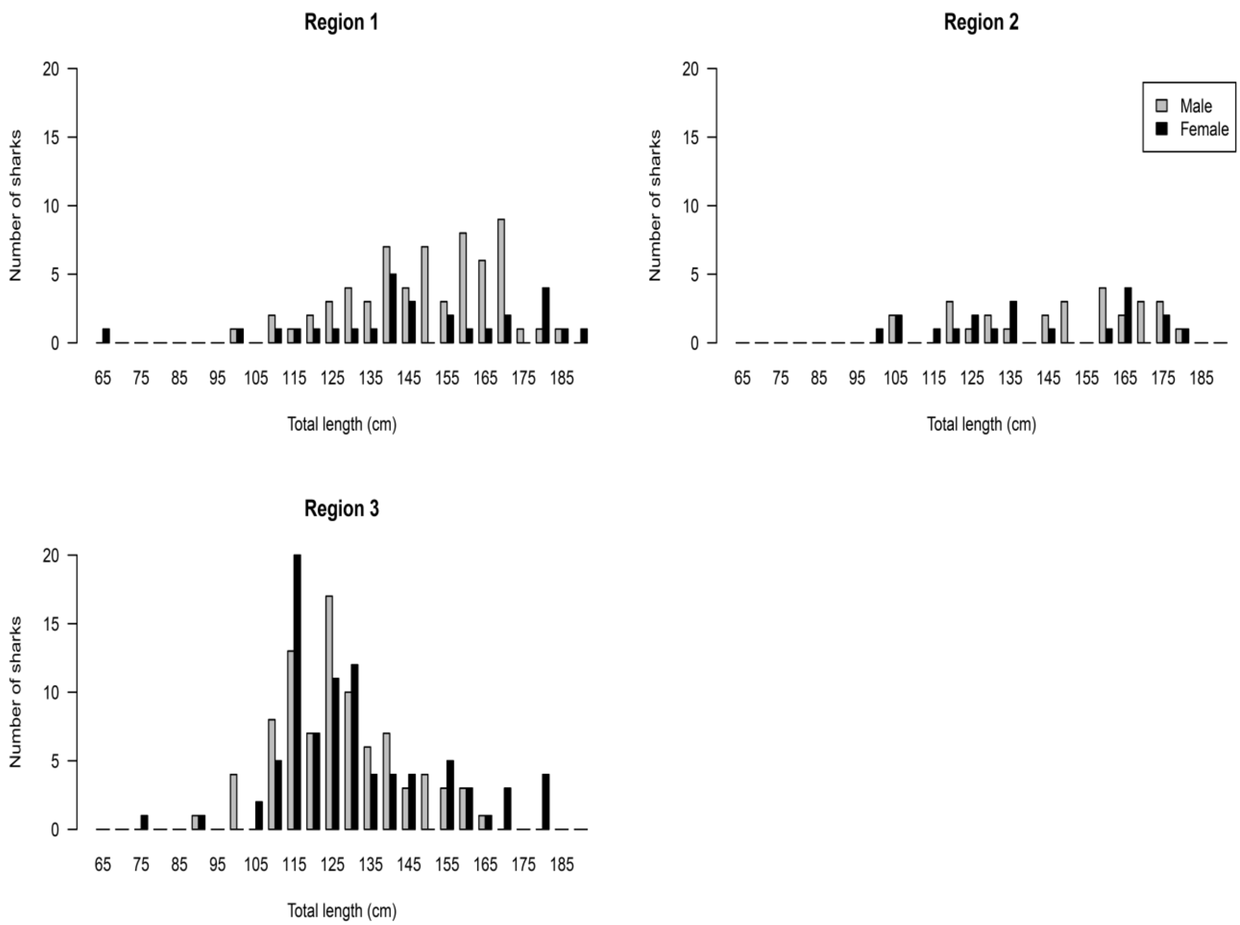

Figure 5. Regional length frequencies for male and female Atlantic blacktip shark (*Carcharhinus limbatus*) collected by the VASMAP longline survey during years 1974-1975, 1980-1981, 1983, 1987-1988, 1990-1992, 1995-2002, 2004, 2006-2018 (missing years correspond to zero Atlantic blacktip shark catches; no sampling occurred in 1985 and 1994).

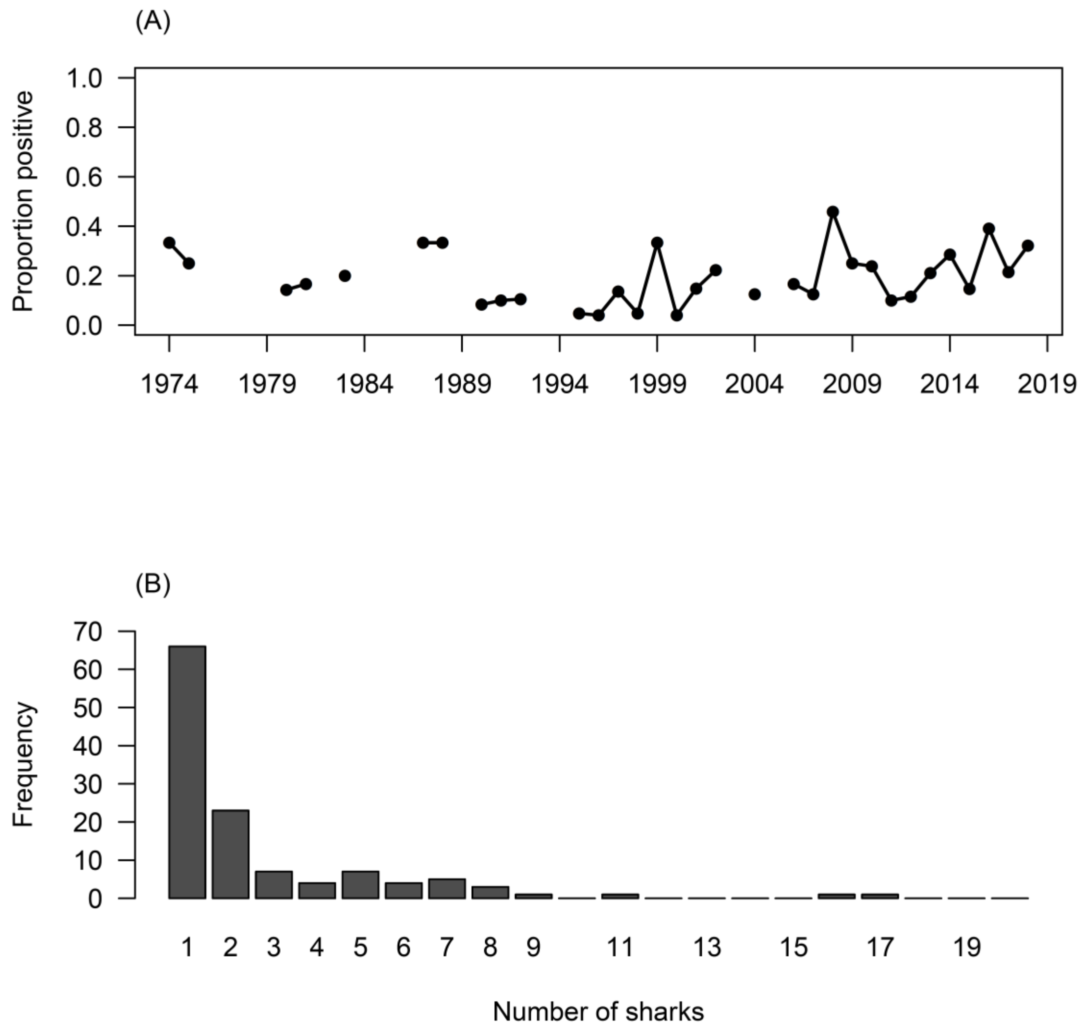

Figure 6. (A) Proportion of longline sets where at least one Atlantic blacktip shark was captured and (B) frequencies of total nonzero catches of longlines set by the VASMAP survey during years 1974-1975, 1980-1981, 1983, 1987-1988, 1990-1992, 1995-2002, 2004, 2006-2018 (missing years correspond to zero Atlantic blacktip shark catches; no sampling occurred in 1985 and 1994).

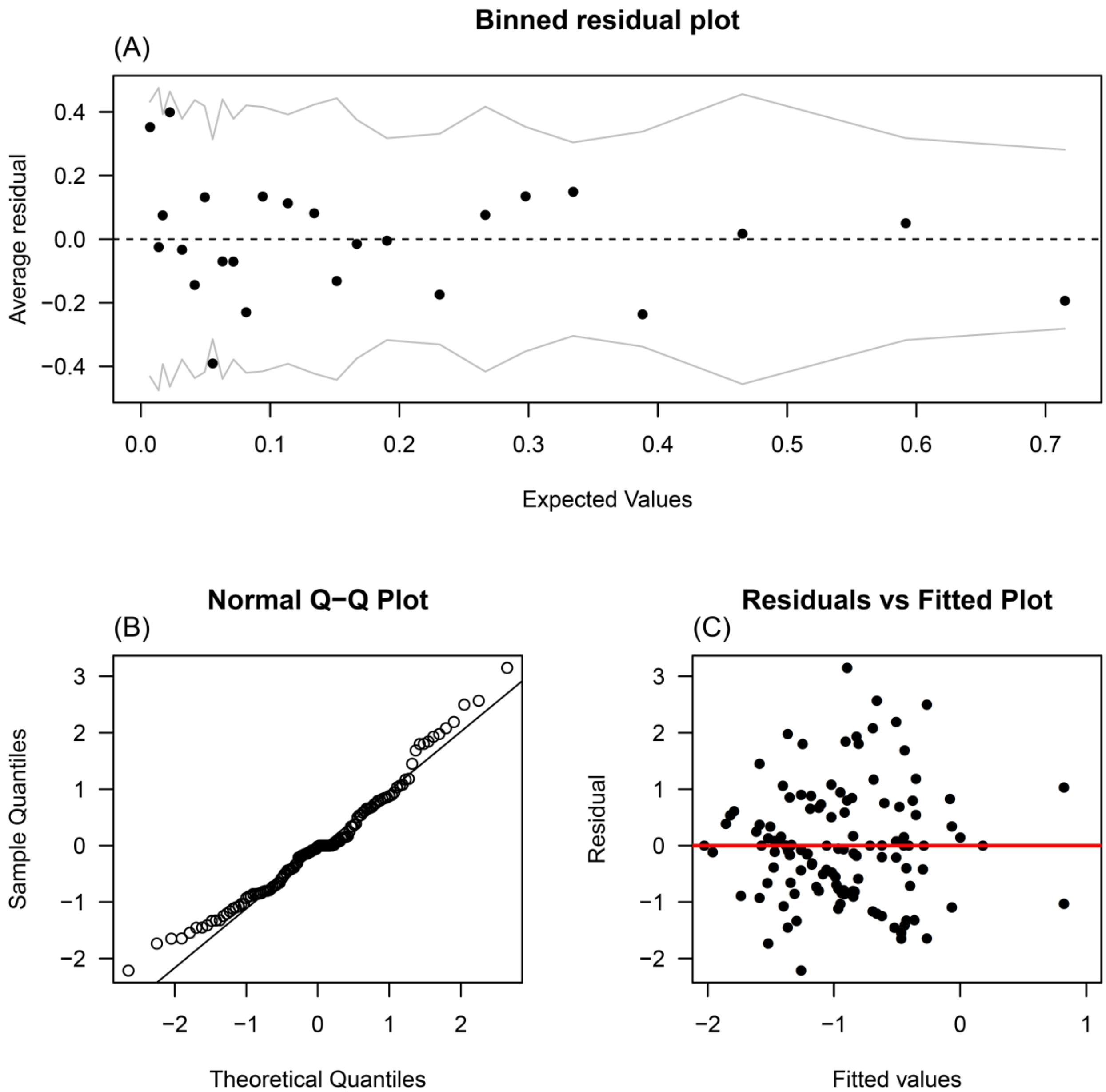

Figure 7. (A) Binned residuals plot for the fully saturated binomial GLM depicting the average residual versus the average fitted value across categorically defined bins, (B) normal QQ plot for residuals of lognormal GLM model M_2, and (C) residuals versus fitted values from the lognormal GLM model M_2. Both models were applied to VASMAP survey data from years 1974-1975, 1980-1981, 1983, 1987-1988, 1990-1992, 1995-2002, 2004, 2006-2018 (missing years correspond to zero Atlantic blacktip shark catches; no sampling occurred in 1985 and 1994).

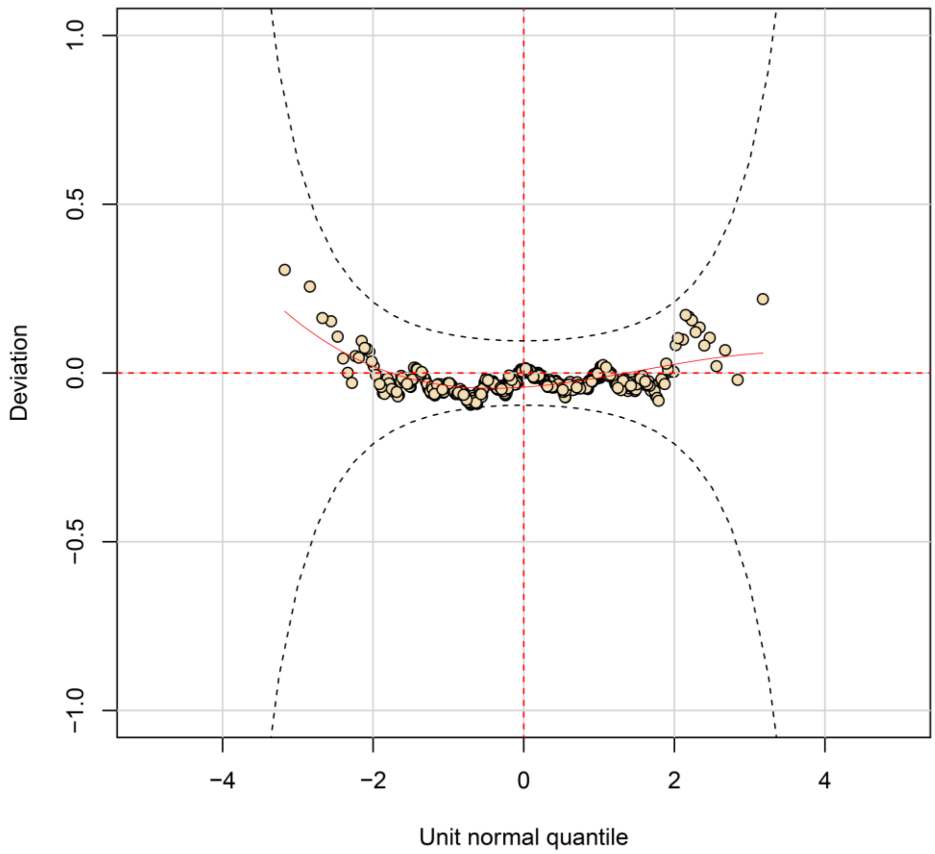

Figure 8. Worm plot of the residuals (detrended version of a normal QQ plot) associated with the fully saturated *COUNT* GLM fitted to VASMAP survey data from years 1974-1975, 1980-1981, 1983, 1987-1988, 1990-1992, 1995-2002, 2004, 2006-2018 (missing years correspond to zero Atlantic blacktip shark catches; no sampling occurred in 1985 and 1994).

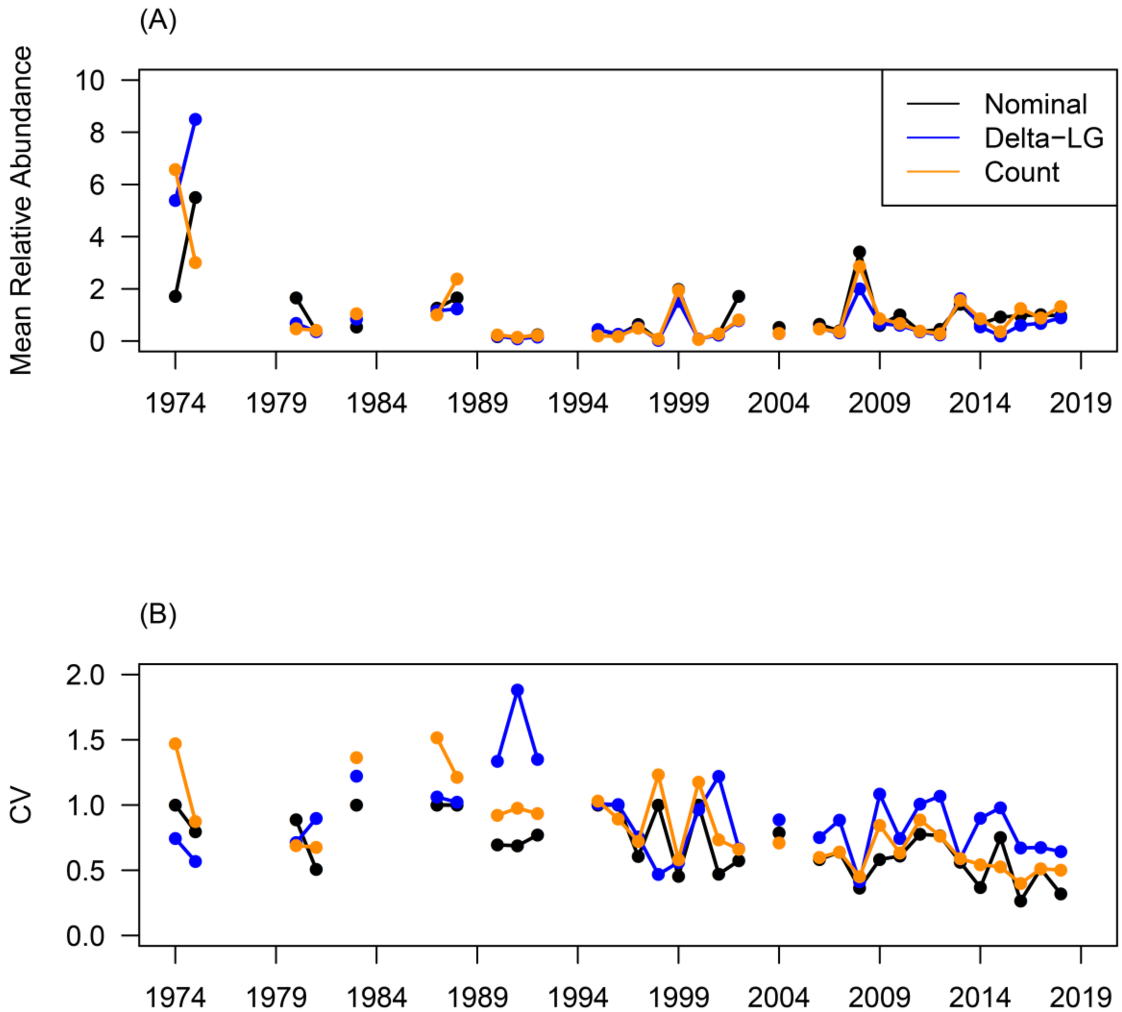

Figure 9. (A) Time-series of Atlantic blacktip shark *Nominal* (black), *Delta-LG* (delta-lognormal GLM, blue), and *COUNT* (Sichel GLM, orange) indices of relative abundance scaled to their respective means, (B) estimated coefficients of variation associated with the respective annual indices. VASMAP survey data from years 1974-1975, 1980-1981, 1983, 1987-1988, 1990-1992, 1995-2002, 2004, 2006-2018 (missing years correspond to zero Atlantic blacktip shark catches; no sampling occurred in 1985 and 1994).