Relative abundance indices for sandbar sharks (*Carcharhinus plumbeus*) in the northwest Atlantic Ocean from the Shark Bottom Longline and Shark Research Fishery

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Relative abundance indices for sandbar sharks (*Carcharhinus plumbeus*) in the northwest Atlantic Ocean from the Shark Bottom Longline and Shark Research Fishery

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Introduction

Observations by at-sea observers of the shark bottom longline fishery in the Atlantic Ocean and Gulf of Mexico have been conducted since 1994 (e.g. Morgan et al. 2009; Mathers et al. 2024). Historically, vessels in this fishery primarily targeted sandbar shark and fish from North Carolina to the eastern Gulf of Mexico. With the introduction of the Shark Research Fishery in 2008, vessels outside the research fishery were not permitted to target or land sandbar sharks. This change in management regulations likely influences the time series of abundance for sharks such that vessels fishing in the research fishery should be modeled separately from those outside the research fishery. Therefore, two indices of abundance were created from this data series; 1994-2007 for all vessels participating in the shark bottom longline fishery (i.e Shark Bottom Longline Fishery) and from 2008-2025 for vessels only participating in the Shark Research Fishery (i.e. Shark Research Fishery). Following the definition of the south Atlantic and Gulf of Mexico by the Highly Migratory Species Division, abundance trends were developed for the Atlantic Ocean, Gulf of Mexico and all areas. A previous stock assessment for sandbar shark utilized data from this fishery as an index of abundance and as an input to the stock assessment model (SEDAR21-DW-02; SEDAR54-WP-02). Herein, we re-analyze the abundance time series index.

Methods

Catch rate analysis

Depending on the data source, a number of factors and covariates were selected that were hypothesized to influence the catch of a sandbar shark (Table 1). The standardization method was a delta lognormal model approach which is a common approach for standardizing fisheries data to correct for factors unrelated to abundance (Maunder and Punt, 2004). The delta modeling approach estimates the predicted relative abundance as the result of two processes; the probability of encountering at least one sandbar shark (proportion of positive catch) assuming a binomial distribution and logit link and the mean catch rate. Catch rate (i.e. CPUE) was defined as the natural log of the number of sandbar sharks caught per 10,000 hooks assuming a lognormal distribution and identity link.

We used two modeling approaches when developing standardized indices of relative abundance. The first modeling approach to model sandbar shark catch rates was performed with generalized linear models with fixed effect factors (GLM; McCullagh and Nelder, 1989). Each factor was ranked from greatest to least reduction in deviance per degree of freedom when compared to the null model with no factors (e.g., Ortiz & Arocha 2004, Cortés et al., 2007; Cass-Calay & Schmidt 2009). The factor with the greatest reduction in deviance was then incorporated into the model providing the effect was significant at $p<0.05$ based on a Chi-Square test and was reduced by at least 5% from the less complex model (Ortiz and Arocha 2004; Forrestal et al. 2019). The process was continued until no factors met the criterion for incorporation into the final model. Regardless of its level of significance, year was retained in all models.

The fixed factors determined through the GLM modelling procedure were then modeled using a generalized linear mixed model (GLMM) with the variables year and sampling strategy as random variables to account for repeated observations within sampling year and fixed areas and that all years and fixed areas are not sampled at the same rate. Only first-order interactions were considered due to the potential to overparameterize the model. Model goodness-of-fit was

evaluated using -2 Residual Log-Likelihood (RLL), Bayesian information criterion (BIC), Akaike's information criterion (AIC). Model validation used residuals diagnostics, quantile-quantile plots and the distribution of transformed CPUE with graphical checks.

The standardized CPUE values were calculated as the product of the expected probability of a non-zero catch and the expected conditional catch rate for sets that had a non-zero catch. The expected probability and expected conditional catch rate were the least square means of the factor year from each of the two sub-models that constituted an analysis using the Delta model approach (Lo et al., 1992). GLM and GLMM analysis was conducted using the PROC GENMOD and PROC GLIMMIX procedure in the SAS statistical computer software (ver 9.4). All standardized CPUEs were estimated using a SAS macro, GLIMMIX (glmm800MaOB.sas: Russ Wolfinger, SAS Institute Inc.) and the PROC MIXED procedure.

Table 1. Candidate covariates hypothesized to affect catch rates of sandbar shark. Covariates were considered in both the binomial and lognormal models

Data series	Covariate	Type	Description
Shark Bottom Longline Fishery Shark Research Fishery	Year	Categorical	1994-2007 2008-2025
Shark Bottom Longline Fishery Shark Research Fishery	Area	Categorical	US south Atlantic and Gulf of Mexico as defined by the Highly Migratory Species Division
Shark Bottom Longline Fishery Shark Research Fishery	Season	Categorical	Winter = January-March Spring = April-June Summer = July-September Fall = October-December
Shark Bottom Longline Fishery Shark Research Fishery	Hook type	Categorical	Circle hook J style hook Undefined
Shark Bottom Longline Fishery Shark Research Fishery	Bait type	Categorical	Elasmobranch Teleost Other (undefined or multiple bait types)
Shark Research Fishery	Hook size	Categorical	Large (>9/0) Small/Medium (6/0-9/0) Unknown
Shark Research Fishery	Target	Categorical	Sandbar shark Shark Other
Shark Bottom Longline Fishery Shark Research Fishery	Set depth (ft)	Categorical	6-762
Shark Bottom Longline Fishery Shark Research Fishery	Set begin time	Categorical	Day = 0501-1800 hrs Night = 1801-0500 hrs
Shark Bottom	Soak (hr)	Continuous	Time from when the first hook was set until the

Longline Fishery Shark Research Fishery			first hook was removed during haulback

Results and Discussion

A total of 1542 longline sets were made from 1994-2007 in the Shark Bottom Longline Fishery (Figure 1) and 1636 sets from 2008-2025 in the Shark Research Fishery (Figure 2). The proportion of positive sets (i.e. at least one sandbar shark was caught) was 71.5% in the Shark Bottom Longline Fishery and 86.7% in the Shark Research Fishery. However, in some years the proportion positive in the Shark Research Fishery was 100% (Figure 3). Therefore, a lognormal model on all values of CPUE was considered (e.g. CPUE+1) for the shark research fishery (Figure 4). The stepwise construction of the models is summarized in Table 2 for the Shark Bottom Longline Fishery and in Table 3 for the Shark Research Fishery. Results of the generalized linear mixed models used to develop the indices are in Table 4. The index statistics can be found in Table 5 for the Shark Bottom Longline Fishery and Table 6 for the Shark Research Fishery. The delta-lognormal abundance index is shown in Figure 4. To allow for visual comparison, the series were scaled to their respective average value. A retrospective analysis for the shark bottom longline fishery is provided in Figure 5 and the model diagnostic plots is in Figure 6 for the Shark Bottom Longline Fishery and Figure 7 for the Shark Research Fishery.

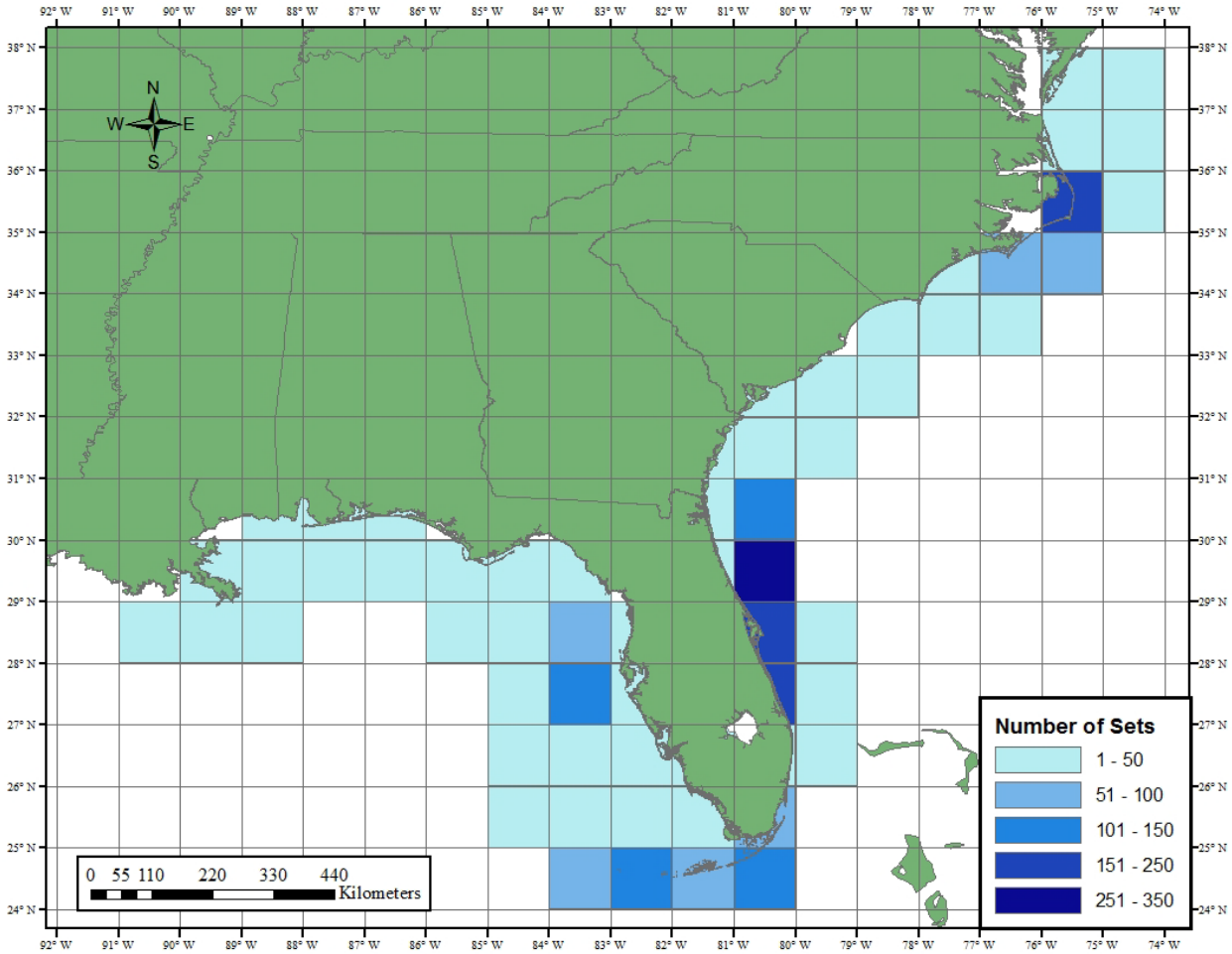

Figure 1. Distribution of fishing effort in the Shark Bottom Longline Fishery 1994-2007. Individual plots by year and in some locations were not possible because of vessel confidentiality.

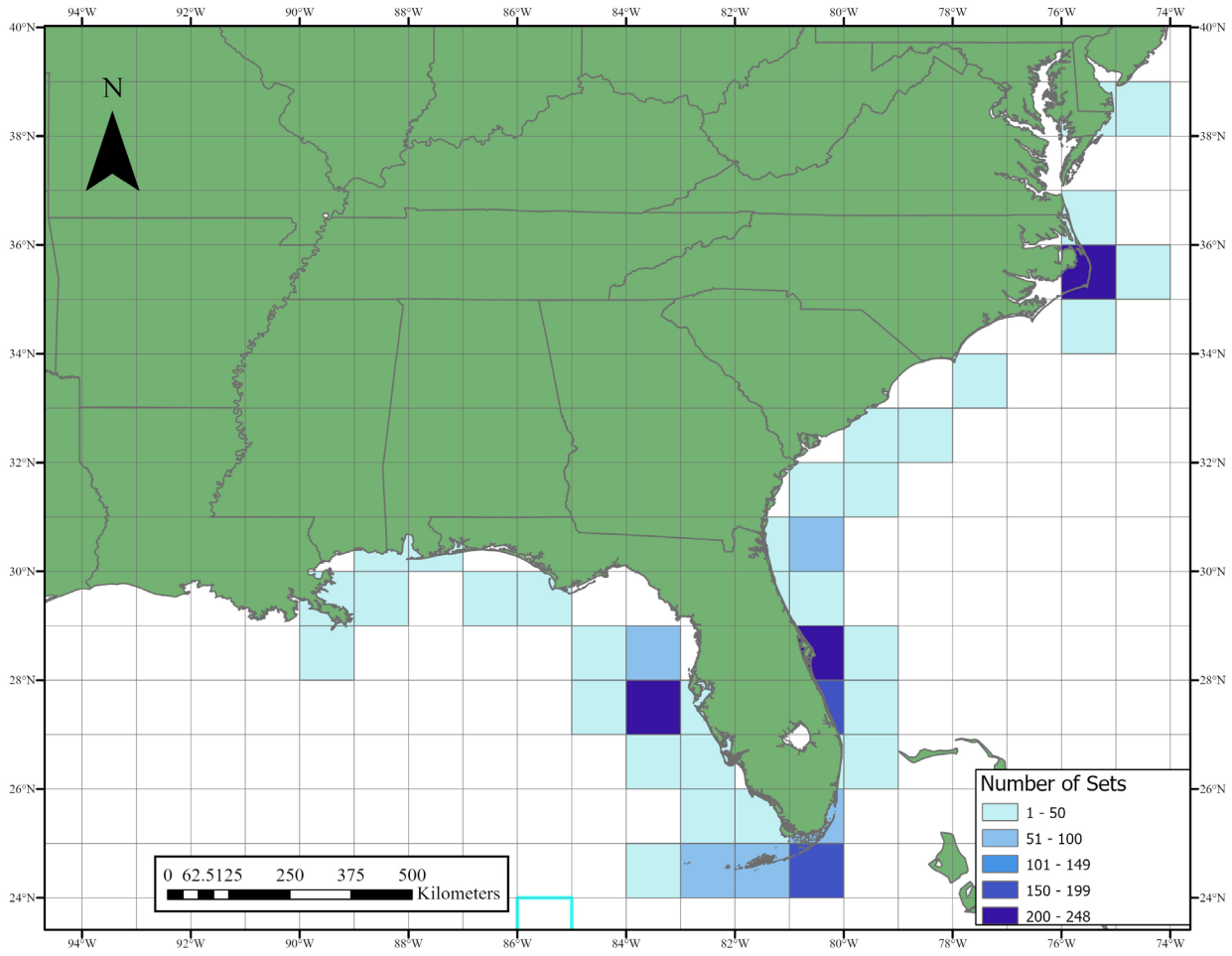

Figure 2. Distribution of fishing effort in the Shark Research Fishery 2008-2025. Individual plots by year and in some locations were not possible because of vessel confidentiality.

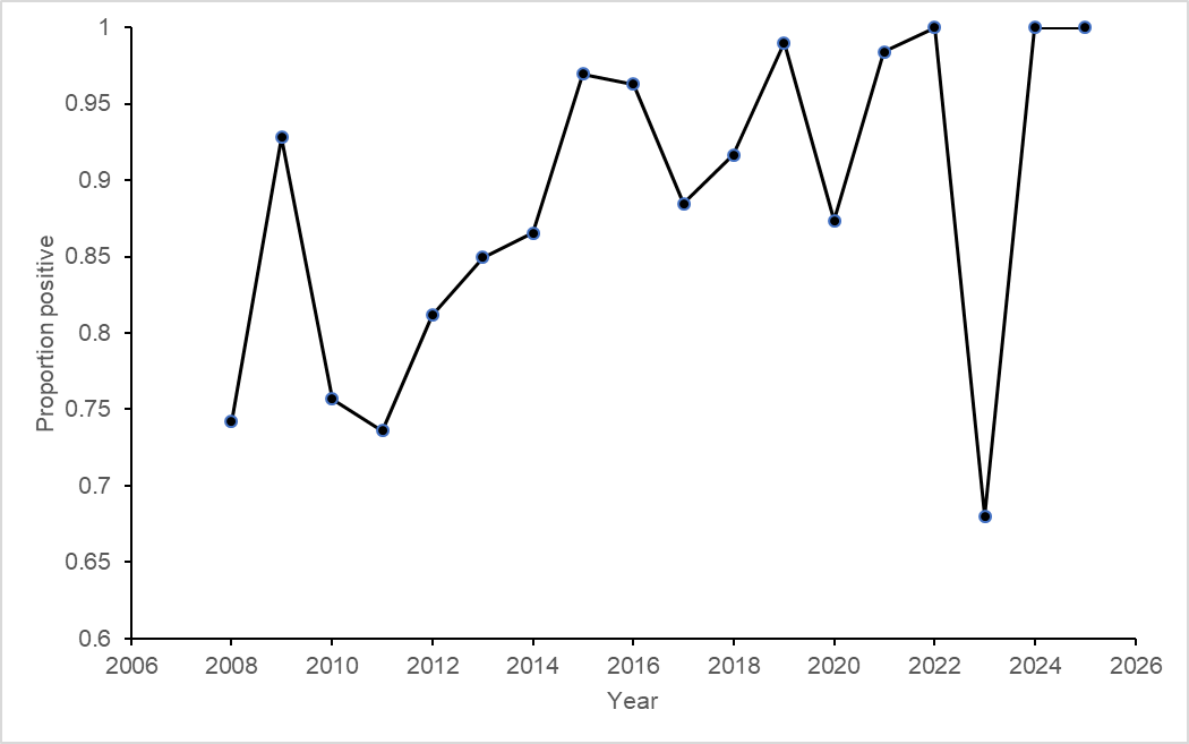

Figure 3. Proportion positive of total sandbar catches per set per year.

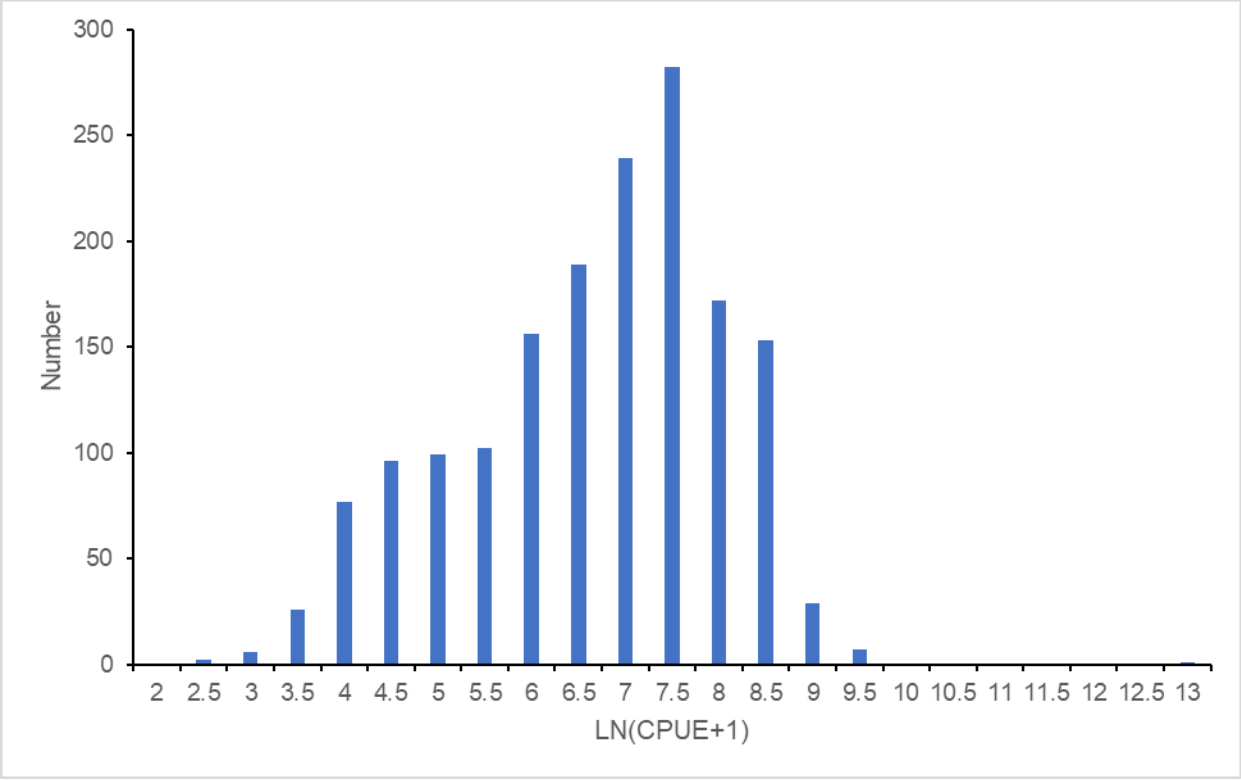

Figure 4. Distribution of CPUE (log of the number of sandbar sharks caught per 10,000 hooks +1).

Table 1. Analysis of deviance of explanatory variables for the binomial and lognormal generalized linear model formulations of the proportion of positive and positive catches of sandbar shark from the Shark Bottom Longline Fishery. Model in bold is the final selected model.

Proportion positive-Binomial error distribution						
FACTOR	**AIC**	**DEVIANCE/DF**	**%DIFF**	**DELTA%**	**CHISQUARE**	**PR>CHI**
NULL		1.2343				
YEAR	1764.3	1.1912	3.492	3.492	78.44	<.0001
YEAR+						
SOAK	1477.5	0.9922	19.614	16.122	288.76	<.0001
TIME	1654.6	1.1147	9.690		111.68	<.0001
DEPTH	1682.3	1.1327	8.231		87.97	<.0001
BAIT	1714.4	1.1555	6.384		53.9	<.0001
AREA	1745.9	1.1779	4.569		20.36	<.0001
HOOKTYPE	1755.4	1.1839	4.083		12.87	0.0016
SEASON	1759.9	1.1864	3.881		10.44	0.0151
YEAR+SOAK+						
TIME	**1439.3**	**0.9636**	**21.931**	**2.317**	**44.2**	**<.0001**
DEPTH	1450.3	0.9726	21.202		29.22	<.0001
BAIT	1471.8	0.9868	20.052		9.77	0.0075
AREA	1471.2	0.9871	20.028		8.31	0.0039
HOOKTYPE	1477.0	0.9897	19.817		6.52	0.0887
SEASON	1479.3	0.992	19.631		2.27	0.3207

Proportion positive-Lognormal error distribution						
FACTOR	**AIC**	**DEVIANCE/DF**	**%DIFF**	**DELTA%**	**CHISQUARE**	**PR>CHI**
NULL		1.7445				
YEAR	3694.7	1.6901	3.118	3.118	47.73	<.0001
YEAR+						
SOAK	**3647.0**	**1.6165**	**7.337**	**4.219**	**49.7**	**<.0001**
AREA	3658.5	1.6336	6.357		38.17	<.0001
DEPTH	3677.9	1.6598	4.855		22.79	<.0001
BAIT	3688.0	1.6768	3.881		10.68	0.0048
HOOKTYPE	3692.5	1.6837	3.485		6.19	0.0453
SEASON	3696.0	1.6877	3.256		4.61	0.2026
TIME	3696.5	1.6915	3.038		0.13	0.7222

Table 2. Analysis of deviance of explanatory variables for the lognormal generalized linear model formulations of sandbar shark from the Shark Research Fishery. Model is bold is the final selected model.

Lognormal error distribution						
FACTOR	AIC	DEVIANCE/DF	%DIFF	DELTA%	CHISQUARE	PR>CHI
NULL		1.4881				
YEAR	4463.0	1.3587	8.696	8.696	145.58	<.0001
YEAR+						
SEASON	4341.7	1.2444	16.377	7.681	127.23	<.0001
TARGET	4411.0	1.3079	12.109		55.94	<.0001
DEPTH	4427.8	1.3245	10.994		37.13	<.0001
SOAK	4436.3	1.3324	10.463		28.63	<.0001
HOOKSIZE	4443.1	1.3379	10.093		23.87	<.0001
AREA	4453.3	1.3486	9.374		11.65	0.0006
BAITTYPE	4457.3	1.3514	9.186		9.69	0.0079
HOOK_TYPE	4464.8	1.3595	8.642		0.19	0.664
TIME	4464.9	1.3597	8.628		0.04	0.8419
YEAR+SEASON+						
TARGET	**4300.0**	**1.2065**	**18.923**	**2.547**	**45.78**	**<.0001**
SOAK	4310.9	1.2167	18.238		32.84	<.0001
DEPTH	4322.2	1.2264	17.586		21.59	<.0001
HOOKSIZE	4324.5	1.2277	17.499		21.2	<.0001
BAITTYPE	4326.9	1.2297	17.364		18.88	<.0001
AREA	4326.9	1.2306	17.304		16.8	<.0001

Table 4. Analyses of generalized linear mixed model formulations for sandbar shark catch rates from the Shark Bottom Longline and Shark Research Fishery. An asterisk indicates that the iteration limit was exceeded or the negative of the Hessian was not positive definite and the model output was deemed questionable. RLL= -2 Residual Log-Likelihood, BIC=Bayesian information criterion, AIC= Akaike's information criterion. Final model selected is in bold

Data Series	Error structure	Model	RLL	BIC	AIC
Shark Bottom Longline Fishery	Binomial	**YEAR+SOAK+DEPTH**	**12361.9**	**12369.2**	**12363.9**
		YEAR*SOAK	7911.5	7916.8	7915.5
		YEAR*DEPTH	*		
	Lognormal	**YEAR+SOAK**	**3676.6**	**3683.6**	**3678.6**
		YEAR*SOAK	3676.6	3683.6	3678.8
Shark Research Fishery	Lognormal	YEAR+SEASON+TARGET	2483.9	2491.3	2485.9
		YEAR*SEASON	**2462.6**	**2470.8**	**2466.6**
		YEAR*TARGET	2474.2	2480.8	2478.2

Table 5. The standardized index (number of sharks per 10,000 hooks per year) of relative abundance, the upper (UCL) and lower (UCL) 95% confidence limits and coefficients of variation (CV) for sandbar shark for the Shark Bottom Longline Fishery.

Year	N	Standardized Index	LCL_mean	UCL_mean	CV
1994	102	185.207	101.365	338.396	0.308
1995	162	257.307	201.242	328.991	0.123
1996	126	183.460	131.580	255.797	0.167
1997	80	296.982	201.864	436.920	0.195
1998	110	268.160	127.472	564.122	0.385
1999	99	264.660	156.455	447.700	0.267
2000	64	198.071	105.324	372.487	0.324
2001	77	431.735	259.692	717.756	0.258
2002	132	250.423	181.682	345.171	0.161
2003	174	344.920	272.879	435.979	0.118
2004	122	313.733	243.416	404.362	0.127
2005	114	349.339	254.316	479.866	0.160
2006	117	318.894	231.193	439.864	0.162
2007	63	534.181	372.908	765.199	0.181

Table 6. The standardized index (number of sharks per 10,000 hooks per year+1) of relative abundance, the upper (UCL) and lower (UCL) 95% confidence limits and coefficients of variation (CV) for sandbar shark for the Shark Research Fishery

Year	N	Standardized Index	LCL_mean	UCL_mean	CV
2008	62	6.357	5.735	6.979	0.05
2009	111	6.369	5.792	6.945	0.05
2010	185	6.380	5.973	6.787	0.03
2011	235	6.114	5.715	6.513	0.03
2012	85	6.448	6.001	6.895	0.04
2013	93	5.875	5.416	6.335	0.04
2014	104	6.265	5.790	6.740	0.04
2015	99	6.678	6.242	7.114	0.03
2016	81	6.399	5.942	6.856	0.04
2017	104	6.509	6.067	6.950	0.03
2018	108	6.600	6.161	7.040	0.03
2019	100	6.737	6.279	7.194	0.03
2020	79	6.257	5.723	6.791	0.04
2021	62	6.801	6.277	7.324	0.04
2022	34	6.861	6.020	7.702	0.06
2023	25	6.077	5.458	6.697	0.05
2024	37	7.125	6.560	7.691	0.04
2025	32	6.678	6.016	7.341	0.05

Figure 4. The standardized relative abundance index (index/mean of the index) for sandbar shark. The index for sandbar shark from SEDAR 54 is provided as a comparison.

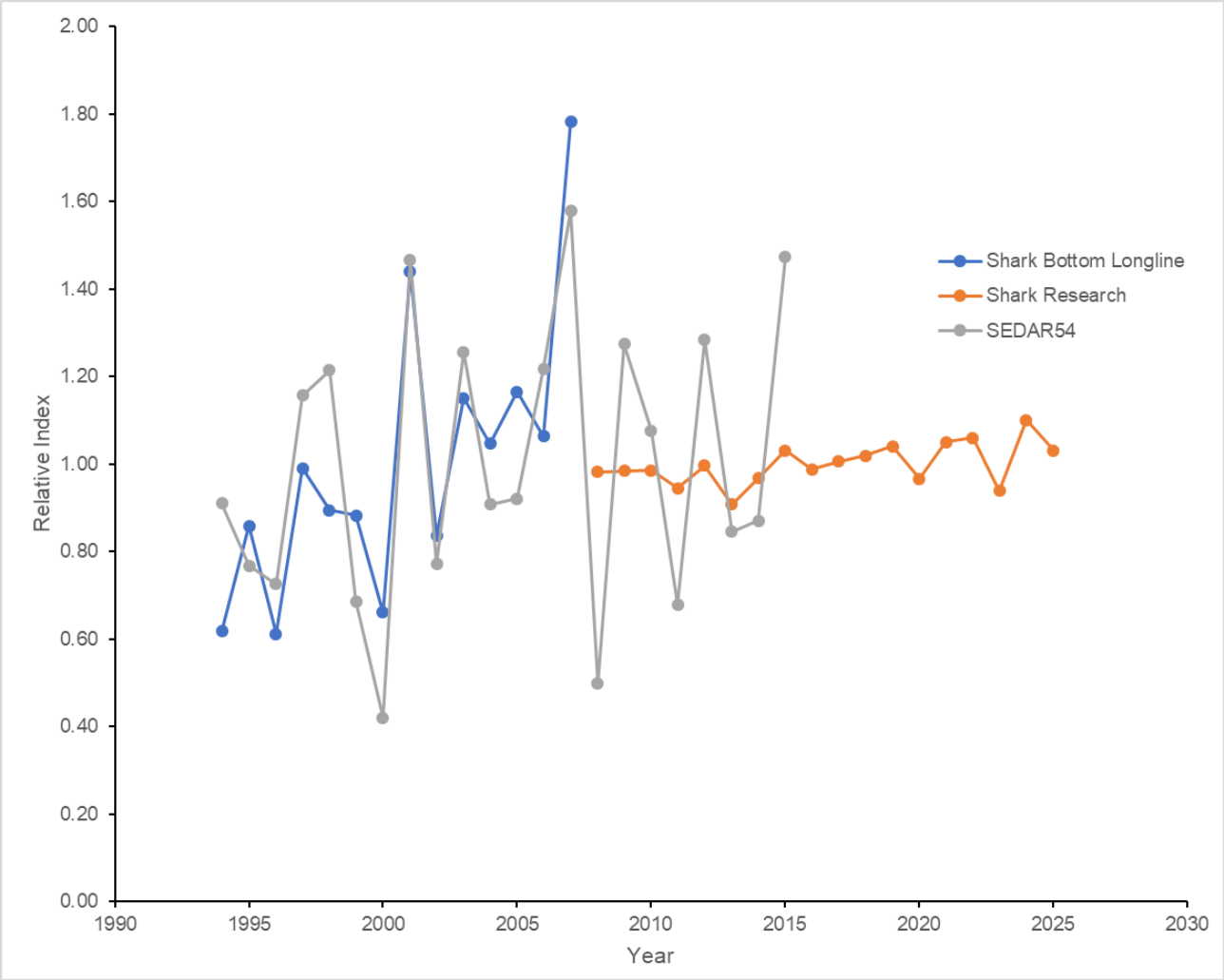

Figure 5. Retrospective analysis of the shark bottom longline index of abundance for sandbar shark.

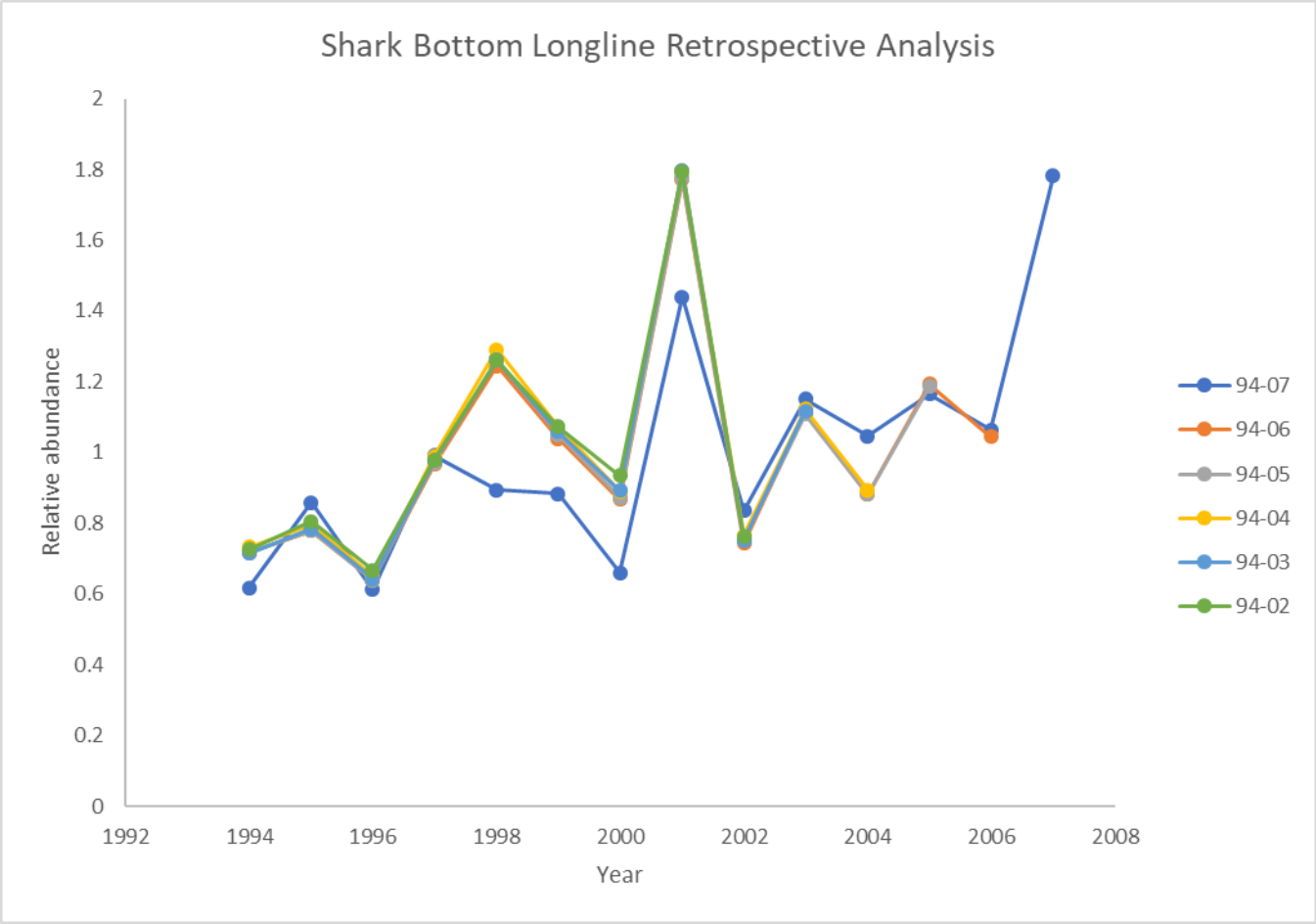

Figure 6. Diagnostic plots from the lognormal model for sandbar shark from the Shark Bottom Longline Fishery.

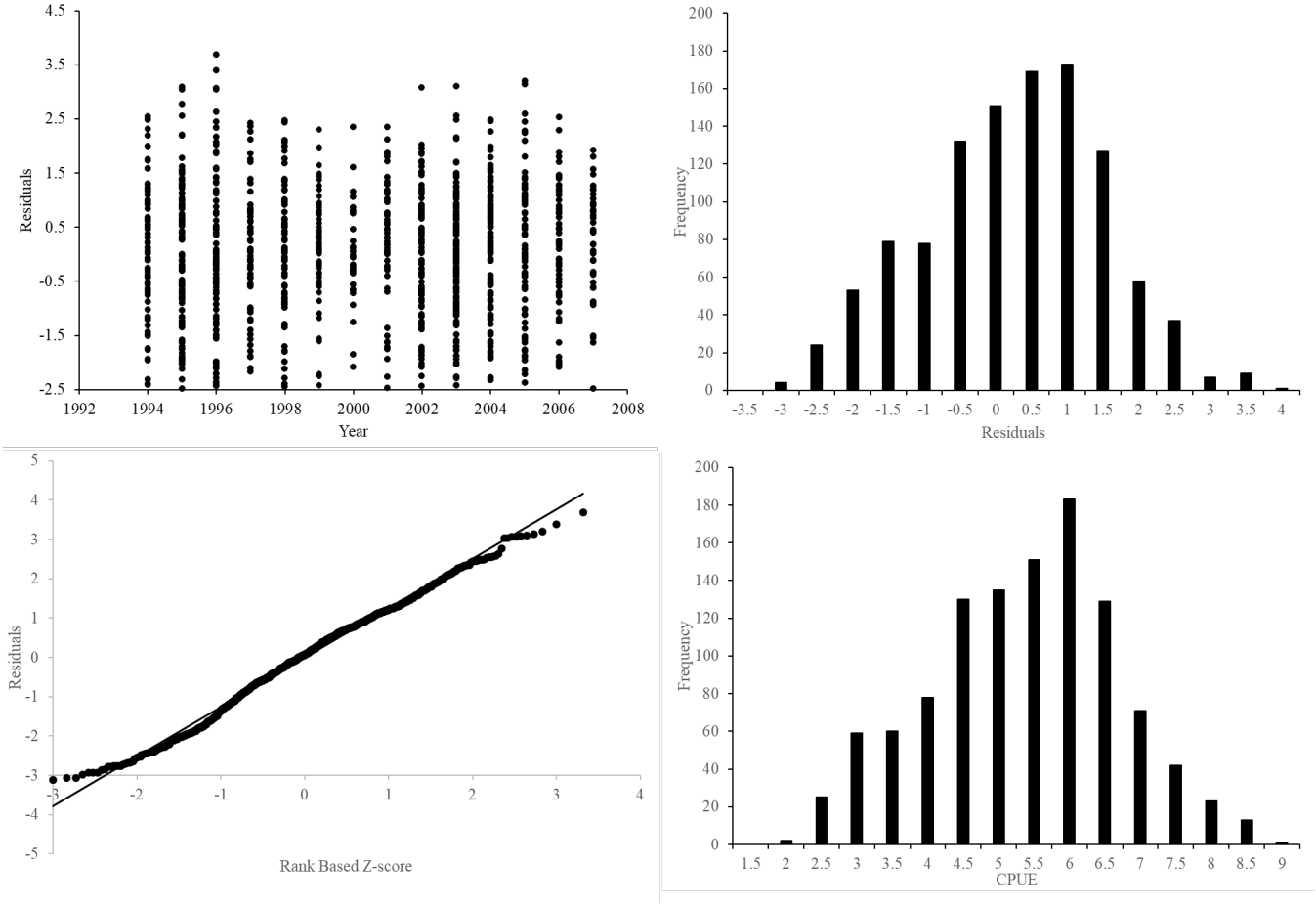

Figure 7. Diagnostic plots from the lognormal model for sandbar shark from the Shark Research Fishery.