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ARTICLE

Long-term trends of bull shark (*Carcharhinus leucas*) in estuarine waters of Texas, USA

John T. Froeschke, Bridgette F. Froeschke, and Charlotte M. Stinson

Abstract: Increases in standardized catch per unit effort (CPUE) and mean length of bull shark (*Carcharhinus leucas*) were observed in coastal estuaries over a 35-year period (1976–2010). Trends in abundance and size were examined using fisheries-independent data from a long-term monitoring survey in Texas, USA. Catch, effort, and environmental covariates that affect bull shark distribution were used to create a standardized index of abundance. Increases in abundance and mean length were detected, potentially due to the initiation of federal management and restrictions on the use of gill nets in nearby Louisiana, USA, waters in 1995. This study provides a long-term perspective of two important demographic indicators (abundance and mean size) of bull shark and provides an encouraging signal in the Gulf of Mexico for a species whose stock status is unknown yet considered near threatened on the International Union for Conservation of Nature red list. Continuing research is needed to gauge effects of management and environmental impacts on shark resources as well as investigations into ecosystem effects of increasing predatory density in coastal waters.

Résumé : Des augmentations des prises par unité d'effort (CPUE) normalisées et de la longueur moyenne des requins bouledogues (*Carcharhinus leucas*) ont été observées dans les estuaires côtiers sur une période de 35 ans (1976–2010). Les tendances de l'abondance et de la taille ont été examinées à la lumière de données indépendantes des pêches provenant d'une étude de surveillance à long terme au Texas (États-Unis). Les prises, les efforts et des covariables relatives aux conditions ambiantes qui ont une incidence sur la répartition du requin bouledogue ont été utilisés pour créer un indice d'abondance normalisé. Des augmentations de l'abondance et de la longueur moyenne ont été décelées qui pourraient découler de l'entrée en vigueur, en 1995, de mesures de gestion et de restrictions relatives à l'utilisation de filets maillants imposées par le gouvernement fédéral dans les eaux de l'État voisin de la Louisiane. L'étude jette un éclairage à long terme sur deux indicateurs démographiques importants (l'abondance et la taille moyenne) des requins bouledogues et fait ressortir des signes encourageants dans le golfe du Mexique pour cette espèce qui, bien que son statut soit inconnu, figure sur la liste rouge de l'Union Internationale pour la Conservation de la Nature comme étant quasi menacée. Au vu des résultats, il apparaît nécessaire de poursuivre les travaux visant à évaluer les effets de la gestion et les impacts environnementaux sur les ressources de requins ainsi que les effets écosystémiques de l'augmentation de la densité de prédateurs dans les eaux côtières. [Traduit par la Rédaction]

Introduction

In the western Atlantic Ocean, dramatic declines of coastal sharks have been reported by several investigators (Baum et al. 2003; Shepherd and Myers 2005; Baum and Blanchard 2010), although the severity of these declines have been questioned, especially in reference to coastal species (Burgess et al. 2005*a*, 2005*b*). Previous investigators have focused on oceanic species, but several coastal stocks have also been characterized as depleted (SEDAR 2006). More recent analyses of trends in abundance of oceanic and coastal sharks in the northwest Atlantic Ocean also suggest substantial declines in shark stocks over the previous two decades (Baum and Blanchard 2010). Baum and Blanchard (2010) incorporated multiple data sources and accounted for variability in environmental conditions, location, and fishery characteristics (e.g., hook type, bait species) affecting catch rates — factors that limited previous examinations of shark fisheries. However, Carlson et al. (2012) reviewed fishery data from the bottom longline shark fishery off of the US east coast and reported increasing catch per unit effort (CPUE) for large bull shark (*Carcharhinus lecuas*), spinner shark (*Carcharhinus brevipinna*), tiger shark (*Galeocerdo civier*), and lemon shark (*Negaprion brevirostris*) from 1994 to 2009. Despite long periods of inquiry, considerable uncertainty remains concerning the status of coastal stocks in many regions, especially for those stocks of ecological or fisheries importance (Lotze et al. 2011; Fig.1). For large coastal sharks in the US Atlantic and Gulf of Mexico, only blacktip shark (*Carcharhinus limbatus*), sandbar shark (*Carcharhinus plumbeus*), and scalloped hammerhead (*Sphyrna lewini*) have been assessed on a single-species basis, with the latter three species being characterized as overfished (Hayes et al. 2009; SEDAR 2011; SEDAR 2012). In the United States, ten species of large coastal sharks are managed as a group. The status of this group (collectively and individually) is undetermined as of the most recent stock assessment (SEDAR 2006). Bull shark is a prominent species in the large coastal species group, yet temporal patterns of abundance and size structure are uncertain for this species in the Gulf of Mexico (SEDAR 2006).

Despite the uncertainty of bull shark population status, there is ample cause for concern. Shepherd and Myers (2005) reported reductions in shallow water coastal elasmobranchs (Bancroft's numbfish (*Narcine bancroftii*), Atlantic sharpnose shark (*Rhizoprionodon terraenovae*), southern stingray (*Dasyatis americana*), cownose ray (*Rhinoptera bonasus*), bluntnose stingray (*Dasyatis say*), smooth butterfly ray (*Gymnura micura*), bonnethead (*Sphyrna tiburo*), scal-

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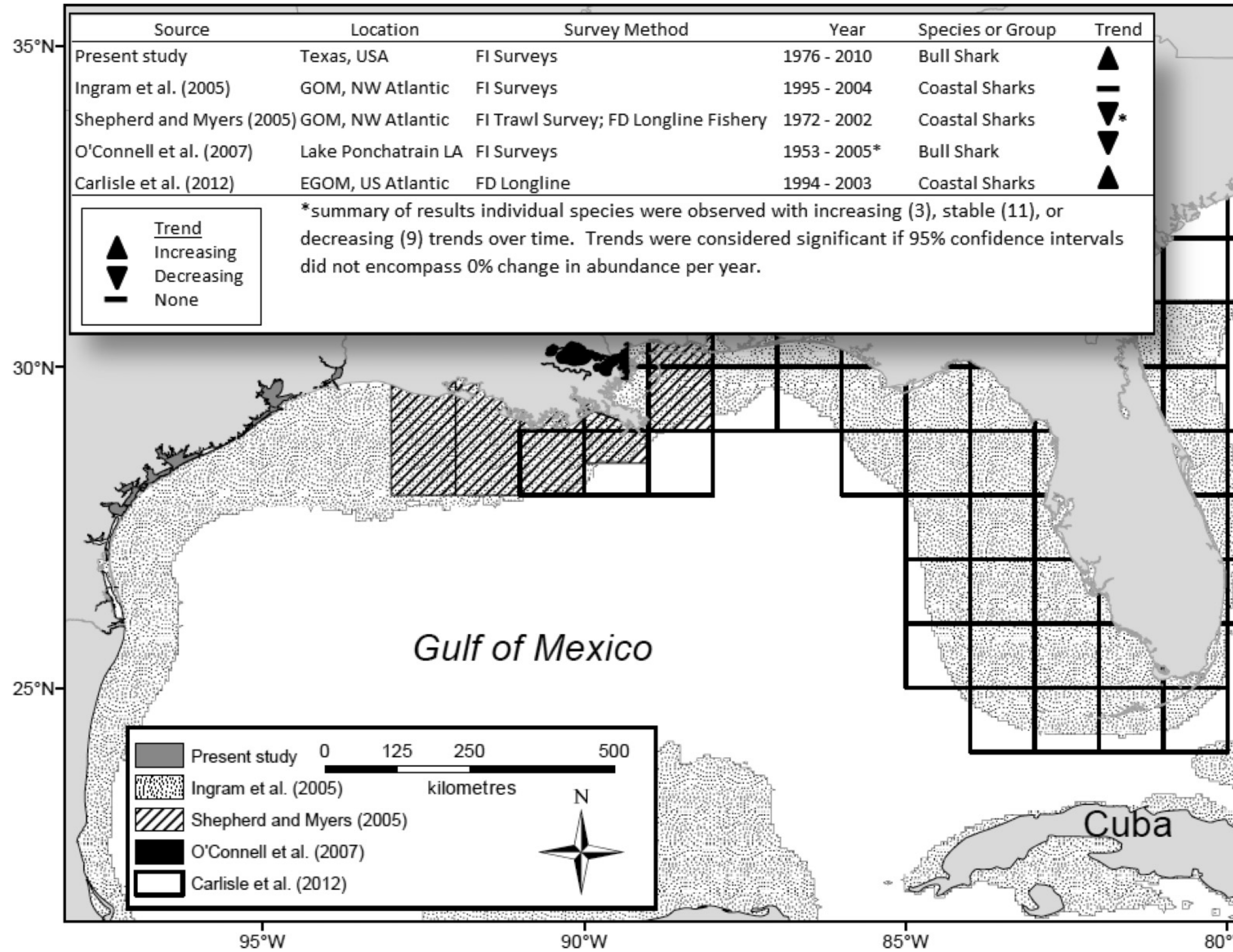
J.T. Froeschke. Gulf of Mexico Fishery Management Council, 2203 N. Lois Avenue, Suite 1100, Tampa, FL 33607, USA.
B.F. Froeschke. University of South Florida, Fla. Center for Community Design and Research, 4202 East Fowler Avenue, HMS 301, Tampa, FL 33620, USA.
C.M. Stinson. University of Tampa, College of Natural and Health Sciences, 401 W. Kennedy Boulevard, Tampa, FL 33606, USA.
Corresponding author: John T. Froeschke (e-mail: john.froeschke@gulfcouncil.org).

Fig. 1. Summary of recent studies examining trends of abundance of coastal sharks in the Gulf of Mexico. Approximate geographic location of relevant studies, survey methodology, study period, species examined, and abundance trends are identified.



loped hammerhead (*Sphyrna lewini*), and silky shark (*Carcharhinus falciformis*)) in the northern Gulf of Mexico and attributed this to bycatch mortality from the shrimp fishery, among other factors. O'Connell et al. (2007) reported long-term declines of bull shark and alligator gar (*Atractosteus spatula*) in southeastern Louisiana owing to poor management and environmental degradation. However, this decline was driven by catches of only a few individuals in the early years of the study and encompassed limited geographic coverage. In contrast, an investigation of bull shark nursery use in adjacent Texas' coastal waters indicated increased CPUE of juveniles over the same time period (Froeschke et al. 2010*b*).

Changes in catch rates alone may be inadequate to assess demographic trends for a given species (Walters 2003; Baum and Blanchard 2010). Size structure of a fish population can also provide an indirect measurement of exploitation pressure (McClenachan 2009). Collectively, changes in catch rate and size structure over time can be integrated to develop an enhanced perspective about trends in population abundance or biomass. For example, a population experiencing an increasing catch rate and mean size could be a positive indicator of increasing population size, while increasing catch rates and declining size is consistent with juvenescence, often an indicator of intense exploitation (Hidalgo et al. 2011).

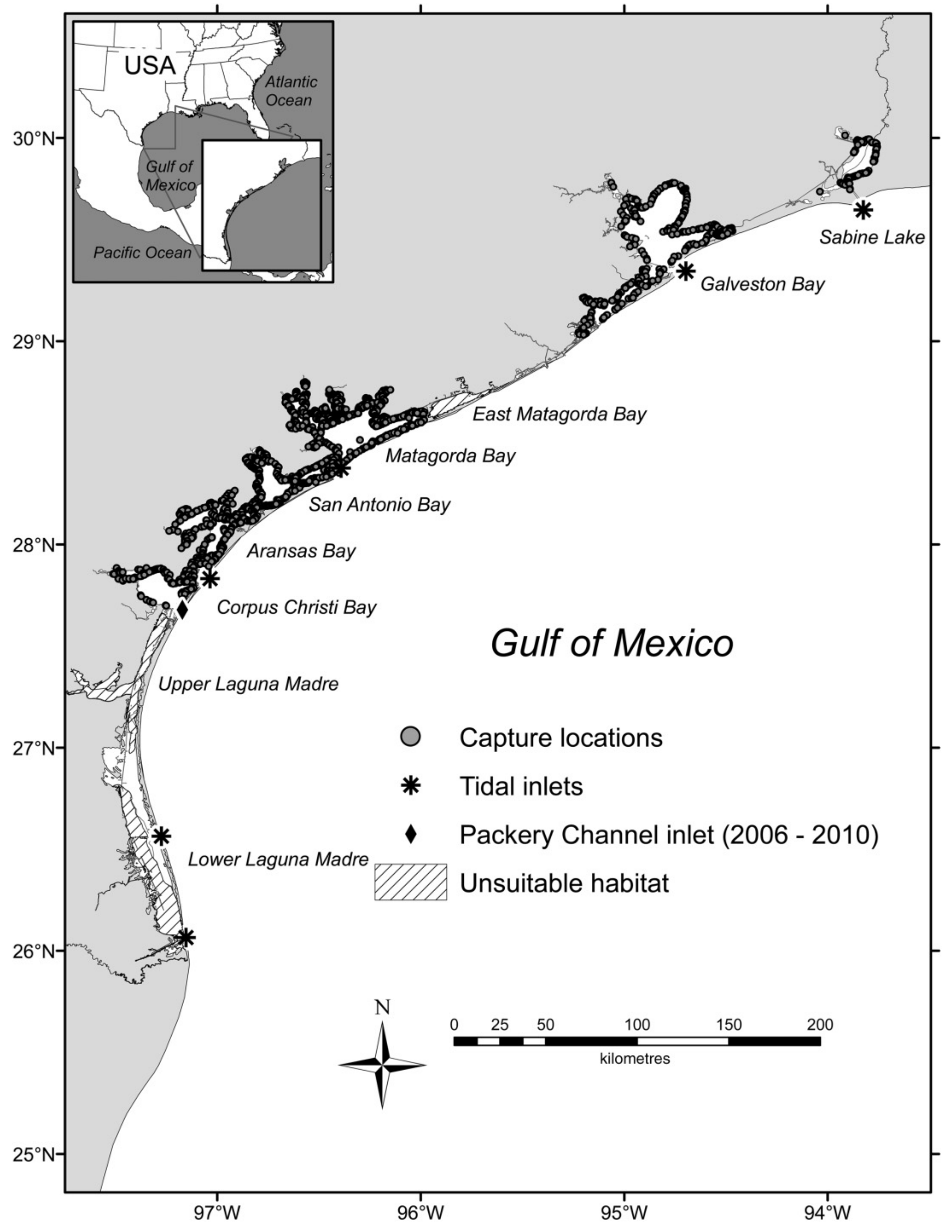
The purpose of this study was to assess spatial and temporal trends in bull shark abundance and size structure in estuaries in Texas, USA. This was facilitated by using long-term (35-year), fishery-independent data with a consistent, scientifically based survey design. The use of fisheries-independent data can provide insight about both trends in size and abundance of an important coastal predator in a region with the potential of fisheries-induced or environmentally driven depletion.

Materials and methods

Study area

This study was conducted in major estuarine systems along the coast of Texas, USA (Fig. 2). Texas estuaries are shallow, subtropical systems that are physically dynamic, and most are located near large human population centers (Froeschke and Froeschke 2011). Froeschke et al. (2010*a*) reported that three estuarine systems in the study area were largely unsuitable for bull sharks because of environmental conditions, namely hypersalinity (Upper and Lower Laguna Madre), or shallow depths that were distant from access points to the Gulf of Mexico (East Matagorda Bay). Therefore, we did not include samples from these systems in our analyses. The spatial and temporal distribution of bull sharks within six remaining estuaries in which bull sharks regularly occur were analyzed using data from 1976 to 2010 to examine spatial or temporal changes in size and abundance of bull shark as an indicator of population trends of a coastal apex predator.

Fig. 2. Coastal shark gill-net survey locations (n = 16 169) from 1976 to 2010 in Texas, USA. Filled gray circles indicate sample locations where bull sharks (*Carcharhinus leucas*) where captured. Estuaries are connected to the Gulf of Mexico through six tidal inlets, from north to south: Sabine Pass, Galveston Pass, Matagorda ship channel, Aransas Pass, Mansfield Pass, and Brazos Santiago Pass. Areas considered unsuitable were due to hypersalinity or shallow depths distant from oceanic connections.



Field collections

Bull shark catch data were obtained from the coast-wide, gill-net survey conducted by Texas Parks and Wildlife Department that was established in Texas in 1975 and continues presently. For this study, data were included from 1976 to 2010 (sampling in 1975 was incomplete), although sampling in Sabine Lake was not initiated until 1985. Data were collected using a stratified cluster sampling design; each estuary is a nonoverlapping strata with a fixed number of samples (n = 45 per estuary per season; n = 20 per estuary per season in Sabine Lake). Gill nets were deployed each spring (April, May, June) and fall (September, October, November). Sample locations were drawn independently and without replacement for each season (Martinez-Andrade et al. 2009). Bull sharks were sampled using standardized, 183 m gill nets set perpendicular to shore. Nets were constructed of four panels with stretched mesh sizes of 76, 102, 127, and 152 mm. Gill nets were deployed 1 hour before sunset, fished overnight, and retrieved within 4 h of sunrise the following day. A total soak time was calculated for each sample. Each captured shark was identified to species and measured to the nearest 1 mm (stretch total length (TL)).

A standardized index of abundance was developed to examine change in CPUE over time (Lo et al. 1992). We standardized these data to account for changes in catch that were unrelated to abundance (Table 1). Bull sharks are strongly influenced by environmental conditions, including temperature (Matich and Heithaus 2012) and salinity (Froeschke et al. 2010*a*), and may also be influenced by seasonal patterns (i.e., month sampled). Salinity and temperature were measured concomitantly with each sample and were considered as explanatory variables in the index. A factor variable was created for each month sampled March–May and September–November. Area was included as a spatial covariate to account for variation in catchability across estuaries. Soak time

Table 1. Predictors used in the development of standardized catch-per-unit-effort (CPUE) index for bull shark (*Carcharhinus leucas*) in estuaries in Texas, USA, from 1976 to 2010.

Variable	Description	Mean	Range
Year	Year sample occurred	NA	1976–2010
Month	Month sample occurred	NA	Mar.–May, Sept.–Nov.
Temperature	Surface temperature at offshore end of gill net	25.9	5.5–37.8
Salinity	Surface salinity at offshore end of the gill net	18.8	0–49
Soak time	Number of hours gill net was deployed	13.6	9.9–25.2
Area	Estuary where sample occurred	NA	NA

Note: NA, not applicable.

was included as a covariate in the model to control for effort related effects on catch rates (Maunder and Punt 2004).

We used a zero-altered negative binomial model (Zeileis et al. 2008) to develop a standardized index of abundance. This method combines two generalized linear models: an analysis of the probability of capture and a second analysis of the number of individuals captured in positive samples. Model selection was performed separately for each model using a forward stepwise procedure using Akaike's information criterion (AIC) and a log-likelihood ratio test to determine whether more complex models were warranted. Fixed factors were added in order of importance as determined by the full model (i.e., all fixed factors and year × area interaction) with the caveat that year was included in all models. This procedure was carried out for both the binomial (all samples) and negative binomial (positive samples) generalized linear models. The delta model (combining binomial and negative binomial models) is the product of fitted values from the binomial and negative binomial model for each observation. Count data can be modeled with a Poisson distribution; however, the variability of the fitted values was greater than the expected variance based on a Poisson process. A negative binomial distribution accommodates this by fitting an additional parameter allowing for a quadratic mean–variance relationship. The improvement to the model from the additional variance parameter was evaluated by comparing the full model with a negative binomial and Poisson distribution using a log-likelihood ratio test and visual inspection of the residuals. The final zero-altered negative binomial was fit using the "hurdle" function in the pscl library (Zeileis et al. 2008) in R 2.13.1 (R Development Core Team 2009).

Each bull shark captured in this study was measured to the nearest 1 mm stretch total length and changes in mean length were examined over time for each estuary. Bull shark CPUE was aggregated into an annual mean value per estuarine system. Preliminary analyses of bull shark lengths indicated that model residuals were not normally distributed, variance differed among estuaries, and residuals were correlated. Weighted least squares with restricted maximum likelihood estimation were used with the following model:

$$y_{ij} = a_i + b_j + ab_{ij} + \varepsilon_{ij}$$

where y_{ij} is length for estuary i in year j, a_i is the effect of estuary i, i = 1, . . ., 6 m, b_j is the effect of year j, j = 1976 . . . 2010, ab_{ij} is the interaction effect of estuary with year, and ε_{ij} is the residual for estuary i in year j. Residuals were given an exponential correlation structure that accounts for year-to-year correlation, yet accommodates missing values (sharks were not captured in all estuaries in all years) where the correlation between two observations a distance r apart over range d is $\varepsilon_{ij}\,(j + r) = e^{(-r/d)}, \eta_{ij} \sim N(0, \sigma^2_{\eta i})$.

AIC and a log-likelihood ratio test were used to determine whether the more complex variance and (or) error structures was warranted. Nonparametric bootstrapping with replacement (n = 1000) was used to estimate confidence intervals of model parameters without making assumptions about the population distribution (Efron and Tibshirani 1993). Analyses were conducted in R 2.13.1 (R Development Core Team 2009) with functions from the "mgcv" (Wood 2008) and "nlme" (Pinheiro et al. 2008) libraries.

Table 2. Sample size and proportion of samples with captures for bull shark in estuaries in Texas, USA, from 1976 to 2010.

Year	n	Proportion positive
1976	83	0.14
1977	91	0.23
1978	99	0.16
1979	180	0.15
1980	140	0.15
1981	285	0.16
1982	450	0.23
1983	450	0.20
1984	450	0.24
1985	450	0.23
1986	540	0.11
1987	539	0.08
1988	539	0.12
1989	540	0.13
1990	540	0.15
1991	540	0.12
1992	540	0.12
1993	540	0.15
1994	539	0.12
1995	540	0.12
1996	540	0.14
1997	540	0.10
1998	540	0.15
1999	539	0.21
2000	540	0.19
2001	540	0.16
2002	540	0.20
2003	539	0.23
2004	538	0.28
2005	540	0.23
2006	540	0.29
2007	540	0.25
2008	538	0.23
2009	540	0.23
2010	540	0.30

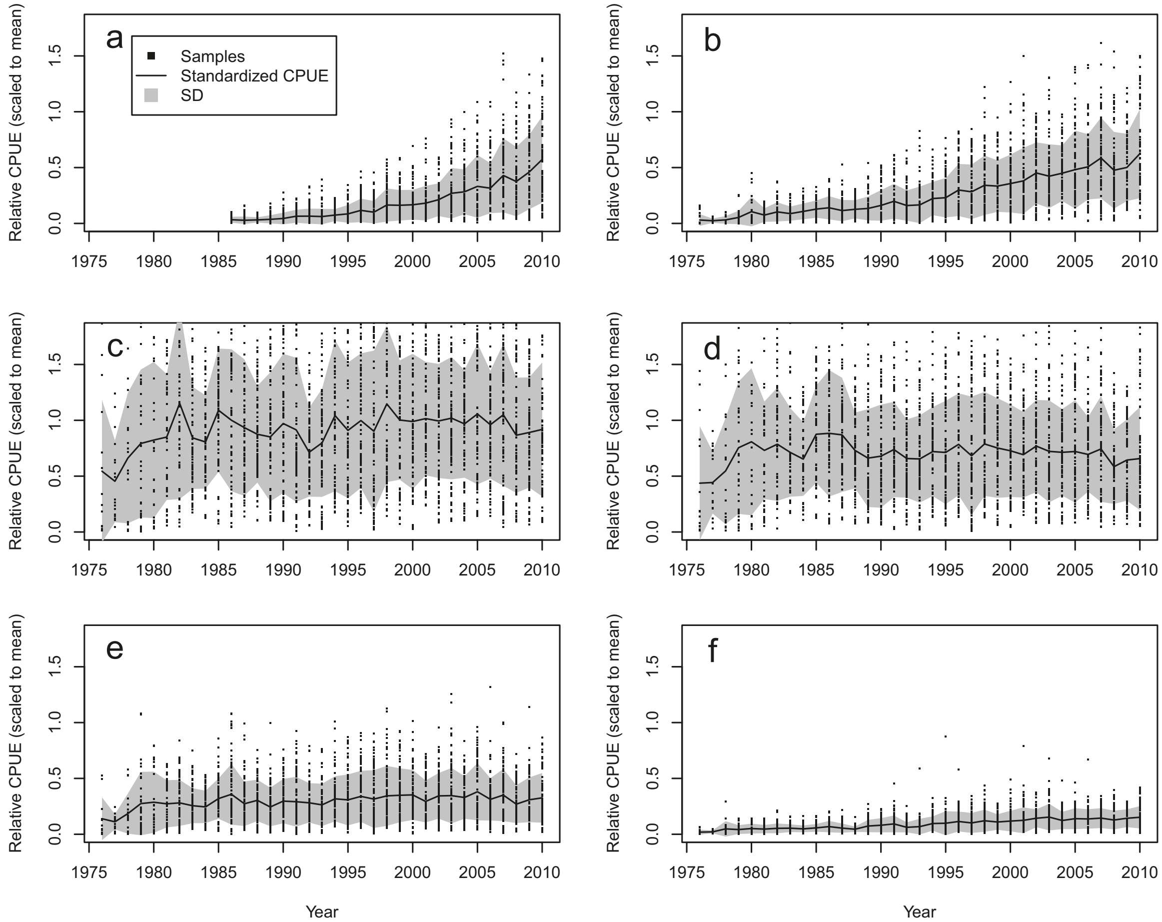
Results

Time series analysis

Gill nets were fished at 16 169 sites across six estuaries along the Texas coast from 1976 to 2010. Overall, bull sharks were captured at 18% of the sites (n = 2920) and 6970 individuals were captured (Fig. 2); the proportion of positive samples ranged from 0.08 in 1987 to 0.30 in 2010 (Table 2). Abundance of bull sharks varied widely over time (1976–2010) and among the six estuaries (Fig. 3). CPUE was greatest in Matagorda Bay, lowest in Corpus Christi Bay, and intermediate in Sabine Lake, Galveston Bay, and Aransas Bay.

Change in CPUE over time was modeled using a zero-altered negative binomial model. The stepwise development of the bino-

Fig. 3. Standardized catch per unit effort (CPUE) of bull shark (1976–2010) for six estuaries. Study areas from north to south: Sabine Lake (*a*), Galveston Bay (*b*), Matagorda Bay (*c*), San Antonio Bay (*d*), Aransas Bay (*e*), Corpus Christi Bay (*f*). Solid line indicates fit from zero-altered negative binomial regression model. Gray shaded regions identify the standard deviation (SD) of model fits.



mial and negative binomial submodel are described in Tables 3 and 4 respectively. The full model combining the binomial and negative binomial models is described in Table 5. The fit of the full model was evaluated by examining model residuals as compared with each factor in the model and indicated an acceptable fit. Overdispersion was identified in exploratory analyses and the model fit of the positive samples (Fig. 4). The likelihood ratio test was used to test the difference in log-likelihood between the Poisson and negative binomial distributions used in the positive samples of the full model and indicated an improved fit to these data using the negative binomial distribution for the positive samples (log-likelihood ratio test, $\chi = 1787.6$, df = 1, $p < 0.001$).

Factors that affected probability of occurrence in the binomial model were year sampled, temperature, area, month, salinity, and year × area interaction. A year × area interaction was necessary in the binomial model, as the proportion of positive samples was increasing at different rates across estuarine systems (Table 2). Factors that affected catch in positive samples included were year sampled, salinity, area, and temperature (Table 3).

The standardized CPUE index indicated an increase for each estuary from 1976 to 2010 (Fig. 5). A linear regression over time indicated a significant increase (2.3%·year^{-1}) in standardized CPUE over time (linear regression df = 1,33, $p < 0.001$, $R^2 = 0.63$). However, the magnitude of increase varied by estuary and was greatest in the northern-most estuaries (Sabine Lake and Galveston Bay; Fig. 6). To assess uncertainty of the index, the standard deviation of model fit was determined. Overall, uncertainty increased nonlinearly with the mean and was greatest in Matagorda and San Antonio bays. Uncertainty also increased through time in Sabine Lake and Galveston Bay as standardized CPUE increased.

Length

Length of captured bull sharks ranged from 550 to 2071 mm stretch TL (Fig. 7). A generalized weighted least squares model was used to test for significant increases in length over time (Table 6). A significant increase in bull shark length was detected in Sabine Lake, Matagorda Bay, and Aransas Bay (Fig. 8). As with CPUE, increases in mean length (mm·year^{-1}) was greatest in Sabine Lake (mean + (95% confidence interval: 7.32 (3.67–11.25)), followed by Matagorda Bay (3.07 (2.01–4.09)) and Aransas Bay (slope = 2.55 (0.35–4.73); Fig. 9). No significant difference in mean length over time was detected in Galveston (slope = –1.95 (–5.10–1.53)), San Antonio (slope = 1.28 (–0.28–2.75)), or Corpus Christi Bays (slope = –0.33 (–3.90–3.31)).

Discussion

Increases in standardized CPUE and mean length were observed throughout the study period, and rates of increase may be accelerating in some regions (e.g., Sabine Lake and Galveston Bay) since the mid 1990s. Overall, standardized abundance increased 2.3% annually over a 35-year period on the Texas coast. This period coincides with changes in management (e.g., initiation of federal management and restrictions on the use of gill nets in Louisiana waters in 1995). Pondella and Allen (2008) reported increased CPUE of four coastal predatory species in California, USA, beginning after the 1994 ban of gill nets in nearshore waters. A similar response for bull shark in the northern Gulf of Mexico is plausible.

Table 3. Deviance table for the binomial model of the standardized bull shark CPUE index sampled in six estuaries along the coast of Texas, USA, from 1976 to 2010.

Binomial model factors	df	Residual deviance	Log-likelihood	*p*	ΔAIC
Null	16 168	NA	−7 636.469	NA	—
Year	16 167	15 163	−7 581.564	<0.001	−108
Year + **Temperature**	16 166	14 164	−7 081.902	<0.001	−1105
Year + Temperature + **Area**	16 161	12 751	−1 1078.67	<0.001	−2508
Year + Temperature + Area + **Month**	16 160	12 735	−6 367.353	<0.001	−2522
Year + Temperature + Area + Month + **Salinity**	16 159	12 730	−6 365.235	0.040	−2525
Year + Temperature + Area + Month + Salinity + **Soak time**	16 158	12 728	−6 364.204	0.151	−2525
Year + Temperature + Area + Month + Salinity + **Year × Area**	16 154	12 496	−6 248.222	<0.001	−2749
Year + Temperature + Area + Month + Salinity + Soak Time **Year × Area**	16 153	12 495	−6 247.263	<0.001	−2748
Final model: Proportion positive = Year + Temperature + Area + Month + Salinity + Year × Area					

Note: Factors were added to the model in forward, stepwise regression. A factor was retained if the model was significantly improved based on AIC and log-likelihood ratio test. The variable added to the model is indicated in bold.

Table 4. Deviance table for the negative binomial model of the standardized bull shark CPUE index sampled in six estuaries along the coast of Texas, USA, from 1976 to 2010.

Negative binomial model factors	df	Residual deviance	Log-likelihood	*p*	ΔAIC
Null	2 919	2 463	−11 206		—
Year	2 918	2 475.7	−11 188	<0.001	−16
Year + **Salinity**	2 917	2 497.2	−11 155	<0.001	−47
Year + Salinity + **Area**	2 912	2 551.9	−11 079	<0.001	−113
Year + Salinity + Area + **Temperature**	2 911	2 598.4	−11 010	<0.001	−180
Year + Salinity + Area + Temperature + **Month**	2 910	2 599.6	−11 007	0.112	−181
Year + Area + Temperature + Month + **Soak time**	2 909	2 585	−11 007	0.915	−179
Year + Salinity + Area + Temperature + Month + **Year × Area**	2 905	2 612.3	−10 990	0.004	−175
Year + Salinity + Area + Temperature + Month + Soak time + **Year × Area**	2 904	2 397	−11 001	0.318	−177
Final model: Catch = Year + Salinity + Area + Temperature					

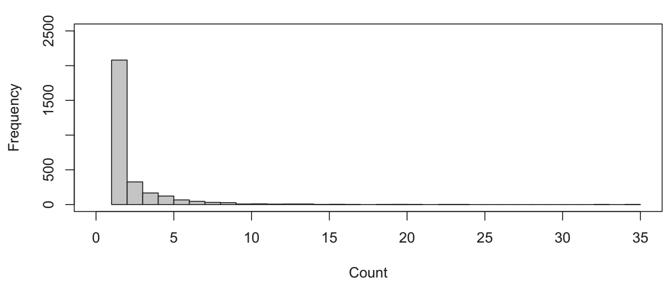
Note: Factors were added to the model in forward, stepwise regression. A factor was retained if the model was significantly improved based on AIC and log-likelihood ratio test. The variable added to the model is indicated in bold.

Table 5. Final model formulation of zero-altered negative binomial model of standardized CPUE index for bull shark.

Count model	Presence model	Distribution	df	AIC
CPUE = Year + Salinity + Area + Temperature	CPUE = Year + Temperature + Area + Month + Salinity + Year × Area	Poisson	24	23 393
CPUE = Year + Salinity + Area + Temperature	CPUE = Year + Temperature + Area + Month + Salinity + Year × Area	Negative binomial	25	21 607

Note: Two nested models were considered that differed only in the distribution of the response variable for the positive samples. The negative binomial distribution allows for a quadratic mean–variance relationship, and the appropriateness of this model was verified using Akaike's information criterion (AIC) and inspection of model residuals.

Fig. 4. Histogram of number of bull sharks in positive captures (n = during the study period).



Sabine Lake and Galveston Bay are proximate to Louisiana, USA, and sharks in these waters had the greatest increase in CPUE and mean size (Sabine Lake). Federal regulations initiated during this period, including reductions in allowable catch in commercial fisheries as well as implementation of minimum size requirement (fork length 1.8 m) for bull shark and bag limit (1·angler^{-1}·day^{-1}) for recreational fisheries, may have also led to increased survivorship for the species (SEDAR 2006). Shepherd and Myers (2005) attributed declines of elasmobranchs in the Gulf of Mexico at least in part to bycatch mortality from shrimp trawls. Shrimp trawl effort has declined precipitously in the Gulf of Mexico over the last decade because of both management and economic conditions.

Environmental factors alone, or in concert with regulatory measures, may also have led to the observed increases in bull shark CPUE. Distribution of bull sharks are strongly affected by environmental conditions (Heithaus et al. 2009; Froeschke et al. 2010*a*; Matich and Heithaus 2012), and the observed increases in CPUE could be manifested by changing environmental conditions in the study area. Estuarine waters in the northern Gulf of Mexico have large intra-annual changes in temperature and salinity (Froeschke and Froeschke 2011), and the frequency of extreme environmental events is predicted to increase (Easterling et al. 2000; Matich and Heithaus 2012).

Examinations of long-term patterns in Texas estuaries indicate increased temperatures (Applebaum et al. 2005), while changes in salinity regime are also possible as a result of increasing demand for fresh water for urban uses or declining precipitation (i.e., increasing salinity) from long-term climate shifts. Froeschke et al. (2010*a*) reported increased probability of occurrence of bull shark capture with increasing temperature and salinity. However, they also suggest thresholds to this pattern and potential severe declines are possible if hypersaline (e.g., <40 psu) conditions become

Fig. 5. Standardized catch per unit effort (CPUE) of bull shark (1976–2010). A linear regression (dashed line) of the over time indicated a significant increase (2.3%·year^{-1}) in standardized CPUE over time (linear regression df = 1, 33; $p < 0.001$, $R^2 = 0.63$).

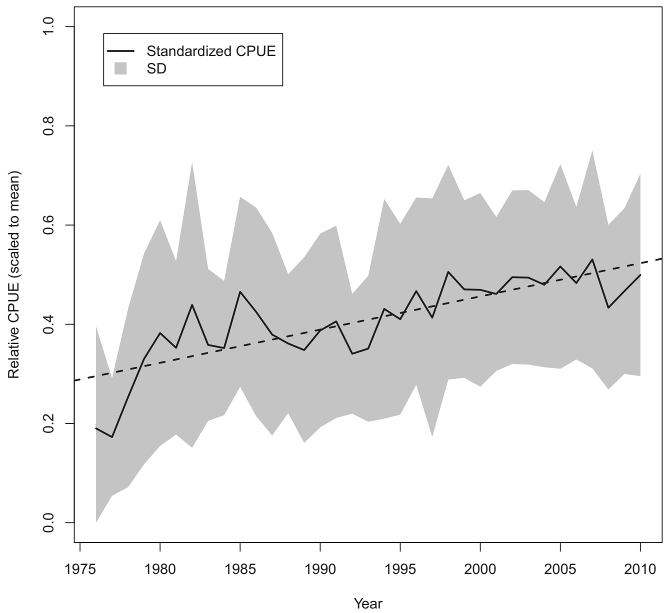
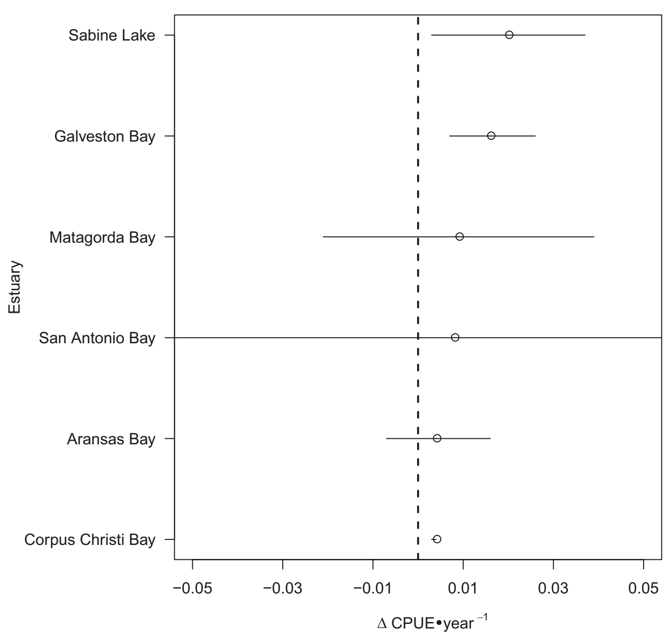


Fig. 6. Instantaneous catch per unit effort (±1 SD) of bull shark for six different estuarine systems off the Texas coast, USA. Vertical dashed line demarcates slope equal to zero (i.e., no change over the study period).



more prevalent or temperatures tolerances (32 °C) are exceeded (Froeschke et al. 2010*a*).

Data presented in this study provide a long-term perspective of demographic trends over three decades for an important coastal predator. To our knowledge, these data represent the longest continuous, fishery-independent survey of nearshore sharks in the Gulf of Mexico. While spatially limited (i.e., Texas coastal waters only) and considering that the gear may not have sampled large (i.e., <2 m TL) individuals well (Carlson and Cortes 2003), these data result from an intense, scientific sampling program — limitations that complicate interpretation of results based on fisheries-dependent information (Marchal et al. 2006; Baum and Blanchard 2010). However, because of the limited spatial coverage of the current study, it alone is inadequate to draw stock-wide inferences about trends in size or abundance of the bull shark population. Ingram et al. (2005) examined catch rate, distribution, and size composition of large coastal shark from longline surveys in the Gulf of Mexico and US Atlantic Ocean and reported an increase in standardized abundance from 1994 to 2005. However, in this study bull shark comprised only 5.5% of the large coastal shark complex; thus, it is difficult to infer patterns of abundance of bull shark from this group index. Carlson et al. (2012) examined shark fishery data in the Gulf of Mexico and western Atlantic and also reported increasing CPUE for bull shark from 1994 to 2009, suggesting that increasing bull shark abundance may not be a localized phenomenon. Our results support a similar conclusion while encompassing a much longer time series from which to gauge results in light of the "shifting baselines" phenomenon (Jackson et al. 2001). Despite this encouraging signal, others have reported dramatic declines of coastal sharks over similar time periods in the same region. Shepherd and Myers (2005) reported significant declines of nine species of elasmobranchs in the Gulf of Mexico, although bull shark was sparsely sampled. O'Connell et al. (2007) reported a decline in bull shark in Louisiana, but sampling was limited to a single estuary, and the pattern was driven by capture of a few sharks in the early part of the study.

Fig. 7. Histogram of length bull shark at capture from 1976 to 2010 in six Texas estuaries (n = 6970). Size at capture ranged from 550 to 2071 mm stretched total length. Size at maturity is indicated by dashed vertical line (Branstetter and Stiles 1987).

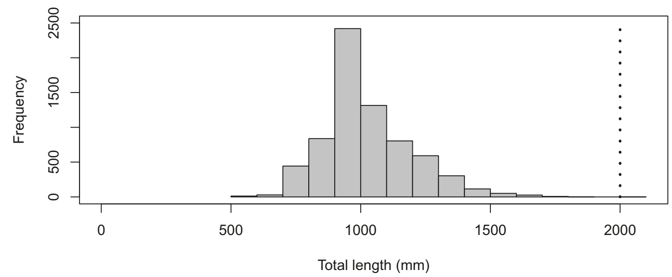


Table 6. Parameter estimates from weighted least squares model for mean bull shark length sampled in six estuaries along the Texas coast from 1976 to 2010.

Variable	df	F	p
Year	1.00	32 626.70	<0.0017
Area	5.00	7.59	<0.001
Year × Area	5.00	2.00	0.080

Note: The variable Year was an annual mean length of bull sharks captured in each estuary, Area was a factor variable with six levels (i.e., one for each estuarine system), and the Year × Area interaction was a random effect evaluating the interaction of the Year variable across estuaries.

In the United States, bull shark has been federally managed since 1993 as part of the large coastal shark complex that includes ten shark species (SEDAR 2006). Despite considerable management history, including five stock assessments in 1992, 1996, 1998, 2002, and 2006, regulatory changes, and litigation, this complex has been considered overfished (1992–2002) or uncertain (2006) throughout this period (SEDAR 2006). However, bull shark has only been assessed in this process as part of the large coastal shark complex, and it is possible that increases in abundance for bull shark could have been masked by declines in other species in the complex. Ultimately, greater understanding must be gained about

Fig. 8. Mean length of bull shark (1976–2010). Study areas from north to south: Sabine Lake (*a*), Galveston Bay (*b*), Matagorda Bay (*c*), San Antonio Bay (*d*), Aransas Bay (*e*), Corpus Christi Bay (*f*). Solid line indicates generalized least-squares regression line.

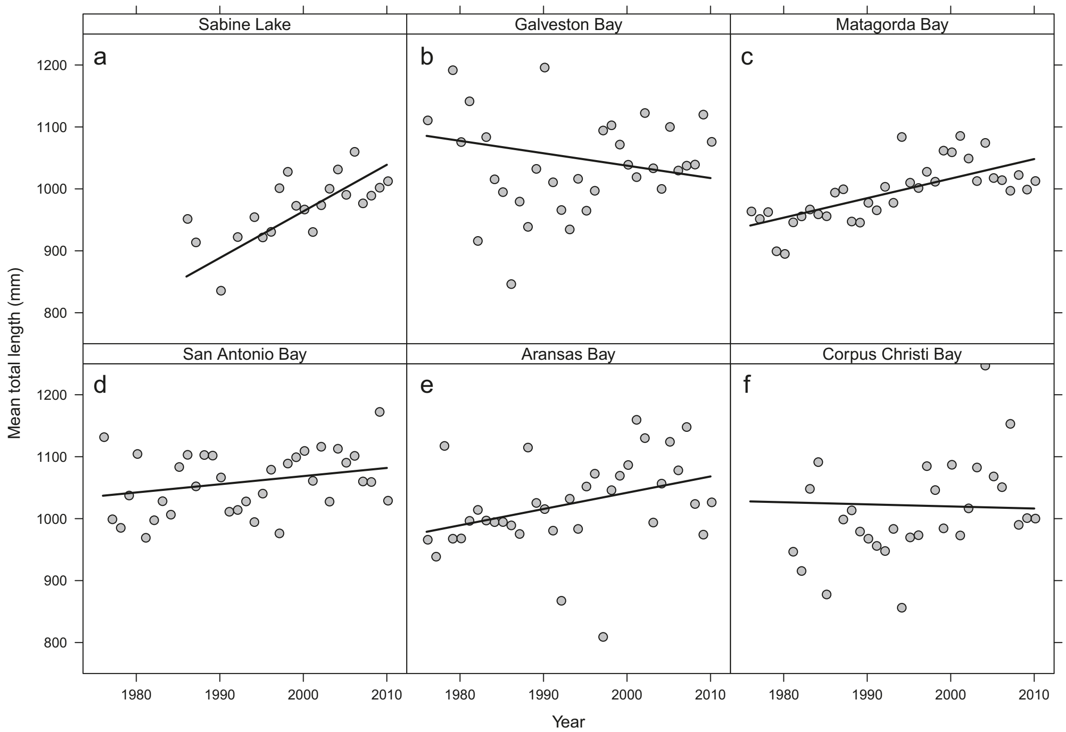
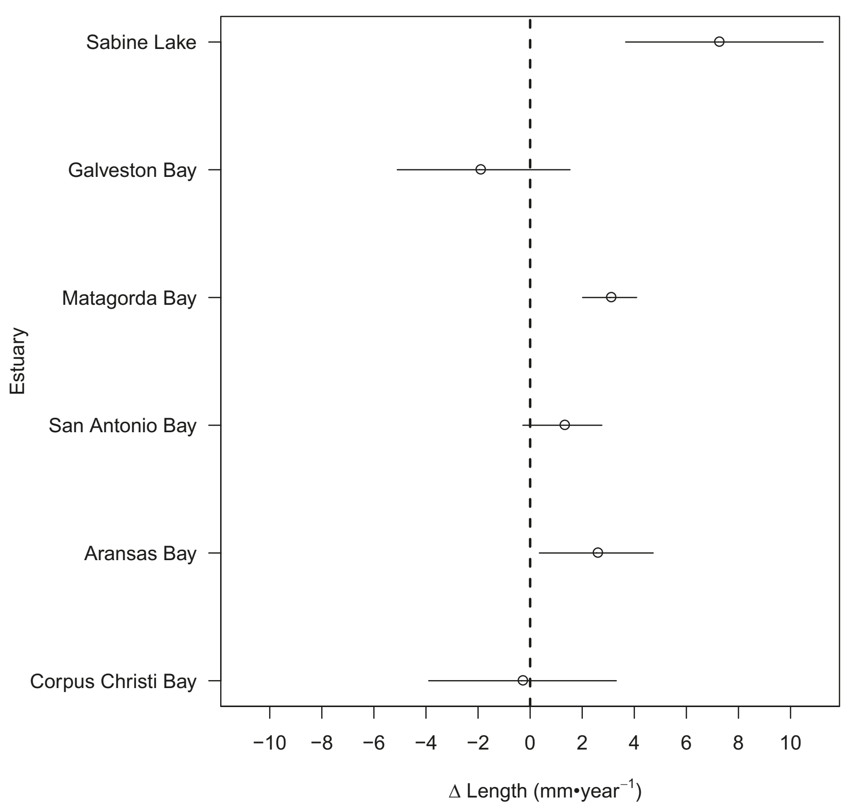


Fig. 9. Annual change in mean length (mm·year⁻¹) ± 95 CI of bull shark in six Texas estuaries from 1976 to 2010. Vertical dashed line demarcates slope equal to zero (i.e., no change in mean length over the study period). Confidence intervals were estimated via bootstrapping where confidence intervals that do not contain the value zero were considered significant (α = 0.05).



the mechanism in which the environment and human activities interact to affect shark populations.

Because of their life history (Musick et al. 2000) and value as a fisheries resource, sustainable management of shark populations is difficult. Demographic trends of many species are poorly characterized, a fact complicated by difficulties in sampling large, wide-ranging animals (Baum and Blanchard 2010) and the potential for other prized species to dominate resource agency focus. However, progressing toward ecosystem management is a stated goal of the National Oceanic and Atmospheric Administration, and this will undoubtedly require improved understanding of temporal and spatial distribution patterns of apex predators and the habitat requirements of these species. The current study represents an important long-term perspective of two important demographic indicators (abundance and mean size) of bull shark in coastal waters of Texas, USA, and provides an encouraging signal in the Gulf of Mexico for a species considered near threatened on the IUCN red list (IUCN 2008). Continuing research is needed to gauge effects of management and environmental impacts on shark resources as well as investigations into ecosystem effects of increasing predatory density in coastal waters.

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