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ARTICLE

Was Everything Bigger in Texas? Characterization and Trends of a Land-Based Recreational Shark Fishery

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Abstract

Although current assessments of shark population trends involve both fishery-independent and fishery-dependent data, the latter are generally limited to commercial landings that may neglect nearshore coastal habitats. Texas has supported the longest organized land-based recreational shark fishery in the United States, yet no studies have used this "non-traditional" data source to characterize the catch composition or trends in this multidecadal fishery. We analyzed catch records from two distinct periods straddling heavy commercial exploitation of sharks in the Gulf of Mexico (historical period = 1973–1986; modern period = 2008–2015) to highlight and make available the current status and historical trends in Texas' land-based shark fishery. Catch records describing large coastal species (>1,800 mm stretched total length [STL]) were examined using multivariate techniques to assess catch seasonality and potential temporal shifts in species composition. These fishery-dependent data revealed consistent seasonality that was independent of the data set examined, although distinct shark assemblages were evident between the two periods. Similarity percentage analysis suggested decreased contributions of Lemon Shark *Negaprion brevirostris* over time and a general shift toward the dominance of Bull Shark *Carcharhinus leucas* and Blacktip Shark *C. limbatus*. Comparisons of mean STL for species captured in historical and modern periods further identified significant decreases for both Bull Sharks and Lemon Sharks. Size structure analysis showed a distinct paucity of landed individuals over 2,000 mm STL in recent years. Although inherent biases in reporting and potential gear-related inconsistencies undoubtedly influenced this fishery-dependent data set, the patterns in our findings documented potential declines in the size and occurrence of select large coastal shark species off Texas, consistent with declines reported in the Gulf of Mexico. Future management efforts should consider the use of non-traditional fishery-dependent data sources, such as land-based records, as data streams in stock assessments.

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The vulnerability of sharks to fishing activities is well known. Since the 1960s, shark populations have declined in concert with many other global fisheries (Baum et al. 2003; Baum and Myers 2004; Burgess et al. 2005) and continue to be overexploited in many regions (Worm et al. 2013). In the North Atlantic alone, shark populations have purportedly declined by more than 50% between 1986 and 2003, with Tiger Sharks *Galeocerdo cuvier* and hammerheads *Sphyrna* spp. being among the most affected species (65% and 89% declines, respectively; Baum et al. 2003). Global declines in shark populations are due in part to overexploitation that is related to the commercial targeting of sharks, finning activities, and the desire to remove "dangerous" species from the ecosystem (Camhi et al. 1998; Musick et al. 2000; Baum et al. 2003). These traits, along with the large-scale movements of many shark species, create unique challenges for the management—and when necessary, the rebuilding—of shark populations (Speed et al. 2010).

Much of the current data from which shark population trends are derived originate from fishery surveys that, although standardized, may be limited at spatial or temporal scales. Until recently, fishery-independent survey data (i.e., independent of commercial and recreational fishing) on nearshore shark assemblages of the Gulf of Mexico were limited to federal waters generally greater than 20-m depth. Several groups from the region are now implementing bottom longline surveys in shallower nearshore waters (Hoffmayer et al. 2013a), but those surveys remain sparse and have only been in place within the last decade for most states. Such data sets are limited in explaining abundance and composition trends along nearshore habitats (e.g., surf zone) despite the known use of these habitats by a variety of shark species (Reyier et al. 2008; Thorpe and Frierson 2009; Drymon et al. 2010; Knip et al. 2010; Bethea et al. 2014). Consequently, few long-term data sets describe sharks in shallow nearshore waters throughout much of the Gulf of Mexico and beyond, thereby impeding our understanding of nearshore shark assemblage dynamics. Given the current population trends for most shark species, stock assessments should strive to include all available long-term data sources. Fortunately, there are unique fishery-dependent data sets that may allow for important insights into shark population dynamics.

Despite inherent biases in fishery-dependent data, many studies have successfully used these resources to assess trends in shark populations, shark size, and occurrence patterns (Márquez-Farias 2005; Morgan and Burgess 2005; Damalas and Megalofonou 2010; Powers et al. 2013; Pérez-Jiménez and Mendez-Loeza 2015) as well as potential nursery areas within regions or at scales for which fishery-independent sampling is not logistically feasible (Dicken et al. 2006; Hueter and Tyminski 2007). In particular, records from organized recreational shark fishing can serve as a useful historical baseline for time series comparisons of large species because anglers typically target the largest individuals and use traditional knowledge and methods in focusing their efforts (Gartside et al. 1999; Powers et al. 2013). Another benefit of fishery-dependent data is that they can be relatively low cost (Prentice et al. 1993), and recreational anglers often sample a greater proportion of the largest size-classes, making this information pertinent to assessments of ecological trends in large sharks (Powers et al. 2013). Thus, recreational fishery-dependent sampling may provide unique opportunities to examine trends in shark assemblage dynamics (1) for large coastal species and (2) within regions that are devoid of long-term monitoring efforts.

Land-based recreational shark fishing has been popular in nearshore regions of Texas since the 1960s. This form of fishing involves capturing sharks from relatively shallow depths (generally <500 m from shore and <5-m depth) and landing animals on heavy hook-and-line tackle in the swash zone along a beach or pier. Such methods are used elsewhere around the world, such as South Africa (van der Elst 1979). Off south Texas, the Corpus Christi Shark Association (CCSA) has targeted sharks in this manner and maintained consistent records from 1973 to 1986. More recently, the CCSA and shark angling in general have rapidly transitioned to catch, tag, and release, although the desire to catch the largest individuals has persisted.

We characterized the recreational shark fishery off Texas through analysis of historical records from the CCSA and modern records from anglers participating as citizen scientists in a volunteer tagging network. Shark community assemblage and size structure were compared between the historical and modern data sets to assess the potential changes in shark composition and size over time. Despite potential issues with reporting biases, consistent patterns were apparent, and our comparison revealed changes that were concomitant with fishing and trends reported elsewhere in the Gulf of Mexico.

STUDY AREA

Texas has eight major bay systems encompassed by a 560-km barrier island chain that separates estuaries from the Gulf of Mexico (Figure 1). Although these inshore waters provide essential fish habitat for numerous teleosts, invertebrates, and shark species (Reese et al. 2008; Froeschke et al. 2010), there is far less characterization on the Gulf of Mexico side of the Texas barrier islands, and there has been only a single examination of sharks (Hueter and Tyminski 2007). Padre Island is the longest barrier island in the world: it measures 177 km in length, covering an area from the Rio Grande

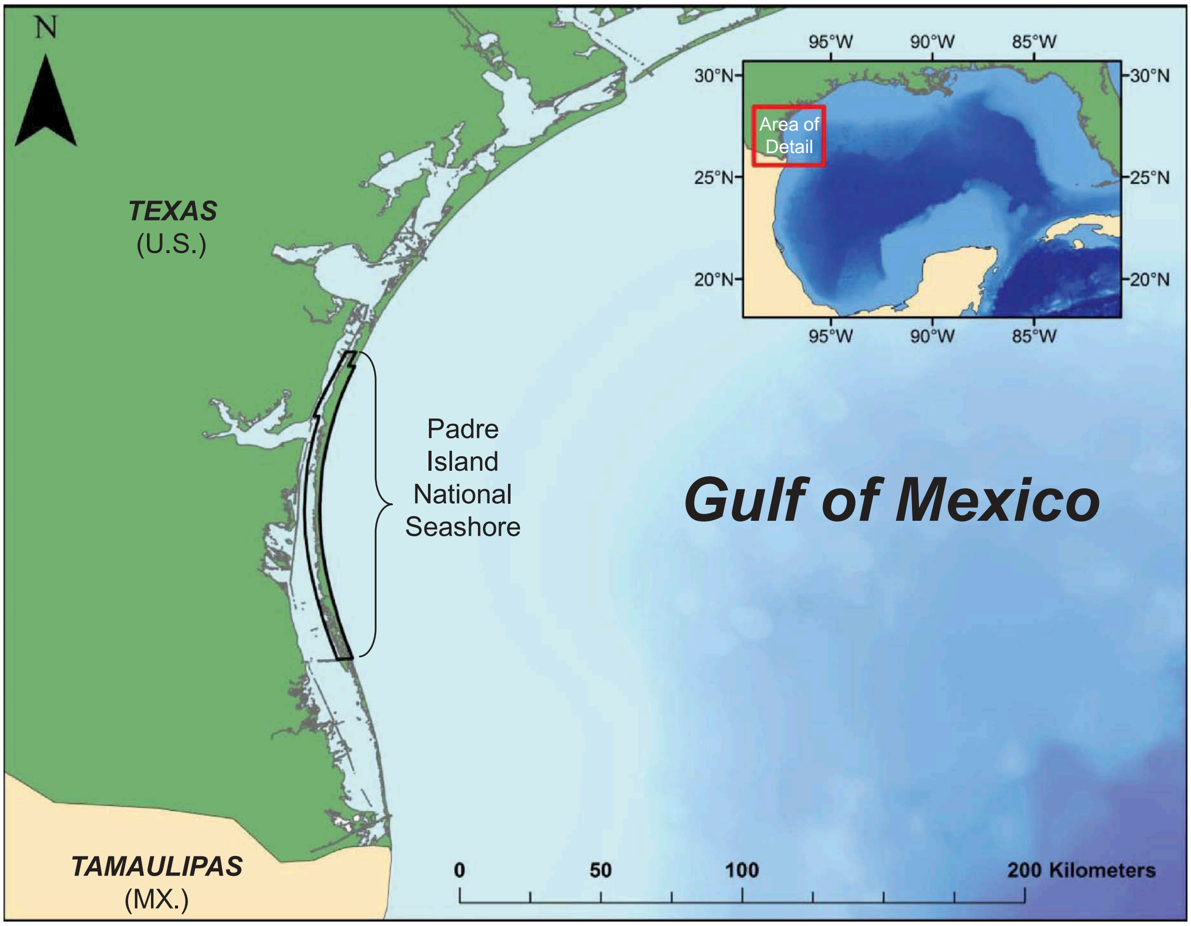

FIGURE 1. Map of the south Texas sampling area, including boundaries of the Padre Island National Seashore (black border). Inset map displays the location of the study area relative to the Gulf of Mexico.

River to Corpus Christi and bearing only a single tidal inlet that connects the hypersaline Laguna Madre to the Gulf of Mexico. Land-based shark fishing from the immediate near-shore waters of Padre Island has a multidecadal history and exerts positive economic impacts on coastal communities in the region (Fisher and Ditton 1993). The majority of the land-based fishery occurs along Padre Island National Seashore, a U.S. National Park. Since 1966, the park has attracted between 152,400 and 960,700 visitors each year, with consistent visitation rates of over 500,000 per year in the last decade (Aldrich 2009). For example, one shark tournament (Sharkathon.com) alone attracts over 600 anglers during an annual one-weekend event (Figure 2). These short-term events coupled with additional year-round shark fishing activities provide opportunities to examine fishery-dependent shark catch statistics.

METHODS

We had access to two major data sets. A historical data set of sharks caught in the Texas recreational shark fishery was developed from catch logs of the CCSA, which were provided by Captain Billy Sandifer. These data logs recorded shark catches from 1973 to 1986. Data were filtered to include records that satisfied the following criteria: (1) a complete date was included with the catch, (2) sharks were identified to the species level, (3) an approximate location could be determined, and (4) the location was within surf waters along Padre Island. The CCSA historical data set encompassed an initial period during which commercial landings of sharks were absent (1973–1978) as well as the onset of a burst of intense commercial shark fishing activity in the mid-1980s (Figure 3). Although no data on shark catch throughout the 1990s were available, this period experienced variable fishing activity but included some of the state's highest commercial catches, particularly in the middle of the decade. Records from the CCSA were limited to sharks larger than 1,800 mm, with the exception of the last 3 years of the historical data set (1984–1986), when sharks of all lengths were reported. The modern period (2008–2015) represented the time after which commercial shark landings in Texas had essentially ceased. Recreational

FIGURE 2. Photo depicting angler effort during the annual Sharkathon.com catch-and-release tournament along Padre Island National Seashore, Texas (October 3, 2011).

catch records from the modern period were derived from volunteer anglers ("citizen scientists") collaborating with the Center for Sportfish Science and Conservation at the Harte Research Institute (HRI) for Gulf of Mexico Studies. The HRI has maintained a volunteer angler network in conjunction with a shark tagging program since 2008. Volunteer anglers were provided with M-type dart tags (Floy Tag, Inc.), tag applicators, species identification guides (www.sharkid.com/sharkguides.html), and data cards to record pertinent information, including the date, location, stretched total length (STL; measured from the tip of the snout to the tip of the stretched upper caudal lobe), species, and sex. Upon tagging a shark, the anglers either returned the cards to researchers or submitted the data via an online form. The participating anglers were generally very skilled and adept at shark identification; however, the online form typically included an uploaded photo of the released shark to confirm species identification.

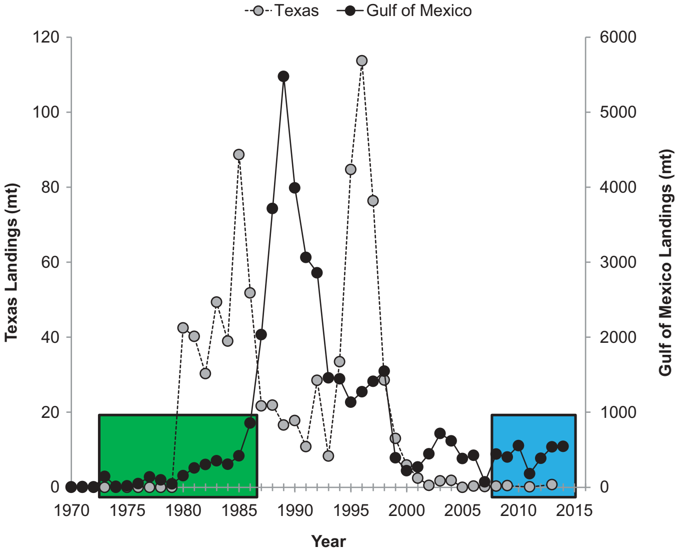

FIGURE 3. Scatter-line plot of total shark commercial landings (metric tons [mt]) in the state of Texas (gray-shaded circles) and Gulf of Mexico (black-shaded circles) from 1970 to 2015. Superimposed on the plot are the periods covered by the two data sets used in this study (green = historical data set, 1973–1986; blue = modern data set, 2008–2015).

Although variation exists amongst individual anglers, the general strategy for land-based fishing in Texas involves the use of large reels spooled with 800–1,000 m of 50-lb (22.68-kg) to 100-lb (45.36-kg) test line (monofilament or braided) with approximately 100 m of monofilament top shot of increased strength. A wire or monofilament leader, consisting of a weight and a line with a circle or J-hook ranging in size from 13/0 to 24/0, is connected to the top-shot line. The hook is baited with large sections of stingray *Rhinoptera* spp. or *Dasyatis* spp., Crevalle Jack *Caranx hippos*, or Striped Mullet *Mugil cephalus* and is either surf cast or kayaked out 100–400 m offshore.

Two critical assumptions were made in this study regarding population subsamples and gear bias in the data sets. The first was that sharks in the catch were an accurate representative subsample of the shark community that was present in the nearshore population. It was also assumed that gear and tackle modifications over time introduced negligible bias. Although fishing technology has changed over the past few decades, resulting in stronger materials, the method of targeting and catching sharks has remained consistent and is a tradition that is passed from angler to angler (B. Sandifer, personal communication). Furthermore, despite a shift from J-hooks to circle hooks in recreational fisheries over the course of recent decades (Cooke and Suski 2004; Serafy et al. 2012), we assumed no impacts of this transition on shark catchability, as supported by Godin et al. (2012). All measurements were made using soft tape measures across years, so length data were assumed to be consistent as well.

*Data analysis.—*Using the STL and sex, all individual records were classified into one of three life stages: young of the year (age 0), juvenile, and adult. Classifications were made based on published studies of shark life history in the Gulf of Mexico (Branstetter 1987; Branstetter and Stiles 1987; Carlson et al. 1999, 2003, 2007; Carlson and Baremore 2003, 2005; Lombardi-Carlson et al. 2003; Piercy et al. 2007; Sulikowski et al. 2007; Baremore and Hale 2012; Baremore and Passeroti 2013; Hoffmayer et al. 2013b). For each data set, these values were used to determine the presence and absence of the various life stages for all species given the a priori knowledge that juvenile and age-0 sharks were likely underreported for a major segment of the historical period (i.e., 1973–1983) during which only sharks over 1,800 mm STL were documented.

Community assemblage comparisons were conducted on landings of sharks larger than 1,800 mm STL between historical and modern data sets by using a series of semiparametric multivariate analyses in PRIMER 6 (version 6.1.16) with PERMANOVA+ (version 1.0.6; PRIMER E+ Ltd.). To account for variation in fishing effort that could introduce bias, data were standardized by computing a monthly catch proportion for each species (the number of individuals of a species caught in a single month divided by the total number of individuals caught in that same month). Species were input into PRIMER 6 as variables and month–year as samples. Given the lack of winter records during the historical period, we constrained our statistical analyses to data from spring (March–May), summer (June–August), and fall (September–November) to ensure consistency across data sets.

A Bray–Curtis resemblance matrix was constructed from standardized catch data for subsequent multivariate analyses. First, distances among yearly centroids were calculated to qualitatively assess relationships in species assemblages through time. These data were used to create a nonmetric multidimensional scaling plot. The matrix was then exposed to a two-way permutational ANOVA (PERMANOVA) to examine the potential impacts of period (historical and modern), season (spring, summer, and fall), and period × season interaction on shark catch composition. Pairwise comparison tests were conducted for significant factors ($P < 0.05$). To evaluate homogeneity of multivariate dispersions, which can affect the interpretation of PERMANOVA results (Anderson et al. 2006), we accompanied our analyses with distance-based tests (PERMDISP) on the resemblance matrix for both factors. A similarity percentage (SIMPER) analysis was then performed to determine which species caused the dissimilarity among dissimilar factors.

Changes in size were examined in large sharks (>1,800 mm STL) for species occurring in the catch for at least six years total. Additionally, these species had to occur in at least three modern years and three historical years for sufficient sample sizes. Differences in mean STL were compared between the periods by using two-sample *t*-tests with the significance level α set at 0.05. Prior to analysis, data were tested for normality and for homogeneity of variances. Data sets that did not meet these assumption criteria were analyzed by using nonparametric Mann–Whitney *U*-tests ($\alpha = 0.05$).

Overall variation in the size composition of large sharks was also assessed between the historical period ($n = 175$) and the modern period ($n = 416$). Given the considerable sample sizes of large Bull Sharks *Carcharhinus leucas* in both data sets (historical: $n = 73$; modern: $n = 202$), further size structure analysis was conducted for this species as well. Density histograms of STL were constructed for all large sharks and for Bull Sharks in both the historical and modern data sets by using ggplot2 version 1.0.0 (Wickham 2009) in R version 3.1.0 (R Core Team 2014). Using the Cramer package version 0.8.1 (Franz 2006) in R, we conducted nonparametric two-sample Cramér tests to examine the equality in underlying distributions between the historical and modern periods. The two-sample Cramér test is a more powerful analog to the popular Kolmogorov–Smirnov (K–S) and Cramér–von Mises tests (Baringhaus and Franz 2004) and was used to examine the null hypothesis of even similar distributions between the two periods. The two-sample Cramér test was also selected over the K–S test due to its lessened sensitivity to gaps in distributions (Arnold and Emerson 2011), which were prominent in the historical data set. Results of the tests were based on 1,000 ordinary (with replacement) bootstrap replicates, all performed in R via the "boot" package version 1.3-11 (Canty and Ripley 2014).

RESULTS

The various data sets documented a total of 17 different shark species (Table 1). Sharks spanned life stages from age 0 to juveniles and adults. The historical data set was dominated by species at the adult stage and included Blacktip Sharks, Bull Sharks, Great Hammerheads, Lemon Sharks, Sandbar Sharks, Sand Tigers, Scalloped Hammerheads, Smooth Hammerheads, Spinner Sharks, and Tiger Sharks. Historical data had a smaller contribution of juveniles, represented by Atlantic Sharpnose Sharks, Blacktip Sharks, Bull Sharks, Dusky Sharks, Finetooth Sharks, Lemon Sharks, Smooth Hammerheads, Spinner Sharks, and Tiger Sharks. Only two species from the historical data set were represented by age-0 individuals—the Bull Shark and Bonnethead—both of which were reported in the final 2 years of that data set (1985 and 1986). The modern data set included three additional species that were absent from the historical data set: the Blacknose Shark, Shortfin Mako, and Silky Shark. The modern data set also included age-0 sharks of several species, such as the Atlantic Sharpnose Shark, Blacktip Shark, Dusky Shark,

TABLE 1. Presence (x) and absence (–) of adult (ADU), juvenile (JUV), and young-of-the-year (AGE 0) size-classes for all shark species recorded in historical and modern recreational fishery catch logs. An uppercase bold italic “X” signifies that the capture of the specified life stage for the given species was unique to that period.

	Historical (1973–1986)			Modern (2008–2015)		
Species	ADU	JUV	AGE 0	ADU	JUV	AGE 0
Atlantic Sharpnose Shark *Rhizoprionodon terraenovae*	x	x	–	x	x	***X***
Blacknose Shark *Carcharhinus acronotus*	–	–	–	***X***	***X***	–
Blacktip Shark *Carcharhinus limbatus*	x	x	–	x	x	***X***
Bonnethead *Sphyrna tiburo*	x	x	x	x	x	x
Bull Shark *Carcharhinus leucas*	x	x	x	x	x	x
Dusky Shark *Carcharhinus obscurus*	–	***X***	–	***X***	–	***X***
Finetooth Shark *Carcharhinus isodon*	x	x	–	x	x	***X***
Great Hammerhead *Sphyrna mokarran*	x	–	–	x	***X***	–
Lemon Shark *Negaprion brevirostris*	x	x	–	x	x	–
Sandbar Shark *Carcharhinus plumbeus*	x	–	–	x	***X***	–
Sand Tiger *Carcharias taurus*	***X***	–	–	–	–	–
Scalloped Hammerhead *Sphyrna lewini*	x	–	–	x	***X***	***X***
Shortfin Mako *Isurus oxyrinchus*	–	–	–	***X***	–	–
Silky Shark *Carcharhinus falciformis*	–	–	–	–	***X***	–
Smooth Hammerhead *Sphyrna zygaena*	–	***X***	–	–	–	–
Spinner Shark *Carcharhinus brevipinna*	x	x	–	x	x	–
Tiger Shark *Galeocerdo cuvier*	x	x	–	x	x	–

Finetooth Shark, and Scalloped Hammerhead. Both the Smooth Hammerhead and the Sand Tiger were absent from modern records.

The nonmetric multidimensional scaling ordination of yearly centroids showed separation between historical and modern years, with somewhat wider dispersion of historical shark assemblages across multivariate space (Figure 4). These separations were statistically supported by the results of two-way PERMANOVA, which indicated that the species composition was significantly affected by period (pseudo-$F_{1,88}$ = 9.470, P = 0.001) and season (pseudo-$F_{2,88}$ = 2.825, P = 0.007) but not by the period × season interaction (pseudo-$F_{2,88}$ = 1.814, P = 0.103). The PERMDISP test determined that the significant differences between periods also may have been due to heterogeneity in dispersion between the two data sets (period: $F_{1,88}$ = 7.535, P = 0.022); however, seasonal differences were indeed solely due to variation in multivariate space ($F_{2,88}$ = 0.408, P = 0.754). Pairwise comparisons among seasons showed that distinct assemblages occurred between spring and summer (t = 1.997, P = 0.008) and between spring and fall (t = 1.676, P = 0.037) but not between summer and fall (t = 1.240, P = 0.217).

The SIMPER analysis indicated that increased contributions from Bull Sharks (22.75%) and Blacktip Sharks (16.88%) in modern data sets greatly contributed to dissimilarities between the two periods (Table 2; Figure 5). However, Lemon Sharks also notably decreased in contribution during the modern period and were a main contributor of the dissimilarity (17.13%). Seasonally, spring was found to have higher contributions from Blacktip Sharks and Lemon Sharks and lower contributions from Bull Sharks and Tiger Sharks than summer (Table 3). Differences between spring and fall assemblages were primarily explained by higher contributions of Bull Sharks in fall, while Lemon Sharks and Blacktip Sharks were more common in spring.

Significant differences in mean STL were found for the Bull Shark (Mann–Whitney U-test: U = 646.60, P < 0.0001) and the Lemon Shark (two-sample t-test: t = 2.13, P < 0.05) between historical and modern periods (Table 4). For both species, mean STL was significantly lower during the modern period (Bull Shark: 2,051.2 mm; Lemon Shark: 2,413.0 mm) than during the historical period (Bull Shark: 2,379.3 mm; Lemon Shark: 2,683.2 mm). Mean STL also decreased for Blacktip Sharks, Sandbar Sharks, Spinner Sharks, and Great Hammerheads, but these differences were not significant (Mann–Whitney U-test: P > 0.05). Mean STLs of Tiger Sharks and Scalloped Hammerheads increased from the historical period to the modern period, but these changes were also nonsignificant (two-sample t-test: P > 0.05).

Cramér tests on large-shark size distribution also detected significant differences between the historical and modern data sets (P < 0.0001). Visual inspection of length frequency histograms demonstrated a distribution that was skewed toward smaller individuals in the modern data set, while the historical data set exhibited a patchy yet disproportionately greater number of sharks between 2,000 and 3,000 mm STL

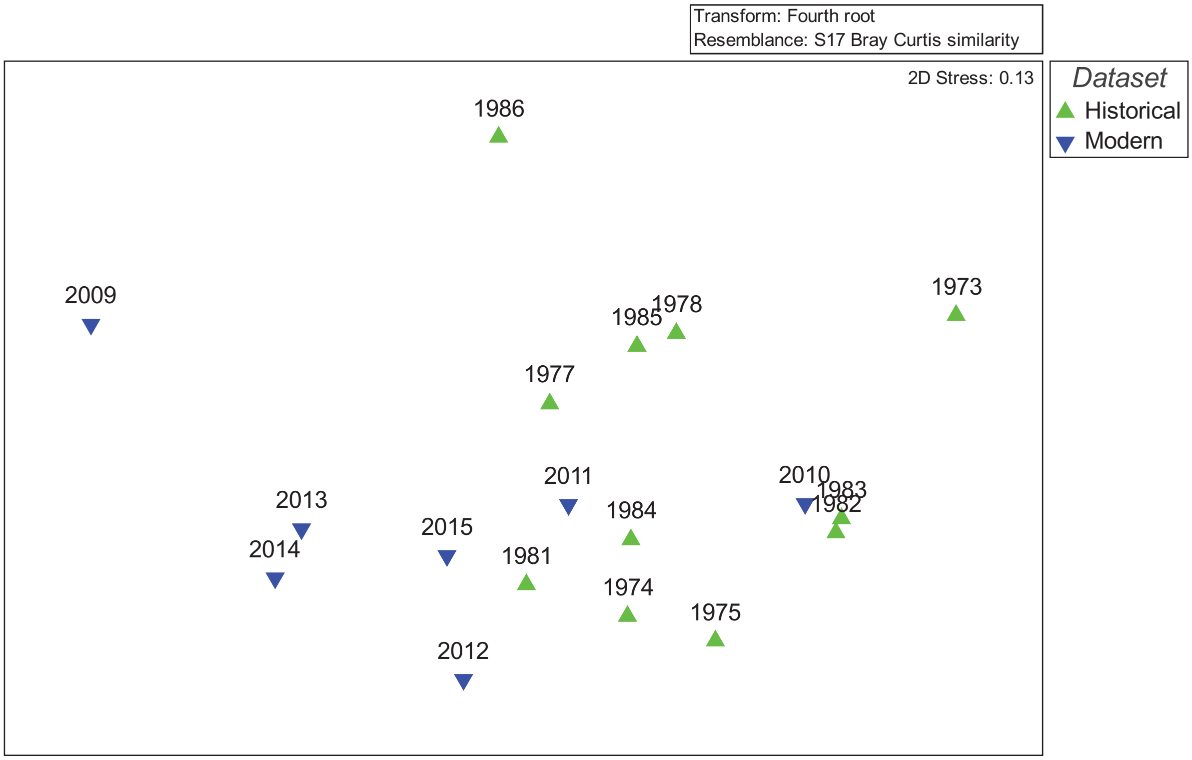

FIGURE 4. Nonmetric multidimensional scaling plot of annual centroids (i.e., relative similarity among years) for large-shark (>1,800 mm) composition data from two periods: historical (1973–1986; green triangles) and modern (2008–2015; blue triangles). Each centroid is labeled with the year.

(Figure 6A). The mean STL of large sharks from historical data (2,402 mm) was significantly greater than the mean STL of sharks from modern data (2,090 mm; two-sample *t*-test: $t = 69.95$; $P < 0.0001$). Bull Sharks, which comprised approximately 40% of the large-shark catch in both data sets, also showed trends similar to those observed in the overall analysis (Figure 6B), with statistically significant differences in distribution between the historical period and the modern period ($P < 0.0001$). Density histograms revealed a more bimodal density distribution for Bull Sharks in the historical period and a skewed distribution (toward a minimum size of 1,800 mm) for Bull Sharks in the modern period.

DISCUSSION

Records from land-based shark fishing off the Texas coast indicate that several species frequent the immediate nearshore region (<5 m). To our knowledge, this may be the most

TABLE 2. Results of similarity percentage (SIMPER) analysis pairwise comparisons between periods for large sharks >1,800 mm). Species contributions that contributed to the dissimilarity between data sets are presented in order of highest to lowest dissimilarity within each comparison. The following data are listed for each species within each comparison: average abundance (avg. abund) for each group, average dissimilarity (avg. diss), dissimilarity divided by the standard deviation (diss/SD), percent contribution (contrib%), and cumulative percent contribution (cumul%).

Species	Historical avg. abund	Modern avg. abund	Avg. diss	Diss/SD	Contrib%	Cumul%
Average dissimilarity = 71.47						
Bull Shark	0.45	0.66	16.26	1.02	22.75	22.75
Lemon Shark	0.38	0.06	12.24	0.78	17.13	39.89
Blacktip Shark	0.10	0.41	12.06	0.95	16.88	56.77
Tiger Shark	0.21	0.23	11.36	0.79	15.89	72.66
Scalloped Hammerhead	0.19	0.07	6.45	0.56	9.03	81.68
Sandbar Shark	0.02	0.21	5.61	0.53	7.85	89.53
Great Hammerhead	0.04	0.13	4.33	0.57	6.06	95.59

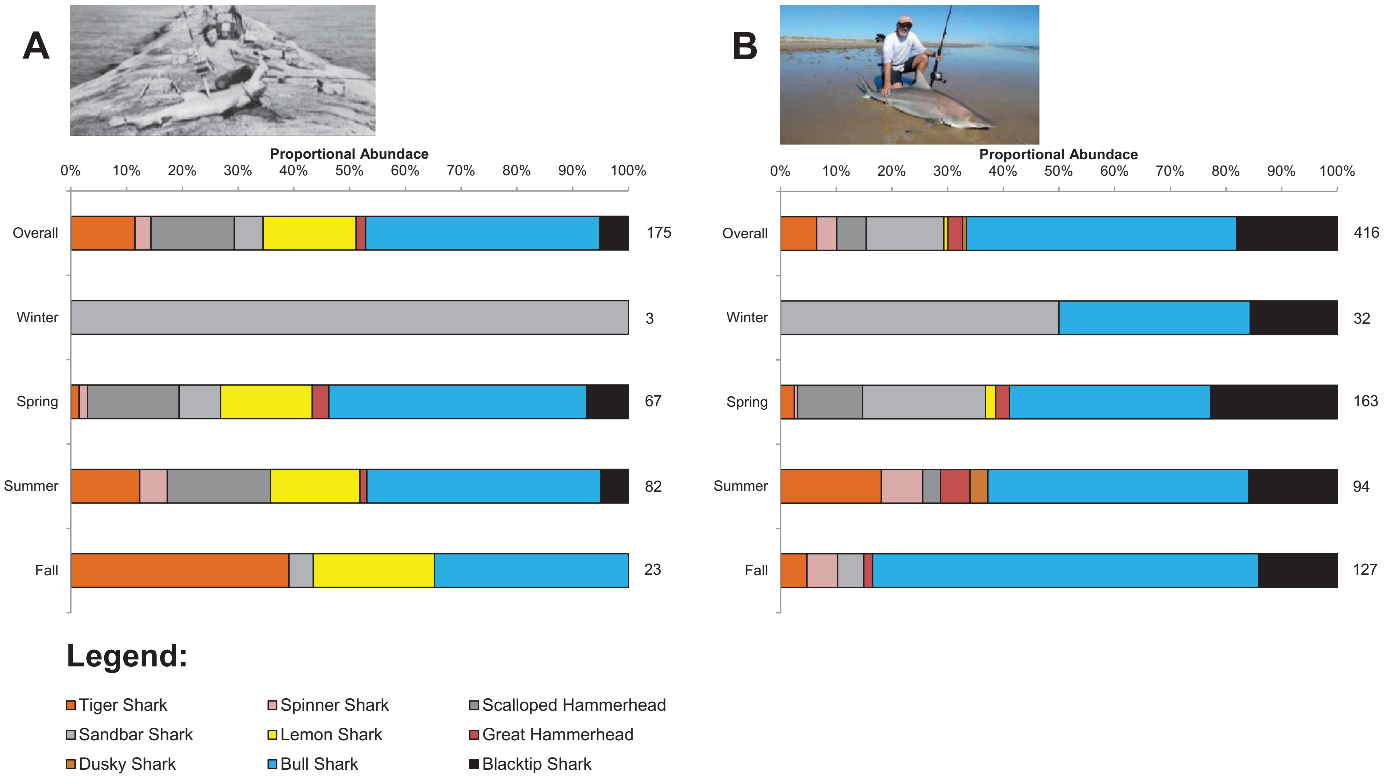

FIGURE 5. Stacked bar plot of species contributions (proportional abundance) to overall and seasonal large-shark (>1,800-mm) catch during **(A)** the historical period (1973–1986) and **(B)** the modern period (2008–2015). The sample size of large coastal sharks is listed to the right of each bar; species are coded by color.

comprehensive characterization of shark occurrence in this habitat along the western Gulf of Mexico. Previous shark habitat assessments in Texas have been limited to areas further offshore (Grace et al. 1997) or inshore (Froeschke et al. 2010), while assessments of nearshore assemblages have been limited to young life stages or smaller species (Hueter and Tyminski 2007). Large coastal shark assessments elsewhere in the Gulf of Mexico are restricted to the north-central (Drymon et al. 2010) and northeastern (Bethea et al. 2014) regions. Documentation of age-0 individuals representing many species (Atlantic Sharpnose Shark, Blacktip Shark, Bonnethead, Dusky Shark, Finetooth Shark, and Scalloped Hammerhead) from recent records suggests that this habitat deserves further investigation as a potential nursery area. As such, continued monitoring of the western nearshore zone may assist the management of these shark species in the Gulf of Mexico.

Our analyses indicate a consistent pattern of seasonality in the recreational landings of large sharks along Texas nearshore waters, likely driven by variation in species-specific habitat preferences. Winter assemblages were not included in the multivariate analyses due to inconsistent reporting among data sets, but modern data indicated that catch during winter is dominated by Sandbar Sharks (94%), a species that is currently listed as recreationally prohibited and commercially limited to a small research fishery in the United States (NMFS 2008). The Sandbar Shark has one of the lower temperature tolerances among the species considered in this study (Ulrich et al. 2007; Gallagher et al. 2014b), which may therefore account for its dominance during the winter period. As waters warm in spring, catch heavily shifts toward the Bull Shark but also includes the Lemon Shark and Blacktip Shark, the latter of which is a species of intensified commercial importance in the Gulf of Mexico due to the Sandbar Shark fishery restrictions (SEDAR 2012). Bull Sharks dominate the summer catch, with notable contributions from Tiger Sharks and Lemon Sharks, which are joined by Blacktip Sharks once again in fall. The Blacktip Shark contributions during both spring and fall (but not summer) are potentially indicative of northward and southward migrations (respectively) along the immediate shoreline, as was suggested by Swinsburg (2013). Collectively, these findings on seasonality in the land-based fishery, particularly for commercially targeted large coastal species like the Sandbar Shark and Blacktip Shark, are of importance to management efforts, as they describe potential patterns of exploitation and interaction between recreational and commercial shark fisheries.

Our examination of land-based records suggests that a potential shift in the nearshore large-shark assemblage occurred between historical and modern years during a period that was characterized by the heaviest shark exploitation in the

TABLE 3. Results from similarity percentage (SIMPER) analysis pairwise comparisons between seasons (spring = March–May; summer = June–August; fall = September–November) for large sharks (>1,800 mm). Species contributions that summed cumulatively to at least 90% of the dissimilarity between data sets are presented in order of highest to lowest dissimilarity within each comparison. The following data are listed for each species within each comparison: average abundance (avg. abund) for each group, average dissimilarity (avg. diss), dissimilarity divided by the standard deviation (diss/SD), percent contribution (contrib %), and cumulative percent contribution (cumul%).

Species	Season 1 avg. abund	Season 2 avg. abund	Avg. diss	Diss/SD	Contrib%	Cumul%
Fall (season 1) versus spring (season 2)						
Average dissimilarity = 64.28						
Bull Shark	0.64	0.49	16.04	0.93	24.96	24.96
Lemon Shark	0.12	0.33	11.31	0.67	17.59	42.55
Blacktip Shark	0.25	0.33	9.17	0.71	14.26	56.81
Tiger Shark	0.22	0.07	8.45	0.62	13.14	69.95
Sandbar Shark	0.15	0.21	8.19	0.74	12.74	82.69
Scalloped Hammerhead	0.00	0.14	4.24	0.39	6.59	89.28
Great Hammerhead	0.02	0.13	4.01	0.47	6.23	95.51
Fall (season 1) versus summer (season 2)						
Average dissimilarity = 63.86						
Tiger Shark	0.22	0.34	15.31	0.93	23.98	23.98
Bull Shark	0.64	0.55	15.05	0.89	23.57	47.55
Lemon Shark	0.12	0.21	8.51	0.53	13.32	60.87
Blacktip Shark	0.25	0.20	8.30	0.73	13.00	73.87
Scalloped Hammerhead	0.00	0.22	6.40	0.51	10.02	83.88
Sandbar Shark	0.15	0.00	4.05	0.42	6.34	90.22
Spring (season 1) versus summer (season 2)						
Average dissimilarity = 67.97						
Bull Shark	0.49	0.55	15.16	0.96	22.31	22.31
Lemon Shark	0.33	0.21	12.22	0.78	17.98	40.29
Tiger Shark	0.07	0.34	10.89	0.74	16.03	56.32
Blacktip Shark	0.33	0.20	9.66	0.75	14.22	70.54
Scalloped Hammerhead	0.14	0.22	9.10	0.66	13.39	83.93
Great Hammerhead	0.13	0.08	4.75	0.54	6.99	90.92

Gulf of Mexico to date. This shift was best explained by increases in the contribution of Bull Sharks and Blacktip Sharks and a prominent decrease in the contribution of Lemon Sharks. Bull Shark occurrence in the Texas land-based recreational fishery appears to have increased over the years, but Bull Shark size has decreased, as demonstrated elsewhere in the Gulf of Mexico (Powers et al. 2013). This species has also increased in commercial importance during recent years in the Gulf of Mexico and in the western North Atlantic Ocean (Natanson et al. 2014), suggesting that continued exploitation may also be limiting the abundance of larger individuals. However, using long-term fishery-independent data over a temporal scale similar to that used in this study, Froeschke et al. (2013) reported that the inshore catch of young Bull Sharks increased along multiple Texas estuaries situated further north. Froeschke et al. (2013) also suggested that while Bull Shark abundance was positively correlated with temperature and salinity, negative responses to hypersaline conditions (≥40‰) were likely (Froeschke et al. 2010). The proximity of the Padre Island National Seashore to hypersaline inlets of the Laguna Madre may have reduced habitat quality for large Bull Sharks in recent years. Degraded coastal habitat via reduced freshwater inflow may therefore provide an alternative explanation for the change in patterns documented from land-based fishery landings. Although further analyses are needed to determine the relative roles of fishing (both recreational and commercial) and environmental impacts on large Bull Sharks, data on both size and occurrence from land-based fishery landings, in concert with other recent studies, suggest that larger individuals are less common in this region.

The sole species that was reported to decrease both in size and occurrence was the Lemon Shark. Lemon Sharks are popular in U.S. commercial and recreational fisheries, and their fins and skin are of very high value worldwide (Sundström 2015). Despite unknown population trends,

TABLE 4. Size trends for multiple large coastal shark species reported in the Texas land-based recreational fishery (STL_{max} = maximum observed STL; historical period = 1973–1986; modern period = 2008–2015). Results of two-sample *t*-tests on mean stretched total length (STL) are shown for eight large coastal shark species that were documented in at least six years. Test statistics for Mann–Whitney *U*-tests or *t*-tests are listed with corresponding *P*-values. Comparisons yielding significant differences in mean STL are shown in bold italics.

Species	Years documented	Year of first report	Year of last report	Year of STL_{max}	Mean historical STL (mm)	Mean modern STL (mm)	*U*	*t*	*P*
Bull Shark	17	1973	2015	1974	2,379.25	2,051.22	646.50	–	***<0.0001***
Lemon Shark	13	1973	2015	1986	2,683.20	2,413.00	–	2.13	***0.04***
Tiger Shark	13	1973	2015	2015	2,698.12	2,837.29	–	–0.86	0.40
Blacktip Shark	12	1973	2015	1978	1,885.24	1,863.30	238.50	–	0.16
Sandbar Shark	12	1974	2015	1978	2,085.62	2,039.88	185.00	–	0.44
Scalloped Hammerhead	9	1973	2015	2015	2,142.88	2,154.39	–	–0.215	0.83
Spinner Shark	6	1974	2015	1982	2,052.49	2,015.49	–	–0.562	0.58
Great Hammerhead	6	1973	2015	1973	3,073.40	2,438.40	10.0	–	0.35
Dusky Shark	4	1986	2015	2015	–	–	–	–	–
Sand Tiger	3	1974	1980	1975	–	–	–	–	–
Silky Shark	2	2011	2012	2011	–	–	–	–	–
Smooth Hammerhead	1	1978	1978	1978	–	–	–	–	–

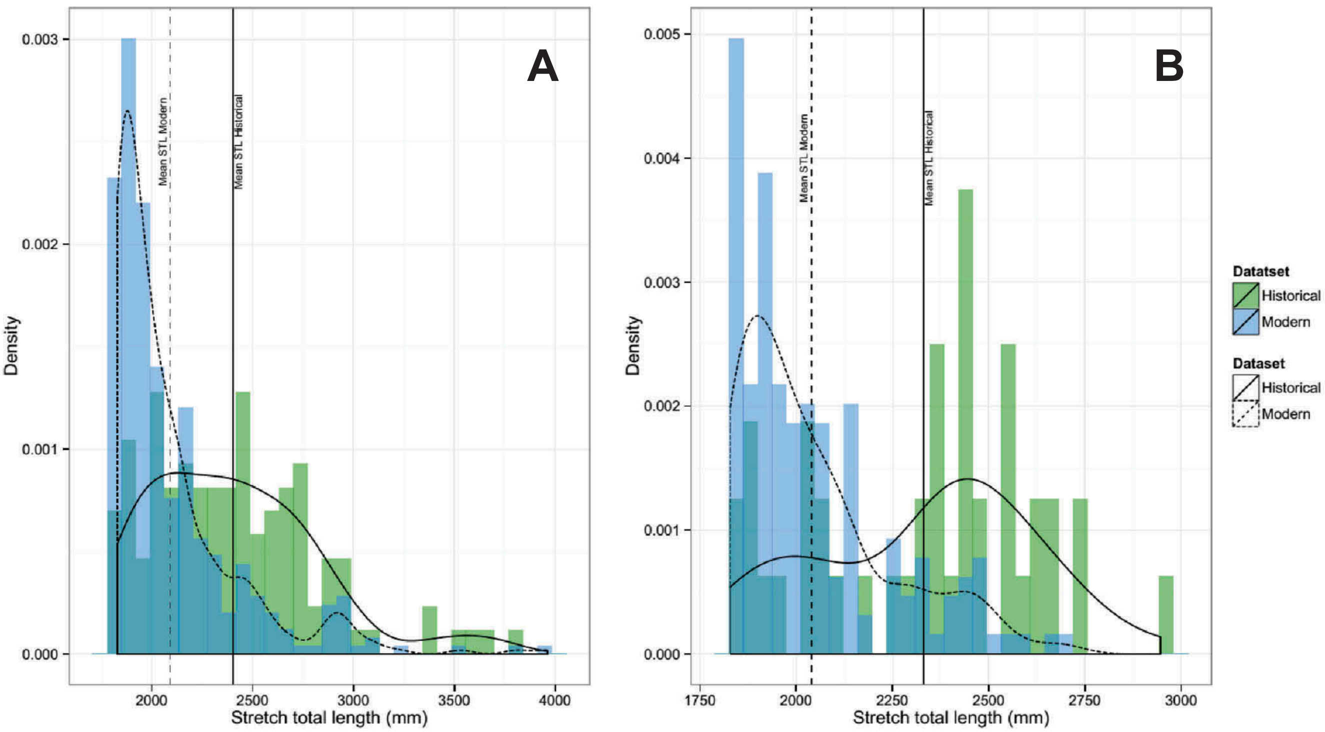

FIGURE 6. Probability density histograms of stretch total length (STL) for **(A)** all large (>1,800-mm) sharks and **(B)** large Bull Sharks landed by the land-based recreational fishery off Texas. Data are shown for the historical period (1973–1986; green) and the modern period (2008–2015; blue). Vertical lines are drawn for the mean STL of both historical (solid) and modern (dashed) records, as well as smoothers representing kernel density estimates.

previous work has suggested that Lemon Sharks cannot sustain even moderate levels of fishing (Cortés 1998), likely due to slow population growth, late maturity (Brown and Gruber 1988), and biennial reproductive cycles (Feldheim et al. 2002). Additionally, Lemon Sharks form large seasonal aggregations in nearshore waters (Reyier et al. 2008), and this behavior may increase vulnerability to coastal fishing. Despite the Lemon Shark's currently designated status of near threatened (Sundström 2015), the declines we observed via analysis of data from the land-based fishery may be indicative of this species' lack of resilience to exploitation. Further focus on Lemon Shark population dynamics in this region is therefore extremely timely and necessary.

Despite the lack of robust evidence for declines in Great Hammerheads, large individuals (i.e., >3,000 mm STL) have not been reported in catch logs since 1973. Both the Scalloped Hammerhead and Great Hammerhead are listed as endangered by the International Union for Conservation of Nature and are highly vulnerable to overexploitation given their popularity in the land-based fishery and known issues with postrelease mortality relative to other sharks, especially on commercial longlines (Morgan and Burgess 2010; Gallagher et al. 2014a, 2014c; Gulak et al. 2015). Given that the Scalloped Hammerhead was recently assessed as overfished, with overfishing occurring in the northwest Atlantic Ocean (Hayes et al. 2009), we recommend further studies on the postrelease behavior of these sensitive species from the land-based fishery to explore additional potential impacts that may limit stock recovery. Such approaches may take advantage of novel technologies, such as acceleration data loggers, which can monitor the postrelease mortality or recovery of sharks (Whitney et al. 2016).

The decline of multiple large coastal shark species is disconcerting, but our land-based data set may support the current stability in Blacktip Shark populations across the Gulf of Mexico. In 2012, the status of the Blacktip Shark was assessed as not overfished, with no overfishing occurring in the Gulf of Mexico (SEDAR 2012). The higher frequency of adult Blacktip Sharks landed in the modern fishery may indicate this species' higher resilience to fishing pressure relative to other larger coastal sharks that were documented to decrease in maximum size or occurrence. Blacktip Sharks have shorter life spans and faster growth rates than other carcharhinid sharks (Branstetter 1987; Hoenig and Gruber 1990) and thus are likely to have a stronger rebound potential (Smith et al. 1998). Such characteristics may have permitted this species to withstand historical exploitation and thus may account for increased popularity in catch during the modern period.

Another potential explanation for the changes in observed shark assemblages—particularly the appearance of small coastal sharks in modern data sets—is the proliferation of circle hooks in recreational fisheries. Although the sole meta-analysis comparing shark catch between circle hooks and J-hooks revealed no effects (Godin et al. 2012), the study was dominated by comparisons of pelagic longline data. Two studies from standardized bottom longline surveys (which fish baits in a manner similar to that used by land-based fishers in Texas) have demonstrated that shark species caught by use of Mustad 15/0 circle hooks and number-3 J-hooks differed in both abundance and size (Ingram et al. 2005; Hannan et al. 2013). Those studies have specifically found that circle hooks increase CPUE for a variety of species, such as the Atlantic Sharpnose Shark, Blacktip Shark, Blacknose Shark, and Finetooth Shark (Ingram et al. 2005; Hannan et al. 2013). Furthermore, circle hooks were demonstrated to catch significantly smaller Atlantic Sharpnose Sharks, Bull Sharks, Blacktip Sharks, and Tiger Sharks. Thus, increased use of circle hooks would appear to explain the decreases in Bull Shark size from the Texas land-based fishery between the historical period and the modern period as well as the increased dominance of Blacktip Sharks and the appearance of small coastal species; however, it does not explain the increased dominance of Bull Sharks and does not support the lack of size differences in Blacktip Sharks and Tiger Sharks between the historical and modern periods. These inconsistencies may be caused by the continued use of both circle hooks and J-hooks by land-based shark fishermen in Texas (B. Sandifer, personal communication) and a wider range of hook sizes (13/0 to 24/0). Unfortunately, we could not quantify potential temporal changes in hook use specifically for the land-based fishery off Texas. Future studies should attempt to collect more detailed information on hook type and size to help guide data interpretation. Although these nuances complicate the interpretation of our data set, size-based indicators from the large coastal species appear to converge on a general trend of smaller individuals dominating the catch in recent years—particularly Lemon Sharks and possibly Bull Sharks. These decreases warrant further attention from managers of large coastal sharks. Furthermore, continued time series information on the size and occurrence of small coastal shark species landed by recreational fisheries may also permit more robust analyses of these species as well.

Land-based shark fishing along the Texas coast is a recreational activity that is rich in tradition and culture. Contemporary anglers in this fishery are primarily conservation oriented and generally practice catch-and-release methods (Graefe and Ditton 1976; Aldrich 2009), but popularity and participation (e.g., Texas Shark Rodeo, texassharkrodeo.com) are ever increasing. Given the continued commercial and recreational exploitation of coastal sharks and shark poaching by Mexican fishermen that trespass in south Texas waters (Brewster-Geisz et al. 2010), we encourage further monitoring of land-based fisheries of the region and the inclusion of these insightful long-term data sets in future assessments of sharks in the Gulf of Mexico.

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