A Thesis

by

PHILIP D. JOSE

Submitted to the Office of Graduate Studies of Texas A&M University
and Texas A&M University - Corpus Christi
in partial fulfillment of the requirements for the joint degree of

MASTER OF SCIENCE

December, 2014

Major Subject: Marine Biology

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Abstract

POPULATION TRENDS AND MIGRATION PATTERNS OF THE TEXAS NEARSHORE SHARK ASSEMBLAGE

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Chair of Advisory Committee: Dr. Greg W. Stunz

Large sharks are apex predators that play a key role in structuring marine ecosystems. Studies have shown declining shark populations worldwide, increasing the need for the population trends and habitat data necessary on a regional basis to manage these species appropriately. To date, meta-analyses have used limited fishery-independent data and have neglected nearshore coastal habitats. I examined population trends and habitat use of the nearshore environment using recreational catch logs, traditional tagging, and electronic tagging. Using a long-term dataset from recreational anglers, my study assessed the state of the nearshore shark community using size-based indicators (SBI) and multivariate analysis of catch records. Historical and modern catch logs were compared to determine potential changes in assemblage type and shark size since the 1970s. Multivariate techniques revealed a general shift in shark community assemblage from larger to smaller species. The SBI analysis showed a decrease in mean length in the shark community and size spectra analysis suggested a removal of larger species from the nearshore environment. Traditional mark and recapture studies revealed a general trend of southward movement for sharks tagged south of Matagorda Bay, TX and northward movement for sharks tagged north of Matagorda Bay, TX. Acoustically tagged sharks exhibited affinity for the nearshore habitat along north Padre and Mustang

Islands with some individuals using the Aransas Channel repeatedly over time. Pop-up archival transmitting (PAT) satellite tags revealed interconnectivity between the nearshore and continental shelf edge habitats and a general southward movement. My findings document a significant change in the size and composition of Texas' nearshore shark community potentially driven by overfishing and removal of large sharks as demonstrated elsewhere. This study also documented interconnectivity between nearshore and offshore habitat. Future management should account for these changes in community structure and connectivity of habitats when assessing shark stocks.

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Dedication

To my wife, Sara, whose love and support pushes me to achieve more.

Introduction

The decline of major worldwide fisheries has attracted the attention of many scientists (Pauly et al. 2002, Myers & Worm 2003, Worm et al. 2006, Jackson et al. 2001) resulting in a paradigm shift in management policies (Hilborn 2007, Worm et al. 2009). In 1996, the United States government reauthorized the Magnuson-Stevens Fishery Conservation and Management Act (MSA) in response to declining fish stocks (NMFS 2011). The renewed act, also known as the Sustainable Fisheries Act of 1996 (SFA), included amendments to rebuild overfished stocks and promote sustainable fishing practices. Federal regulations within the SFA stipulated the inclusion of Essential Fish Habitat (EFH) in all fisheries management plans, a regulation presently enforced (NOAA 1996). The application of EFH in management recognizes the importance of specific habitats throughout a species life cycle and the need to protect these habitats as a key component of effective fisheries management (NMFS 2006). Although these changes improved management, the single species management approach used did not drastically improve many fish stocks (Pikitch et al. 2004). In response, fisheries management has shifted away from single species management towards a more holistic ecosystem-based fisheries management (EBFM) approach (Pikitch et al. 2004, Smith et al. 2007). The EBFM approach prioritizes ecosystem needs over the needs of a target species and recognizes the importance of both the connectivity of species with each other and their abiotic environment. This approach requires an understanding of intraspecific relationships, individual species life histories, abiotic, and anthropogenic factors (Pikitch et al. 2004). Effective application of EBFM requires understanding single species in the context of the entire community. Integrating EFH and EBFM is difficult but essential to understanding and managing fisheries.

Apex predators, such as large sharks, are an important element in coastal marine ecosystems, making them a key component in EBFM. Removal of these predators has cascading effects on coastal ecosystems through density-dependent and indirect behavioral interactions within an ecosystem (Myers et al. 2007, Frid et al. 2008, Heithaus et al. 2008, Christensen et al. 2003). For example, trophic cascades can occur when mesopredators are released from predation pressures, increasing mesopredator abundance and foraging behaviors that results in altered predation pressure on lower trophic levels. An example in the Atlantic has occurred, where overfishing large sharks has resulted in an increase in cownose ray populations, which caused large decreases in abundance of the rays' primary prey, bay scallops (Myers et al. 2007). In addition to density-dependent effects, loss of predatory sharks can cause indirect behavioral effects (risk effects) on foraging times and choices of mesopredators (Frid et al. 2008, Heithaus et al. 2008). This ability to affect other trophic levels renders shark species a principal component of ecosystems where they naturally occur. Consequently, applying EBFM in these systems requires detailed knowledge of population structure and life history patterns to properly manage shark populations.

Sharks are also a valuable economic resource, as they are targeted by recreational and commercial fisheries. Sharks are considered a large trophy fish by recreational anglers and have historically been targeted for their jaws. Recently, anglers are moving toward practicing catch and release fishing with large sharks, releasing 95% of the sharks caught in 2010 (NMFS 2011). Increased awareness of marine conservation issues coupled with the advent of compact, inexpensive, high quality digital cameras may be contributing to this shift in angler behavior. Many anglers target sharks for the thrill of the fight and upon landing the shark record their catch with their digital camera before returning the shark to the water. Recreational anglers targeting all species of fishes spent an estimated $1.4 billion in Texas in 2011 (Lovell et al. 2013). In Corpus Christi, TX the annual Sharkathon tournament contributes to these angler expenditures as participants from across the United States purchase food, tackle, and lodging (personal observation). Tournaments that target sharks, such as Sharkathon, provide a boost to local economies. Commercially, sharks have been targeted for their liver oil, meat, and skin (Rose 1996). In Texas, the commercial seafood industry generated over $2 billion in 2010 (NMFS 2011). Although sharks are not a key species in the Texas commercial fishery, they are an important species for other commercial fisheries across the Gulf of Mexico (NMFS 2011). For instance, the collapse of bay scallop populations resulted in the closure of the bay scallop fishery in North Carolina. It is hypothesized that the bay scallop collapse was caused by trophic cascade when scallop predators were released from predation pressure with the removal of large shark species (Myers et al. 2007). This type of cause and effect relationship is instrumental in understanding the need for EBFM approaches to conservation and management. Sharks are an important economic species for both recreational and commercial fisheries throughout the Gulf of Mexico (Fowler et al. 2005). Shark conservation is not only a matter of ecological importance but also economic.

Since the 1960s, shark populations have declined along with many other global fisheries (Baum et al. 2003, Baum & Myers 2004, Burgess et al. 2005). In the North

Atlantic alone, shark populations declined more than 50% between 1986 and 2003, with Tiger Sharks and hammerheads being some of the most affected species (65% and 89%, respectively) (Baum et al. 2003). Global declines in shark populations are due in part to overexploitation related to 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). Commercial targeting of sharks for their fins increased dramatically in the 1980s and continues today, because of an increase in demand from Asian countries, especially China, for shark fin soup (Fabinyi, 2011). This demand coincides with the economic growth of Asian countries and is fueled by the traditionally held belief that shark fin soup is a delicacy that equates social status (Fabinyi 2011). Additionally, sharks make up a large portion of the total bycatch of commercial fisheries targeting non-elasmobranch species (de Silva et al. 2001). Sharks are particularly susceptible to overfishing because of slow growth rates, late maturity, and low fecundity (Musick et al. 2000). These traits along with the large-scale movement of many shark species create unique challenges for managers working to manage and rebuild declining shark populations (Speed et al. 2010).

The Southeast Fisheries Science Center of NOAA Fisheries conducted stock assessment workshops for shark species in 2005, 2007, 2010, 2012, and 2013 as part of the South East Data, Assessment, and Review (SEDAR, http://www.sefsc.noaa.gov/sedar/). These assessments have defined shark stocks, identified overfishing, and made recommendations for management of shark species (i.e. rebuilding targets and allowable catch). These assessments aggregate sharks into three classes: the Large Coastal Species (LCS) complex, the Small Coastal Species Complex

(SCS), and Pelagic Species. The LCS includes Blacktip, Bull, Scalloped hammerhead, Great hammerhead, Smooth hammerhead, Lemon, Nurse, Sandbar, Silky, Spinner and Tiger Sharks. The SCS includes Atlantic Sharpnose, Blacknose, Bonnethead, and Finetooth Sharks. The Pelagic Species includes Blue, Common Thresher, Oceanic Whitetip, Porbeagle, and Shortfin Mako Sharks. Single species analyses have been conducted in response to exploitation practices, assessing overfishing of single species or maintaining sustainable harvests (SEDAR 21, 29, 34). These assessments are used to help managers determine fishing regulations that will rebuild stocks as mandated by the SFA. Although shark species are grouped into larger management units that reflect a shift towards a more holistic EBFM approach, these groupings largely neglect examining trends within these management units. These groupings are focused on landings and abundance of "sharks" and do not distinguish trends among species within these units. Therefore, we have very broad information about "sharks" or very detailed information about a single species, but lack information about the effects of a single species within the context of the larger management unit.

Until recently, shark stock assessments and fisheries independent research have largely ignored nearshore habitat. Nearshore habitat use has been generalized for all shark species and has resulted in a lack of species-specific information in this habitat (Knip et al. 2010). This generalization led to a dearth of knowledge about nearshore sharks and the connectivity between the inshore, offshore, and nearshore environments.

The purpose of this study is to elucidate patterns within the nearshore shark community of Texas using recreational fishery data. The objectives are:

Chapter 1

I. Characterize the community assemblage in the historical and modern shark fishery
II. Determine if seasonal changes in community assemblage occur
III. Determine if changes in community assemblage have occurred over time

These patterns will be further investigated using conventional mark and recapture as well as electronic tagging. Electronic tags will be deployed with the help of recreational anglers, but once active will be independent of the recreational fishery. The objectives of this study are:

Chapter 2

I. Assess habitat use along the Texas coast
II. Understand connectivity amongst the inshore, nearshore, and offshore waters

This study will increase understanding of seasonal, temporal, and spatial trends of the nearshore shark community along the Texas coast. Information regarding trends within shark complexes (LCS and SCS) and nearshore habitat connectivity will be examined. This knowledge will provide insight to properly manage these species and inform policy makers. Furthermore, this study will key baseline data on shark abundance for future studies examining the nearshore shark community along the Texas coast.

Chapter 1 - Characterization of the coastal recreational shark fishery of Texas

ABSTRACT

Large sharks are apex predators that play a crucial role in structuring marine ecosystems. By examining historical trends in fisheries, numerous studies have shown declining shark populations worldwide as a result of overfishing of these k-selected species. However, these meta-analyses have used limited fishery-independent data and have neglected nearshore coastal habitats. Using a long-term dataset from recreational anglers targeting sharks in nearshore Texas waters, our study assessed the state of the nearshore shark community using size based indicators (SBI) and multivariate analysis of monthly catch records. We compared historical and contemporary catch data to determine potential changes in assemblage type and shark size since the 1970s. Multivariate techniques revealed a general shift in shark community assemblage from larger to smaller species. Specifically, Bull Shark abundance declined while Blacktip abundance increased. SBI analysis showed a decrease in mean total length in the shark community from 201.6 cm to 122.6 cm. Examination of the dominant species over time showed a large decrease in mean length of Bull Sharks from 232.8 cm to 175.1 cm and a modest increase in Blacktip Sharks from 125.1 cm to 127.9 cm. Size spectra analysis indicated a removal of large predators occurred. Our findings document a significant change in the size and composition of Texas' nearshore shark community potentially driven by overfishing and removal of large sharks as demonstrated in other regions of the Gulf of

Mexico. Future management decisions should account for this removal and address rebuilding stocks of large sharks.

Introduction

Apex predators, such as large sharks, are an important element in coastal marine ecosystems, making them a key component in Ecosystem Based Fisheries Management (EBFM). Removal of these predators has cascading effects on coastal ecosystems through density-dependent and indirect behavioral interactions within an ecosystem (Christensen et al. 2003, Frid et al. 2008, Heithaus et al. 2008, Myers et al. 2007). This ability to affect other trophic levels renders shark species a principal component of ecosystems where they naturally occur. Thus, having a strong understanding of shark population abundance and trends will improve our understanding and management of our oceans.

Sharks are also a valuable economic resource, as they are targeted by recreational and commercial fisheries. Sharks are considered a large trophy fish by recreational anglers and have historically been harvested for their jaws, while commercial fisheries have harvested sharks for their fins. Recently, anglers have been practicing catch and release fishing with large sharks, releasing 95% of the sharks caught in 2010 (NMFS 2011). Recreational anglers targeting all species of fishes spent an estimated $1.4 billion in Texas in 2011 (Lovell et al. 2013). Although sharks are not a key species in the Texas commercial fishery, they are a key species for other commercial fisheries across the Gulf of Mexico (NMFS 2011). Sharks are an important economic species for both recreational and commercial fisheries throughout the Gulf of Mexico (Fowler et al. 2005).

Since the 1960s, shark populations have declined in concert with most other global fisheries (Baum et al. 2003, Baum & Myers 2004, Burgess et al. 2005). In the North Atlantic alone, shark populations declined more than 50% between 1986 and 2003, with Tiger Sharks and hammerheads being some of the most affected species (65% and

89%, respectively) (Baum et al. 2003). Global declines in shark populations are due in part to overexploitation related to 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 movement of many shark species create unique challenges for managers working to manage and rebuild declining shark populations (Speed et al. 2010).

Overexploitation of apex predators has numerous direct and indirect effects. Changes in abundance are among these effects and usually cited as an indicator of ecosystem change. Size selectivity of fish also affects populations and ecosystems. Targeting and harvesting of large individuals, common in historical recreational shark fishing, results in the removal of these individuals from the population. These removals result in a truncated size structure of a species experiencing overfishing, particularly in sharks (Ward and Myers 2005). Furthermore, the removal of large predators can change behavior and habitat use of prey items, altering the food web of an ecosystem (Lewin et al. 2009). Determining overexploitation of a fish species and changes in ecosystems are challenges faced by managers seeking to rebuild fisheries. Understanding inter-specific interactions further complicates management when employing EBFM. Since sharks exert top-down effects in marine ecosystems, understanding changes in the shark community can provide insight into ecosystem changes.

Few data exist on the nearshore shark assemblage of Texas. However, land-based shark fishing has been popular in the state since the 1960s. The Corpus Christi Shark Club is an organization that targeted sharks along the Texas coast and maintained catch records from 1973 to 1986. Although there are inherent biases in fisheries dependent data, records from organized recreational fishing are useful as a historical baseline for time series comparisons of large species because these anglers heavily target the largest individuals and use traditional knowledge and methods in focusing their efforts (Powers et al. 2013). The advantage to fisheries independent data is that recreational anglers often sample a greater proportion of the largest size classes, making this pertinent information when assessing ecological trends in large fishes (Powers et al. 2013).

This study examines trends in the recreational shark fishery of Texas by comparing historical records (1973 to 1986) to modern records (2008 to 2013). Seasonality of the shark community assemblage was investigated to determine if changes in species composition occurred over time. Sex ratio and size structure was examined in the most commonly encountered species to resolve changes in population parameters. Changes in community size composition were ascertained using size spectra analysis. Examining differences in the historical and modern recreational shark catch allow us to infer community changes in the nearshore shark assemblage and assess the effects of exploitation and possible overfishing.

Materials and methods

Study site - This study was conducted along the coast of Texas in the northwestern Gulf of Mexico. Texas has eight major bay systems encompassed by a 560 km barrier island chain that separates estuaries from the Gulf of Mexico. The barrier island chain is comprised of 5 islands from north to south: Galveston, Matagorda, Saint Joseph's (San Jose), Mustang, and Padre Islands. Padre Island is the longest barrier island in the world measuring 177 km in length, covering an area from the Rio Grande River to Corpus Christi, TX, and has only one tidal inlet that connects the hyper saline Laguna Madre to the Gulf. Six major tidal inlets promote saltwater exchange between the Gulf of Mexico and shallow subtropical estuaries. A variety of habitats are supported by this region including soft bottom non-vegetated areas marked by submerged hard bottom structures such as remnant reefs along the Gulf side of the barrier island chain. Nearshore environments of Texas provide essential fish habitat (EFH) for numerous teleost, invertebrates, and shark species (Reese et al. 2008, NMFS 2009, Froeschke et al. 2010).

Volunteer angler network - The Center of Sportfish Science & Conservation has maintained network of volunteer anglers in conjunction with a shark tagging program since 2007. These anglers use hook-and-line gear to fish from piers, jetties, or the beach. This method is referred to as "land-based shark fishing" by enthusiasts and anglers are generally targeting large "trophy" sharks. Although variation exists amongst individual anglers, the general strategy for catching sharks from the beach in Texas involves using large reels spooled with about 800 to 1000 yards of 50# to 100# test line (monofilament or braided) with approximately 100 yards of topshot monofilament of increased strength.

A wire or monofilament leader consisting of a weight and a line with a hook ranging in size from 6/0 to 20/0 is connected to the topshot line. The hook is baited with large chunks of stingray, jackfish, or mullet and either surf cast or kayaked out 100 to 400 yards offshore. The majority of land based shark fishing effort occurs along the barrier islands of South Texas, Matagorda Bay, and San Luis Pass at the West end of Galveston Island, TX.

Anglers are provided with M-type dart tags (FLOY TAG, Inc.), tag applicators, and data cards to record pertinent information including date, location, stretch total length (STL), species, and sex. Upon tagging a shark, the cards are either returned to researchers or the data is submitted via an online form (http://www.harteresearchinstitute.org/shark-tags). Data were compiled in a Microsoft Access 2010 database file, quality checked for erroneous and missing data, and exported to Microsoft Excel 2010 file for importation into statistical programs for analysis. These data (2008 – 2013) comprise the modern dataset used in analyzing long-term trends in the shark fishery as tagging reports were used as a proxy of the shark catch.

A historical dataset of sharks caught in Texas recreational shark fishery was developed from catch logs of the Corpus Christi Shark Club provided by Captain Billy Sandifer. These data logs record shark catches from 1973 to 1986. A database was created in Microsoft Excel 2010 and data were filtered to include sharks that satisfied the following criteria: a complete date was included with the catch, sharks were identified to species level, an approximate location could be determined, and the location was within nearshore waters. The remaining sharks were compiled to construct the historic dataset used in analyzing long-term trends in the recreational shark fishery of Texas.

Two critical assumptions are made in this study regarding population subsamples and gear bias. The first is that sharks tagged or caught are an accurate representative subsample of the shark community present in nearshore habitat population. The second is that no bias has been introduced by alterations of gear or method of fishing. Although fishing technology has changed over time resulting in stronger materials, the method of targeting and catching sharks remains consistent and is a tradition passed from angler to angler. A high concentration of fishing effort occurred along the southern barrier islands of Texas, especially Padre Island National Seashore, in both historical and modern datasets so location effects are minimal.

Analysis of Sex Ratio - Sex ratio of sharks caught was examined using a Chi-square analysis to test the hypothesis that sharks occur in a 1:1 sex ratio. Tests were carried out using Microsoft Excel 2010. Sex ratios were examined for an aggregate of all shark species and within individual seasons in both the historical and modern datasets. Furthermore, the three most common species present in the modern dataset were tested individually. All sex ratio analyses assumed that reporting of males and females occurred with equal probability.

Characteristics of sharks caught in the modern fishery - Characteristics of the historical and modern recreational shark fishery were examined. These characteristics include the abundance, size range, and percent contribution of individual species. All shark sizes were measured as STL and converted to millimeters (mm) for analysis. Percent contribution was calculated in Microsoft Excel 2010. A barplot of the species composition for each dataset was constructed using the R (version 3.1.1) using the ggplot2 package (R core team 2014, Wickham 2009).

Trends in the recreational shark fishery of Texas - Differences in seasonality, community assemblage, and size structure between historical and modern data sets were examined. Data from both datasets were combined to make a single database in Microsoft Excel 2010. Individual sharks were assigned a dataset value (historical or modern) in this database respective of their source and also assigned a species complex (Large Coastal Species or Small Coastal Species) determined by the species as outlined by NOAA.

Heatmaps for each data set were constructed in R using the gplots, colorRamps, and RColorBrewer packages to compare monthly catches of individual shark species (R core team 2014, Warnes et al. 2014, Keitt 2012, Neuwirth 2011). Monthly abundance was scaled to a relative z-score for each species and plotted by color on a heatmap to determine months with above average occurrences of individual species. These were used to visualize and compare species occurrences throughout time for further analysis in conjunction with community assemblage.

Community assemblage comparisons among datasets and across seasons were conducted using a series of non-parametric multivariate analyses in PRIMER 6 version 6.1.16 with PERMANOVA+ version 1.0.6 (PRIMER E+ ltd., 2013). To account for variation in fishing effort that could introduce bias, data was standardized by computing a daily catch proportion for each species by dividing the number of individuals of a species caught in a single day by the total number of individuals caught in that same day. Species was input into PRIMER 6 as the variable and day as the sample. The following factors were added: year, season, and dataset. Standardized daily catch proportions were 4th-root transformed prior to the statistical analyses. A Bray-Curtis resemblance matrix was constructed and species assemblages were examined using analysis of similarities (ANOSIM) and non-metric multidimensional scaling (MDS) with groupings overlaid based on a CLUSTER analysis of the Bray-Curtis resemblance. A SIMPER analysis was performed to determine the species causing dissimilarity among datasets and seasons. The distance to centroids for the factors season and year were calculated to examine overall trends in these data and provide a clearer picture of tendencies in species assemblage from the recreational shark fishery between seasons and through time. These data were used to create MDS plots with overlaid CLUSTER groupings.

Size structures by STL in millimeters were constructed for yearly shark catch and for Bull and Blacktip within each dataset. Yearly size structures were constructed in a box and whisker plot using the ggplot2 package in R (Wickham 2009, R core team 2014). Density histograms of STL were constructed for Bull and Blacktip Sharks for each dataset using the ggplot2 package in R (Wickham 2009, R core team 2014). Vertical lines for the mean length of each dataset were added to the plots. A Cramer von mises test was run to compare the historical and modern datasets of the two species to determine if there were significant differences in distribution of size classes using R package cramer (R core team 2014, Franz 2006). Community size structure was examined with a size spectra analysis. This analysis plots log-transformed data of abundance given size. Stretch total length of sharks was transformed using the natural log+1 and binned in increments of 0.05. The count of each bin was then transformed by the natural log+1. These points were plotted by dataset and a quadratic model was fitted to each dataset in R (R core team

2014). This analysis was repeated on only the LCS complex to minimize bias introduced by differences in reporting of smaller species between the historical and modern dataset. The curvatures of the fitted models were compared to infer exploitation of shark populations (Shin and Cury 2004).

Results

Analysis of sex ratio

Historical dataset - Female sharks (N = 59) were not captured in significantly higher abundance than males (N = 45) (Chi-square; $p = 0.170$) (Table 1.1). There was a seasonal difference in sex ratios. Spring and summer did not have significantly different sex ratios ($p = 0.501$ and $p = 0.886$, respectively). However, females outnumbered males in the fall ($p = 0.039$). No sharks caught in winter were sexed and no analysis could be performed. Age class did not affect results, with adult and juvenile age classes returning non-significant differences ($p = 0.460$ and $p = 0.384$, respectively). No Young-of-the-year (YOY) were sampled in the historical dataset. Only 104 sharks of the 269 sharks in the historical dataset were sexed. Because of the small number of sharks sexed, individual species analysis was omitted for the historical dataset.

Modern dataset - Female sharks (N = 536) were caught significantly more often than male sharks (N=232) according to Chi-square analysis ($p < 0.01$) (Figure 1.1). Female sharks made up 70% of the total catch (Figure 1.1). Adult and juvenile age classes closely matched this ratio (Figure 1.1). Young-of-the-year had a greater contribution by males; however females still made up over 60% of the individuals caught (Figure 1.1). Chi-square analysis revealed a general trend in an uneven sex ratio across species (Table 1.2). This trend occurred across seasons and age classes. The chi square value for the YOY age class was marginally significant ($p = 0.0495$). Individual species did not necessarily reflect these overall aggregate trends.

Blacktip (modern) - Female sharks (N = 245) occurred more frequently than male sharks (N = 58). Female sharks accounted for over 80% of the aggregate, adult, and juvenile sharks caught (Figure 1.2). Females only accounted for 55% of the YOY sharks caught (Figure1.2). The null hypothesis of an equal sex ratio was rejected for Blacktip Sharks (Table 1.3). Furthermore, the unequal sex ratio occurs in all seasons. Adult and juvenile Blacktip Sharks were found to have unequal sex ratios, while YOY did not.

Bull Shark (modern) - Female sharks (N = 92) occurred more frequently than male sharks (N = 34). Female sharks accounted for over 70% of the aggregate, adult and juvenile groupings (Figure 1.3). No YOY sharks were caught in this study (Figure 1.3). The null hypothesis of an equal sex ratio was rejected for Bull Sharks (Table 1.3). Furthermore, the unequal sex ratio occurred only in fall, when Bull Sharks are most common. Adult Bull Sharks had an equal sex ratio, but juvenile sharks did not. No YOY sharks were caught and therefore no test could be performed on that age class.

Atlantic sharpnose (modern) - Atlantic Sharpnose Sharks occurred in the hypothesized 1:1 sex ratio (Table 1.5). Both spring and summer analysis failed to reject the null, while fall and winter were data deficient. Only the adult grouping of Atlantic Sharpnose Sharks rejected the null hypothesis, with males outnumbering females 4:1 (Figure 1.4). All other age classes occurred in the expected 1:1 ratio.

Table 1.1 Chi-square results for aggregate of all shark species 1973 to 1986. The hypothesis of a 1:1 sex ratio was tested overall and among seasons. Significant values are bolded.

Grouping Tested	χ2	df	p	N
Overall	1.885	1	0.170	104
Spring	0.444	1	0.505	36
Summer	0.020	1	0.886	49
Fall	4.26	1	**0.039**	19
Winter	N/A	1	N/A	0

Table 1.2 Chi-square results for aggregate of all shark species 2008 to 2013. The hypothesis of a 1:1 sex ratio was tested overall, among seasons, and among age class. Significant values are bolded.

Grouping Tested	χ2	df	p	N
Overall	120.333	1	**<0.01**	768
Spring	16.82	1	**<0.01**	200
Summer	35.466	1	**<0.01**	335
Fall	57.346	1	**<0.01**	185
Winter	24.083	1	**<0.01**	48
Adult	44.866	1	**<0.01**	260
Juvenile	74.266	1	**<0.01**	403
YOY	3.857	1	**0.0495**	84

Table 1.3 Chi-square results for Blacktip Sharks 2008 to 2013. The hypothesis of a 1:1 sex ratio was tested overall, among seasons, and among age class. Significant values are bolded.

Grouping Tested	χ2	df	p	N
Overall	115.409	1	**<0.01**	303
Spring	14.720	1	**<0.01**	93
Summer	43.679	1	**<0.01**	109
Fall	46.154	1	**<0.01**	78
Winter	19.174	1	**<0.01**	23
Adult	73.066	1	**<0.01**	181
Juvenile	48.039	1	**<0.01**	102
YOY	0.200	1	0.655	20

Table 1.4 Chi-square results for Bull Sharks 2008 to 2013.
The hypothesis of a 1:1 sex ratio was tested overall, among seasons, and among age class. Significant values are bolded.

Grouping Tested	$\chi 2$	df	p	N
Overall	26.698	1	**<0.01**	126
Spring	2.579	1	0.108	19
Summer	0.806	1	0.369	31
Fall	25.200	1	**<0.01**	70
Winter	2.667	1	0.102	6
Adult	2.778	1	0.0956	9
Juvenile	24.009	1	**<0.01**	117
YOY	N/A	1	N/A	0

Table 1.5 Chi-square results for Atlantic Sharpnose Sharks 2008 to 2013.
The hypothesis of a 1:1 sex ratio was tested overall, among seasons, and among age class. Significant values are bolded.

Grouping Tested	$\chi 2$	df	p	N
Overall	0.036	1	0.849	110
Spring	1.190	1	0.275	21
Summer	0.727	1	0.394	88
Fall	1	1	0.317	1
Winter	N/A	1	N/A	0
Adult	6.368	1	**0.012**	19
Juvenile	2.848	1	0.091	79
YOY	0.333	1	0.564	12

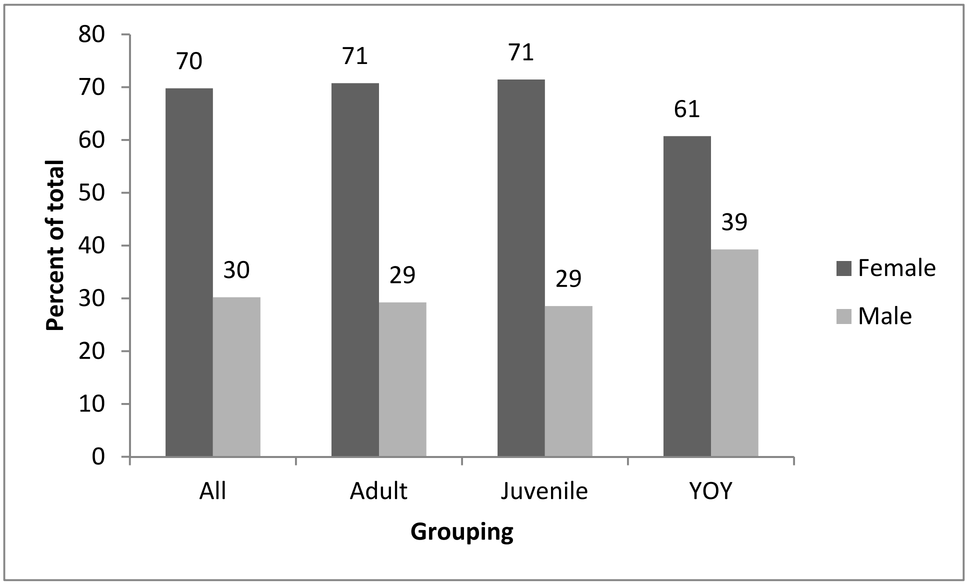


Figure 1.1 Sex ratio of all sharks caught by age class 2008 to 2013.
The sex ratio of sharks caught as a percent of the total grouped by age class. Females are in dark grey and males in light grey. The number above each bar is the percentage of occurrence for each sex within a group.

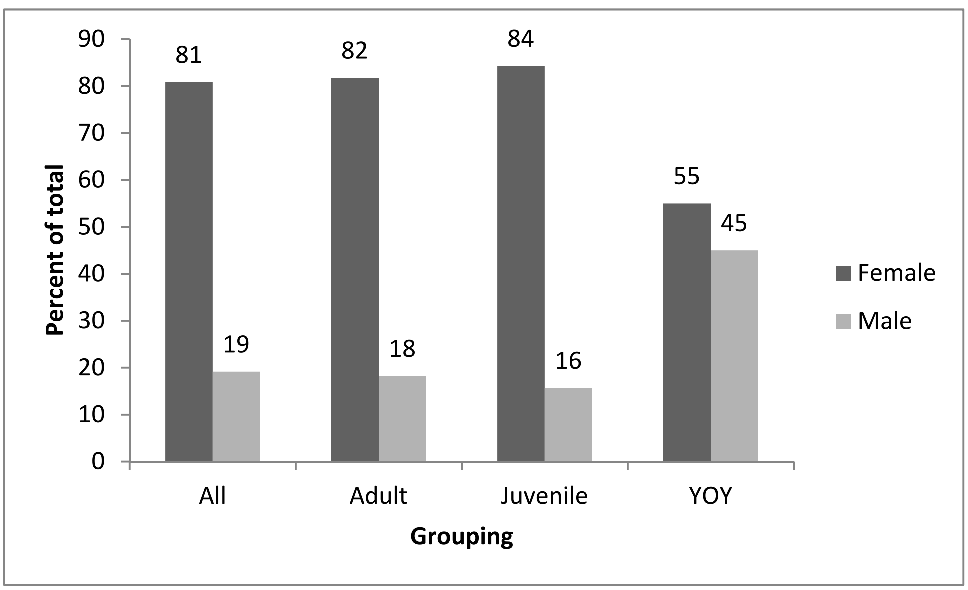


Figure 1.2 Sex ratio of Blacktip sharks caught by age class 2008 to 2013.
The sex ratio of sharks caught as a percentage of the total grouped by age class. Females are in dark grey and males in light grey. The number above each bar is the percentage of occurrence for each sex within a group.

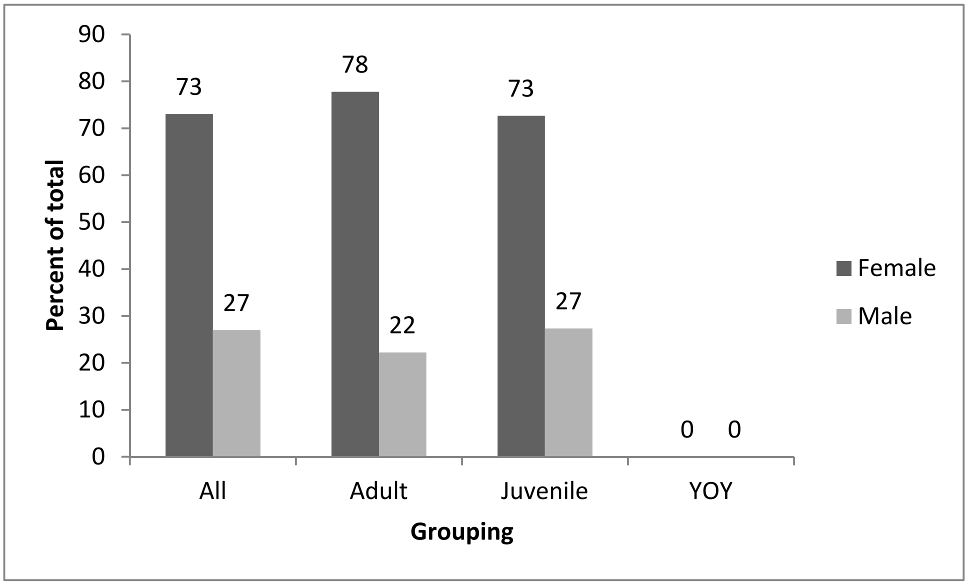


Figure 1.3 Sex ratio of Bull Sharks caught by age class 2008 to 2013.
The sex ratio of sharks caught as a percentage of the total grouped by age class. Females are in dark grey and males in light grey. The number above each bar is the percentage of occurrence for each sex within a group.

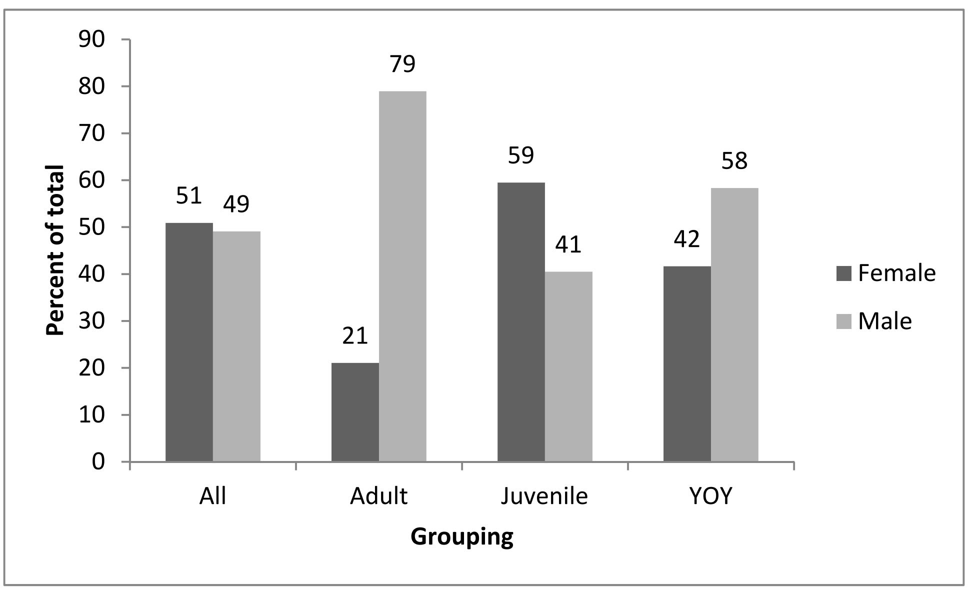


Figure 1.4 Sex ratio of Atlantic Sharpnose Sharks caught by age class 2008 to 2013.
The sex ratio of sharks caught as a percentage of the total grouped by age class. Females are in dark grey and males in light grey. The number above each bar is the percentage of occurrence for each sex within a group.

Characteristics of sharks caught in the modern fishery - A total of 791 sharks were identified from 14 different species (Figure 1.5). Ten sharks were excluded because they were unable to be positively identified to the species level. Only four species occurred greater than 50 times (Table 1.6). The most common species recorded was Blacktip (40%), followed by Bull Shark (17%), Atlantic sharpnose (15%), and Bonnethead (10%). Scalloped hammerheads were the smallest shark on average at 648 mm STL, followed by Bonnethead at 662 mm STL (Table 1.6). A large number of neonate sharks in the data set account for the small average size of Scalloped hammerheads. The smallest shark caught was a 318 mm STL Bonnethead (Table 1.6). Tiger Sharks were the largest average shark at 2546 mm STL and accounted for the largest overall shark caught at 3810 mm STL (Table 1.6).

Trends in the recreational shark fishery of Texas - Seasonality of shark species was evident in the catch of the historical and modern fisheries. Most seasonal patterns appeared to be similar between data sets. Bull Sharks appeared more frequently in early summer and fall in the modern data set. This is a change from the historical data that shows Bull Sharks to be a summer species. Blacktip Sharks appeared more frequently in the summer of the modern data set. The modern data set also had the appearance of two species, Silky and Blacknose sharks, not found in the historical data set (Figures 1.5 and 1.6).

Community analysis revealed differences in community assemblage among seasons and between datasets. Bray-Curtis cluster analysis of seasonal centroids revealed 2 distinct seasonal groupings at 55% similarity, with winter separating out from the other three seasons as evident by the MDS plot (Figure 1.7B). Bray-Curtis cluster analysis of yearly centroids revealed 4 distinct groupings at 50% similarity (Figure 1.7). The years 1980 and 1982 grouped separately from all other groups with 1980 being the most dissimilar (Figure 1.8). All modern dataset years grouped together and the remaining historical dataset years grouped together except for 1984 and 1985 which grouped with modern years. The MDS ordination shows a general trend of dissimilarity between modern and historical datasets with the most recent historical years being more similar to modern years (Figure 1.8B).

Multivariate tests revealed seasonal and temporal differences in community assemblage. Two-way ANOSIM returned significant difference in community structure by season (Global $R = 0.144$, $p < 0.01$) and by dataset (Global $R = 0.135$, $p < 0.01$). Seasonal differences were detected in the historic and modern datasets (Table 1.7). Variation of similarity occurred in non-consecutive seasons. In both analyses fall and spring were not significantly different from each other, while summer and winter were significantly different. Similarity of consecutive seasons varied between seasonal pairings and dataset. Fall and spring, fall and summer, and winter and summer were not significantly different in the historical dataset. In the modern dataset, the only consecutive seasons that were not significantly different were spring and summer.

A two-way SIMPER analysis was used to elucidate which species were contributing the most to differences in season (Tables 1.8 and 1.9) and dataset (Table 1.10). Bull and Blacktip Sharks contributed the most to the fall and spring species assemblage. Winter assemblages were almost completely classified with Sandbar Sharks. Summer assemblages were composed primarily of Bull and Tiger Sharks. Bull and

Blacktip Sharks contributed the most to dissimilarities in datasets. Blacktip Sharks were the most abundant in the modern data set, while Bull Sharks were most abundant in the historical dataset (Figure 1.5). Comparatively, Blacktip abundance increased over 3 fold and Bull Shark abundance decreased slightly. Furthermore, there was a precipitous drop off in Lemon and Scalloped hammerhead abundance over time. There was also a large increase in Bonnethead, Finetooth, and Atlantic sharpnose abundance over time. The data show a decline in larger shark species with an increase in smaller shark species. This includes a shift from large Bull Sharks historically being dominant species to the smaller Blacktip as the dominant species in the modern dataset.

Size structure analysis revealed stable long term trends in size of sharks marked by a severe decline starting in 1984 (Figure 1.9). Size distributions between the historical and modern dataset were significantly different ($p < 0.01$). There was a significant difference in size distribution ($p < 0.01$) marked by a decline in the average size of Bull Sharks over time with very few sharks larger than 2000 mm (Figure 1.10). The average size of Blacktip Sharks increased slightly over the same time period but the distribution was still significantly different ($p = 0.02$) (Figure 1.11). Size spectra analysis was implemented to determine if there was an overall pattern of decline in size of the shark community assemblage (Figure 1.12). This analysis was conducted on all species present in the shark community (Figure 1.12A) and on only the large coastal species (Figure 1.12B). A quadratic curve fit the data better than a linear curve. In both instances, the modern data set had a smaller curvature than the historical data set indicating a reduction in the size of sharks caught in the recreational shark fishery.

Table 1.6 Abundance and length measures of sharks caught.
The total number of sharks caught for all 14 species that occurred in the Texas recreational shark fishery. Mean, minimum, and maximum stretch total lengths are reported.

		Stretch Total Length (mm)		
Species	N	Mean	Minimum	Maximum
Atlantic sharpnose	115	683	335	1346
Blacknose	8	933	686	1130
Blacktip	318	1279	349	1981
Bonnethead	80	662	318	1755
Bull	131	1753	662	2578
Dusky	2	1918	991	2845
Finetooth	22	1091	465	1448
Great hammerhead	6	2167	1753	2565
Lemon	4	1829	1143	2565
Sandbar	23	1816	813	2311
Scalloped hammerhead	27	648	457	2464
Silky	7	1132	1041	1219
Spinner	34	1312	711	2210
Tiger	14	2546	1448	3810

Table 1.7 ANOSIM comparing seasonal shark community assemblages.
Pairwise comparisons between seasons of the shark community using ANOSIM. Seasons with significantly different shark communities are in bold. In all data sets, fall and spring were not significantly different.

	Historic		Modern	
Groups	R statistic	P value (%)	R statistic	P value (%)
Fall, Winter	0.304	**0.8**	0.58	**0.7**
Fall, Spring	0.036	14.7	0.081	9.6
Fall, Summer	0.049	15.2	0.15	**1.2**
Winter, Spring	0.074	15.7	0.402	**1.9**
Winter, Summer	0.484	**0.4**	0.694	**0.2**
Spring, Summer	0.128	**0.2**	0.04	21.1

Table 1.8 SIMPER analyses of seasonal effects on the historic shark community. Species contributions that added cumulatively to >75% are shown.

a

Historical: Fall & Winter						
Average dissimilarity = 90.21	**Fall**	**Winter**				
Species	**Av.Abund**	**Av.Abund**	**Av.Diss**	**Diss/SD**	**Contrib%**	**Cum.%**
Sandbar	0.04	0.71	27.14	1.44	30.08	30.08
Bull	0.46	0.21	17.99	0.97	19.94	50.03
Blacktip	0.27	0	9.86	0.59	10.93	60.95
Tiger	0.29	0	9.73	0.68	10.79	71.74
Dusky	0.04	0.21	7.48	0.61	8.29	80.03

b

Historical: Fall & Spring						
Average dissimilarity = 77.88	**Fall**	**Spring**				
Species	**Av.Abund**	**Av.Abund**	**Av.Diss**	**Diss/SD**	**Contrib%**	**Cum.%**
Bull	0.46	0.39	16.89	0.96	21.69	21.69
Blacktip	0.27	0.28	13.19	0.79	16.94	38.63
Sandbar	0.04	0.26	10.75	0.61	13.8	52.43
Lemon	0.23	0.22	10.36	0.76	13.31	65.73
Tiger	0.29	0.02	9.2	0.68	11.81	77.54

c

Historical: Winter & Spring						
Average dissimilarity = 78.48	**Winter**	**Spring**				
Species	**Av.Abund**	**Av.Abund**	**Av.Diss**	**Diss/SD**	**Contrib%**	**Cum.%**
Sandbar	0.71	0.26	21.37	1.17	27.23	27.23
Bull	0.21	0.39	14.52	0.87	18.5	45.74
Blacktip	0	0.28	9.12	0.62	11.62	57.36
Sandtiger	0.21	0.03	7.1	0.59	9.04	66.4
Lemon	0	0.22	6.65	0.58	8.47	74.87
Dusky	0.21	0	6.56	0.56	8.36	83.23

d

Historical: Fall & Summer						
Average dissimilarity = 71.14	**Fall**	**Summer**				
Species	**Av.Abund**	**Av.Abund**	**Av.Diss**	**Diss/SD**	**Contrib%**	**Cum.%**
Bull	0.46	0.56	15.76	1.04	22.16	22.16
Tiger	0.29	0.32	12.58	0.91	17.68	39.84
Lemon	0.23	0.24	10.76	0.77	15.12	54.96
Blacktip	0.27	0.13	10.33	0.69	14.52	69.48
Scalloped hammerhead	0	0.26	7.32	0.65	10.29	79.77

e

Historical: Winter & Summer						
Average dissimilarity = 92.23	**Winter**	**Summer**				
Species	**Av.Abund**	**Av.Abund**	**Av.Diss**	**Diss/SD**	**Contrib%**	**Cum.%**
Sandbar	0.71	0	25.32	1.49	27.45	27.45
Bull	0.21	0.56	16.37	1.14	17.75	45.2
Tiger	0	0.32	9.93	0.75	10.76	55.96
Lemon	0	0.24	7.74	0.59	8.39	64.35
Scalloped hammerhead	0	0.26	7.52	0.65	8.15	72.5
Sandtiger	0.21	0.02	6.56	0.59	7.11	79.62

f

Historical: Spring & Summer						
Average dissimilarity = 78.10	**Spring**	**Summer**				
Species	**Av.Abund**	**Av.Abund**	**Av.Diss**	**Diss/SD**	**Contrib%**	**Cum.%**
Bull	0.39	0.56	15.11	1.03	19.35	19.35
Lemon	0.22	0.24	9.98	0.77	12.78	32.13
Blacktip	0.28	0.13	9.62	0.71	12.31	44.44
Tiger	0.02	0.32	9.33	0.75	11.95	56.39
Sandbar	0.26	0	9.21	0.57	11.79	68.18
Scalloped hammerhead	0.17	0.26	8.72	0.78	11.16	79.34

Table 1.9 SIMPER analyses of seasonal effects on the modern shark community. Species contributions that added cumulatively to >75% are shown.

a

Modern: Fall & Winter						
Average dissimilarity = 82.73	**Fall**	**Winter**				
Species	**Av.Abund**	**Av.Abund**	**Av.Diss**	**Diss/SD**	**Contrib%**	**Cum.%**
Sandbar	0.06	0.72	21.63	1.36	26.15	26.15
Blacktip	0.7	0.23	17.9	1.18	21.64	47.78
Bull	0.58	0.16	14.46	1.2	17.48	65.26
Finetooth	0.04	0.34	8.29	0.96	10.02	75.28

b

Modern: Fall & Spring						
Average dissimilarity = 57.35	**Fall**	**Spring**				
Species	**Av.Abund**	**Av.Abund**	**Av.Diss**	**Diss/SD**	**Contrib%**	**Cum.%**
Bull	0.58	0.36	11.01	1.02	19.19	19.19
Blacktip	0.7	0.77	8.35	0.73	14.55	33.74
Spinner	0.28	0.07	5.94	0.91	10.36	44.11
Bonnethead	0.06	0.25	5.41	0.69	9.42	53.53
Atlantic sharpnose	0.08	0.22	4.91	0.76	8.56	62.09
Lemon	0.04	0.13	4.33	0.42	7.55	69.64
Sandbar	0.06	0.18	3.93	0.78	6.85	76.49

c

Modern: Winter & Spring						
Average dissimilarity = 77.67	**Winter**	**Spring**				
Species	**Av.Abund**	**Av.Abund**	**Av.Diss**	**Diss/SD**	**Contrib%**	**Cum.%**
Sandbar	0.72	0.18	19.56	1.19	25.18	25.18
Blacktip	0.23	0.77	18.2	1.22	23.43	48.62
Bull	0.16	0.36	9.2	0.94	11.84	60.46
Finetooth	0.34	0.18	8.29	1.03	10.68	71.14
Bonnethead	0.14	0.25	6.61	0.85	8.51	79.65

d

Modern: Fall & Summer						
Average dissimilarity = 56.28	**Fall**	**Summer**				
Species	**Av.Abund**	**Av.Abund**	**Av.Diss**	**Diss/SD**	**Contrib%**	**Cum.%**
Bull	0.58	0.38	9.44	1.06	16.77	16.77
Bonnethead	0.06	0.41	8.69	0.97	15.45	32.22
Spinner	0.28	0.25	6.64	1.02	11.8	44.02
Atlantic sharpnose	0.08	0.32	6.43	0.92	11.43	55.45
Blacktip	0.7	0.77	6.29	0.84	11.18	66.63
Tiger	0.08	0.23	4.98	0.75	8.85	75.48

e

Modern: Winter & Summer						
Average dissimilarity = 84.16	**Winter**	**Summer**				
Species	**Av.Abund**	**Av.Abund**	**Av.Diss**	**Diss/SD**	**Contrib%**	**Cum.%**
Sandbar	0.72	0	18.77	1.39	22.3	22.3
Blacktip	0.23	0.77	16.08	1.48	19.1	41.4
Bonnethead	0.14	0.41	9.34	0.97	11.1	52.5
Bull	0.16	0.38	8.26	1.05	9.82	62.32
Finetooth	0.34	0.07	7.21	0.97	8.57	70.88
Atlantic sharpnose	0	0.32	6.62	0.85	7.86	78.75

f

Modern: Spring & Summer						
Average dissimilarity = 55.89	**Spring**	**Summer**				
Species	**Av.Abund**	**Av.Abund**	**Av.Diss**	**Diss/SD**	**Contrib%**	**Cum.%**
Bonnethead	0.25	0.41	8.29	0.95	14.83	14.83
Bull	0.36	0.38	7.56	1.01	13.53	28.36
Atlantic sharpnose	0.22	0.32	6.67	0.98	11.94	40.3
Spinner	0.07	0.25	4.92	0.82	8.81	49.11
Blacktip	0.77	0.77	4.85	0.72	8.68	57.79
Tiger	0.04	0.23	4.41	0.7	7.89	65.68
Lemon	0.13	0.03	3.61	0.42	6.45	72.14
Finetooth	0.18	0.07	3.42	0.8	6.13	78.26

Table 1.10 SIMPER analysis of significant temporal effects on shark community. Species contributions that added cumulatively to >75% are shown

Modern & Historical Average dissimilarity = 74.00 **Species**	**Modern Av.Abund**	**Historical Av.Abund**	**Av.Diss**	**Diss/SD**	**Contrib%**	**Cum.%**
Blacktip	0.69	0.2	16.6	1.29	22.44	22.44
Bull	0.42	0.47	11.82	1	15.98	38.42
Lemon	0.06	0.22	6.49	0.61	8.77	47.19
Bonnethead	0.22	0.03	6.26	0.71	8.46	55.65
Tiger	0.11	0.2	6.11	0.66	8.26	63.91
Spinner	0.19	0.1	5.69	0.76	7.69	71.59
Atlantic sharpnose	0.18	0.04	5.1	0.7	6.89	78.48

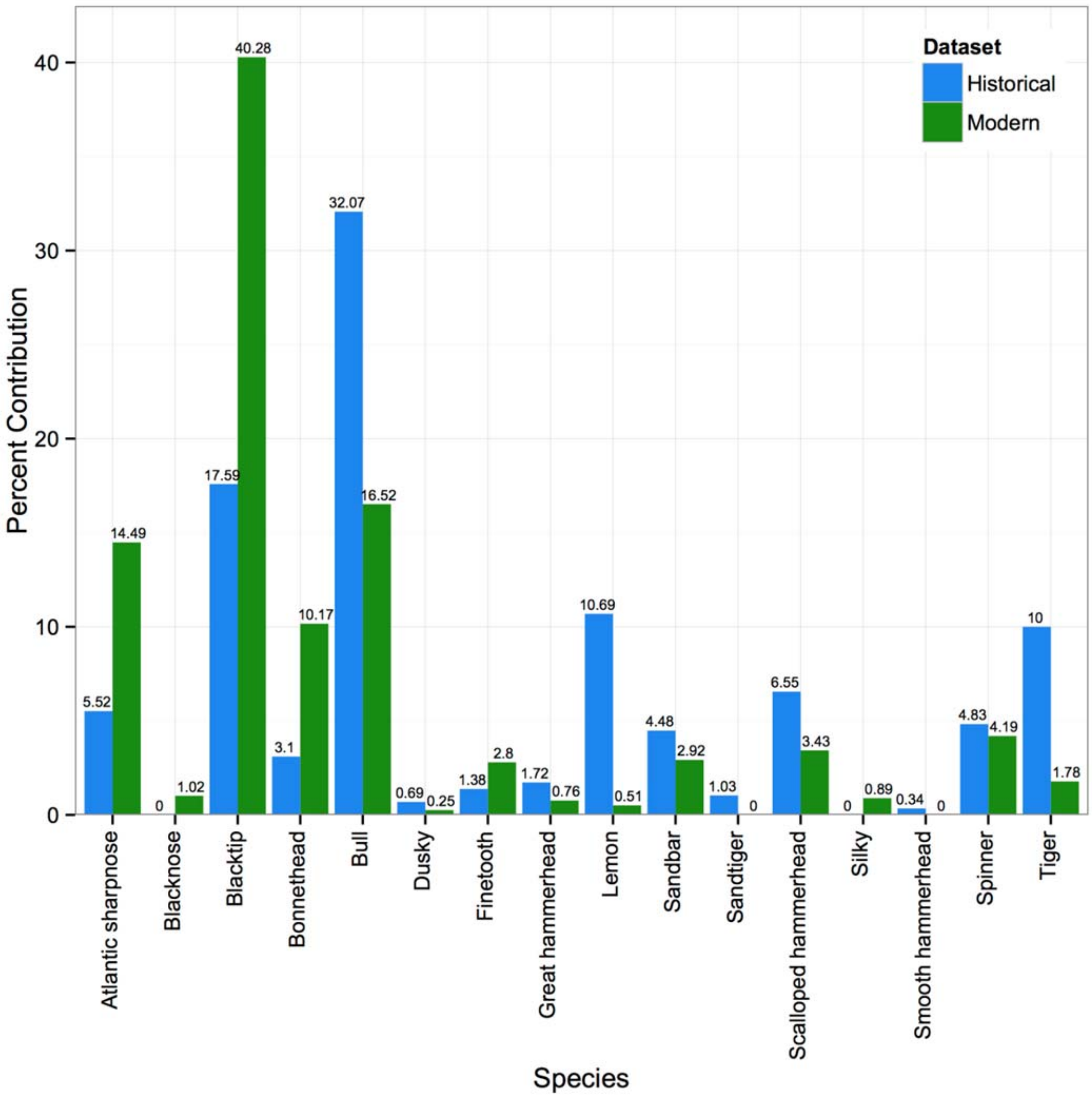
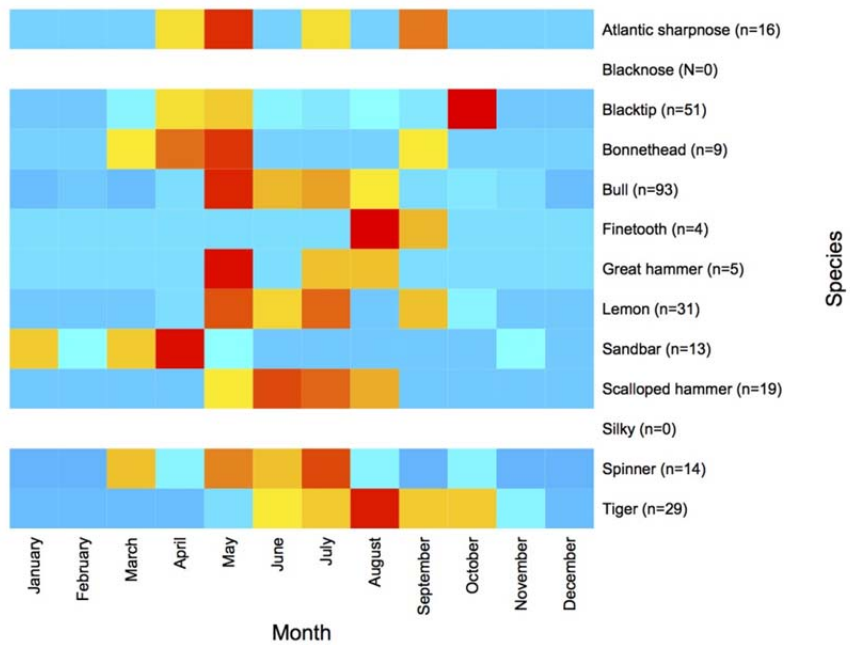


Figure 1.5 Percent contribution of shark species in historical and modern datasets
Number above each bar indicates the percent contribution of the species to their respective datasets.

A)



B)

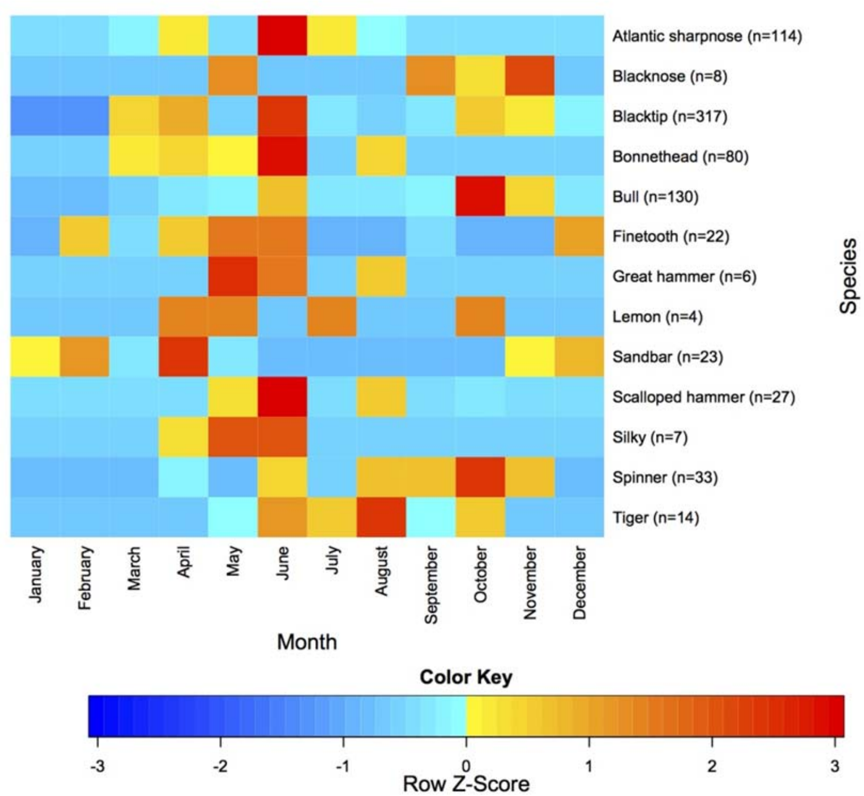
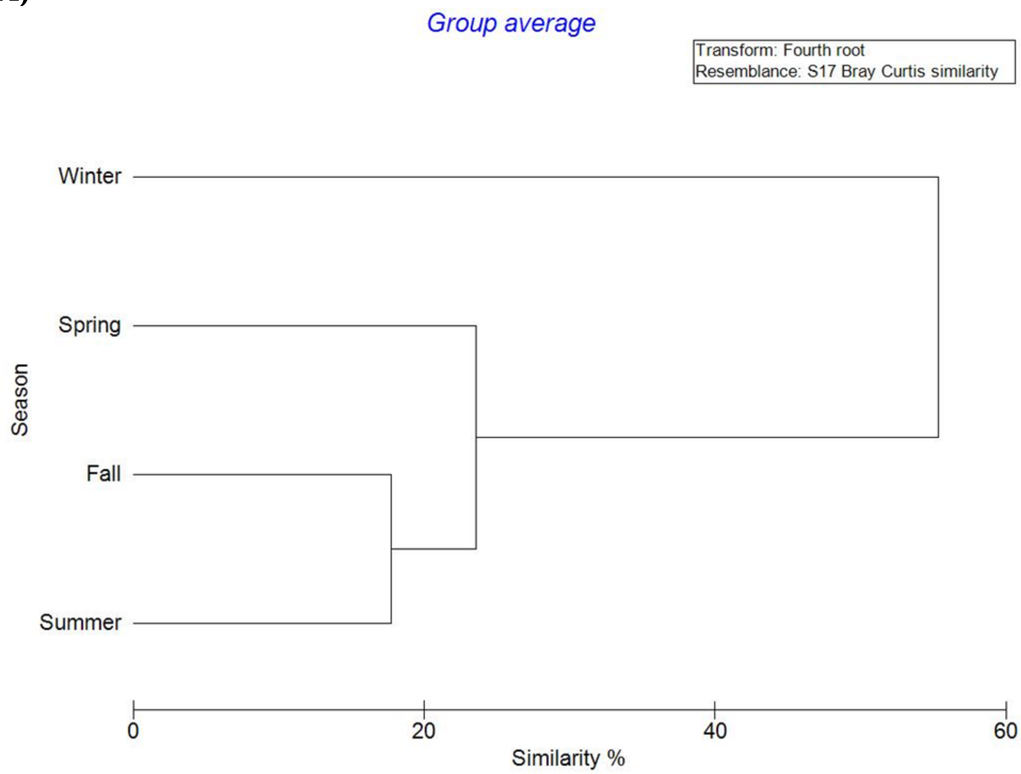


Figure 1.6 Monthly occurrences of sharks in the Texas recreational shark fishery. Heatmap of shark monthly occurrences standardized to individual species. A) Historical catch data from 1973 to 1986. B) Modern catch data from 2008 to 2013. Higher z-scores, displayed as warm colors, indicate higher probability of encountering each species.

A)



B)

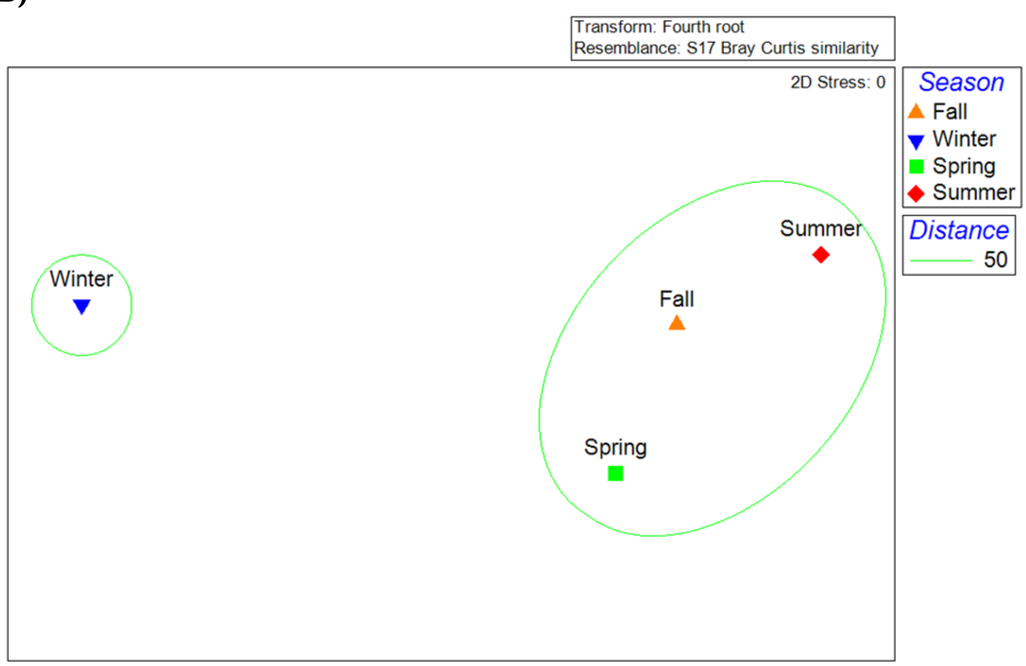


Figure 1.7 Bray-Curtis cluster analysis (A) and MDS ordination (B) of season. Bray-Curtis cluster analysis of seasonal centroids of sharks caught in the recreational shark fishery (A) and an MDS ordination (B) with Bray-Curtis cluster analysis superimposed using 50% similarity of species assemblage.

A)

B)

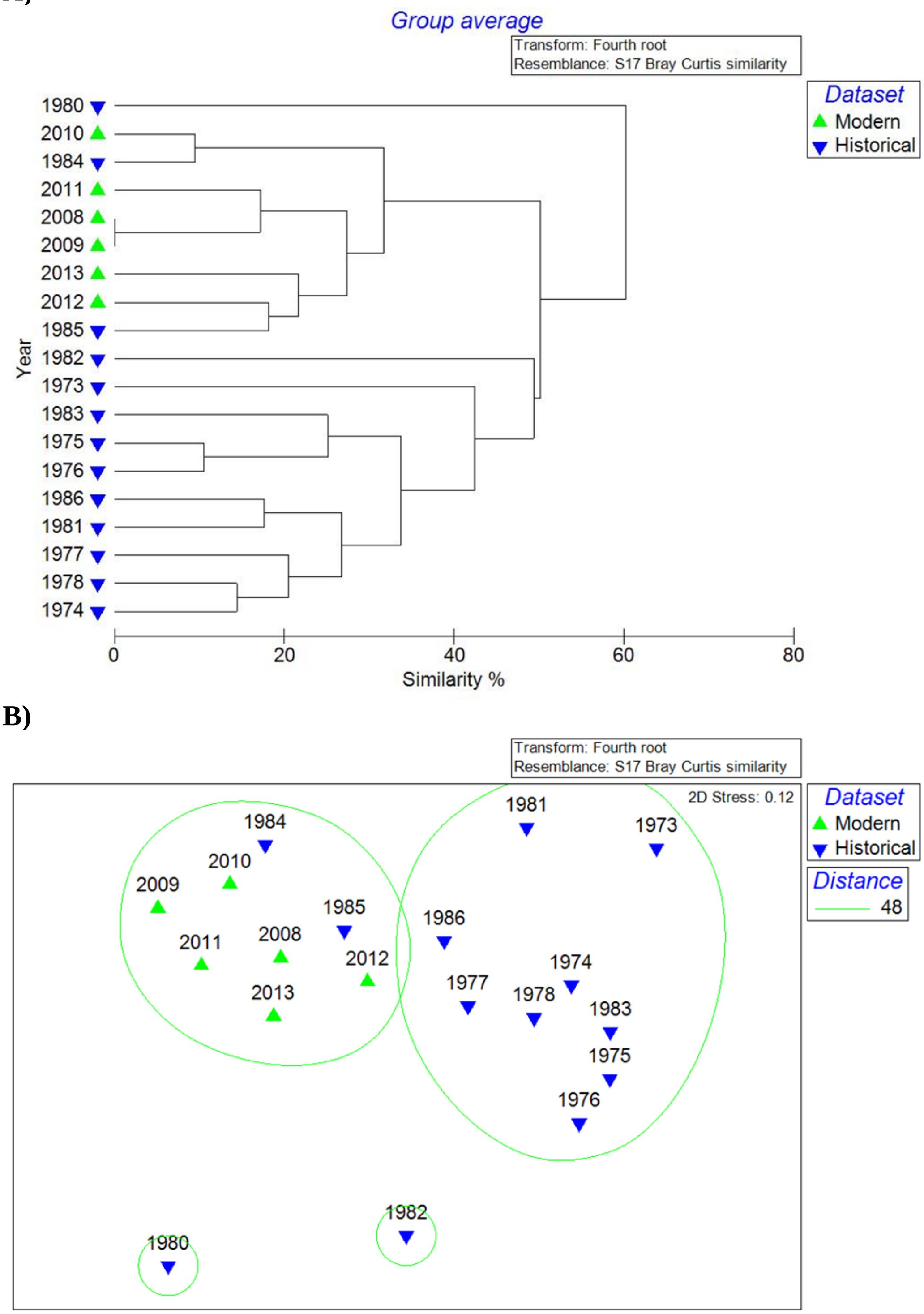


Figure 1.8 Bray-Curtis cluster analysis (A) and MDS ordination (B) of year. Bray-Curtis cluster analysis of yearly centroids of sharks caught in the recreational shark fishery (A) and an MDS ordination (B) with Bray-Curtis cluster analysis superimposed using 48% similarity of species assemblage.

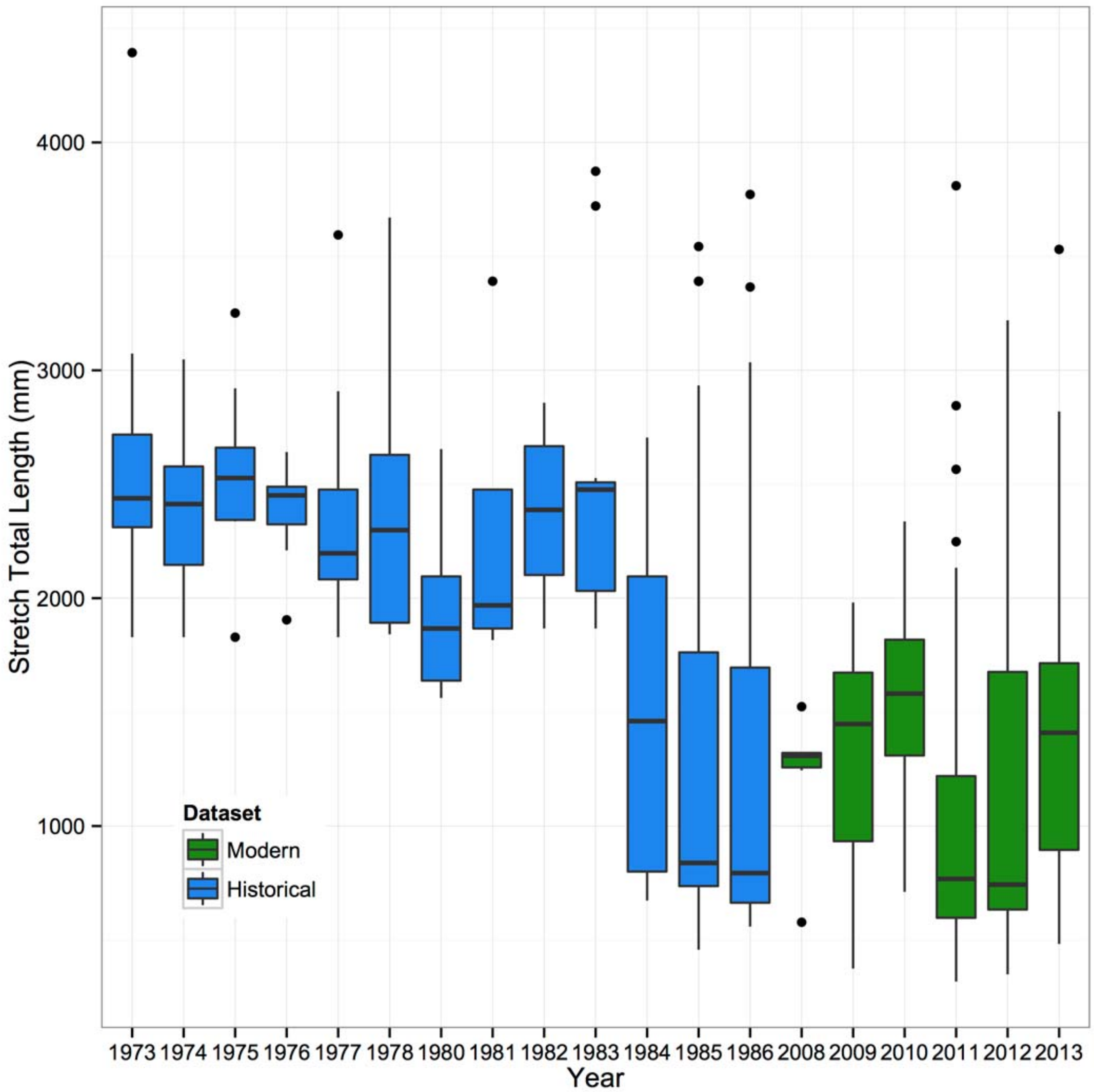


Figure 1.9 Box and whisker of the total lengths of sharks over time.
A boxplot of the total lengths of all shark species caught in the recreational shark fishery of Texas in a single year. Years are colored according to the data set they were assigned, historical (blue) or modern (green). The edges of boxes represent the 1st and 3rd quartiles. The horizontal black lines in the boxes are the medians. Whiskers extend to 1.5*IQR and dots represent outliers.

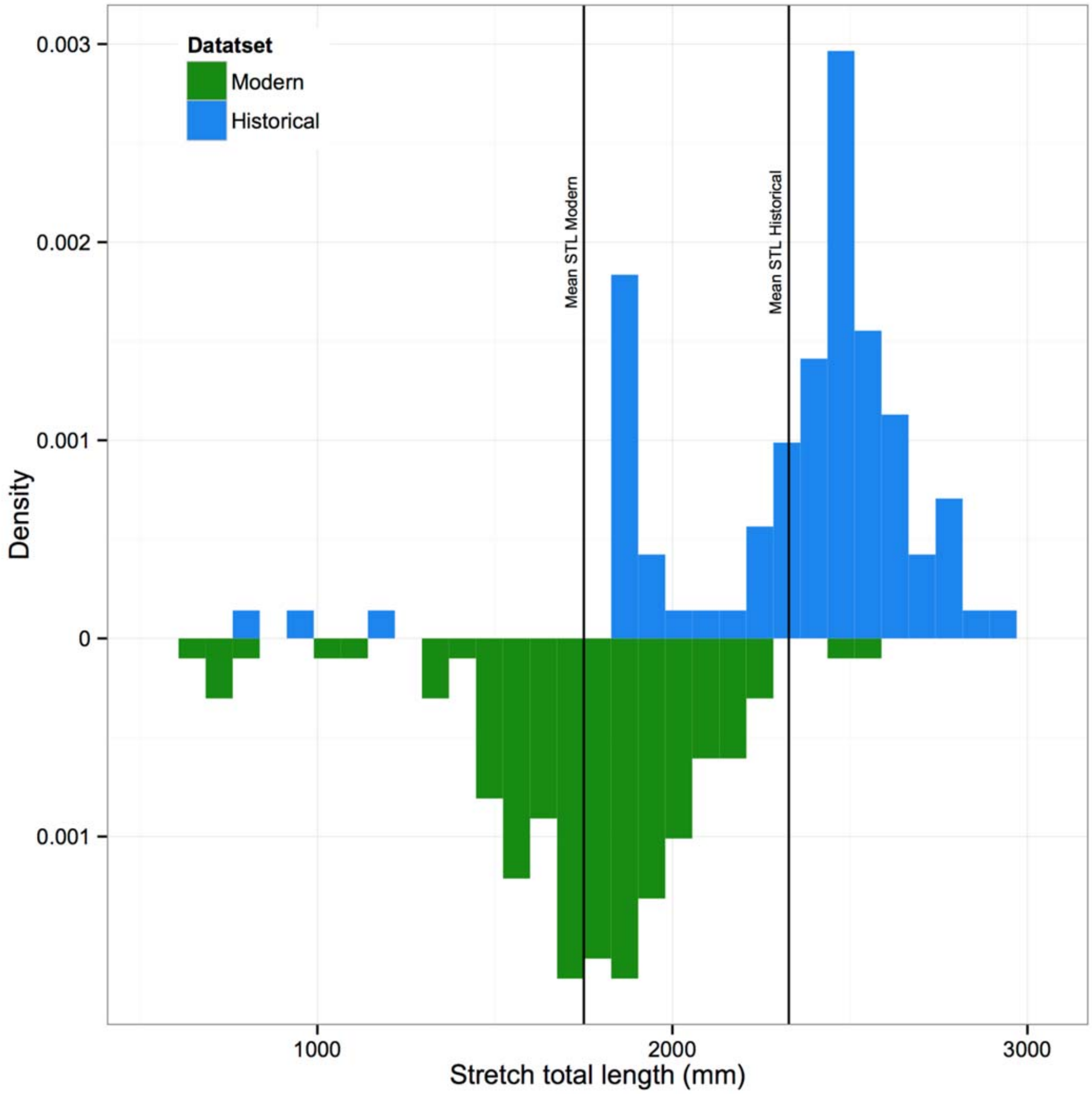


Figure 1.10 Density histogram of the frequency of lengths for Bull Sharks caught. This plot compares historical (blue) to modern (green) shark catch. The stretch total length in mm of sharks caught is on the abscissa. The ordinate is the density of the frequency of that size class caught.

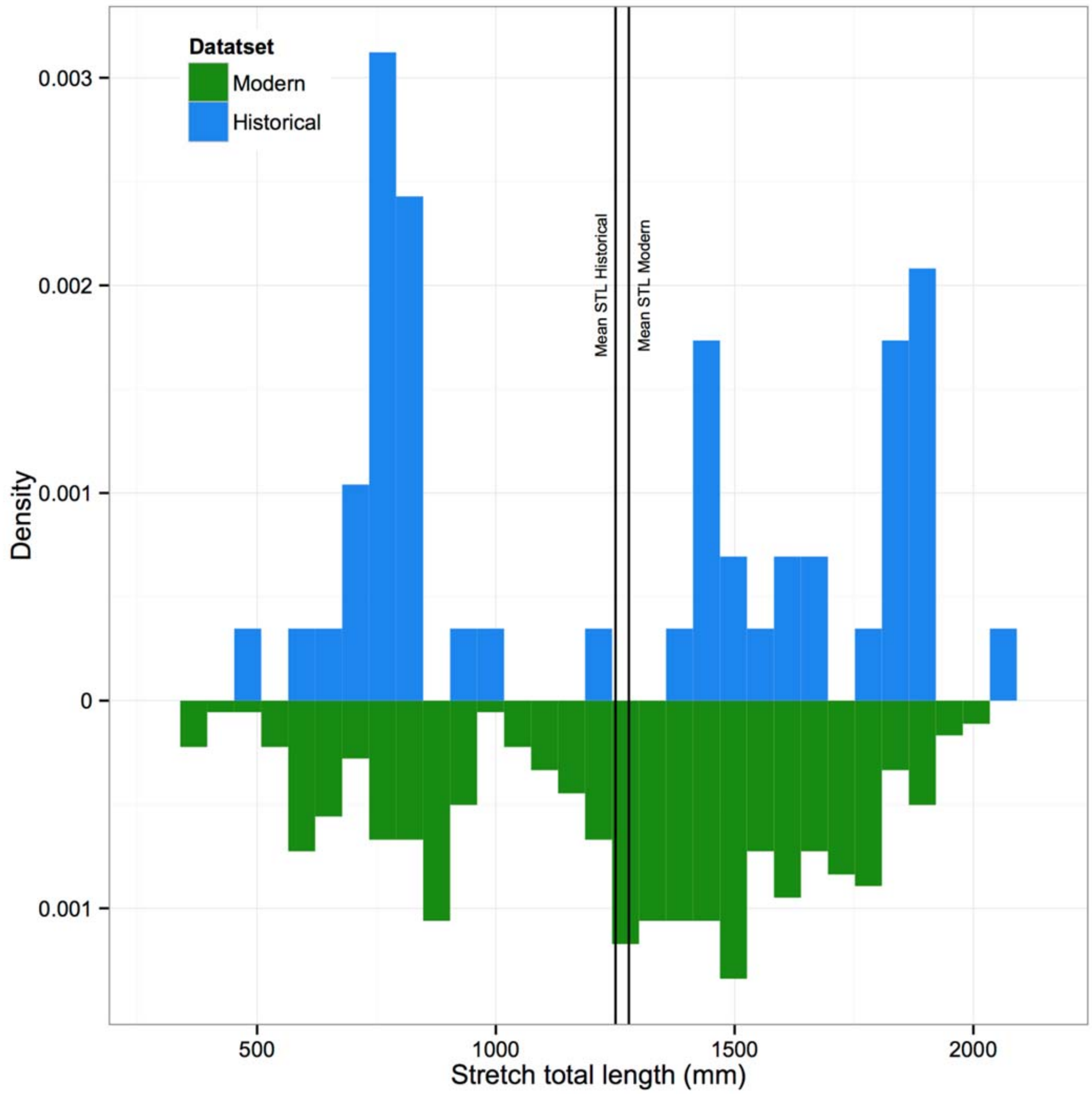
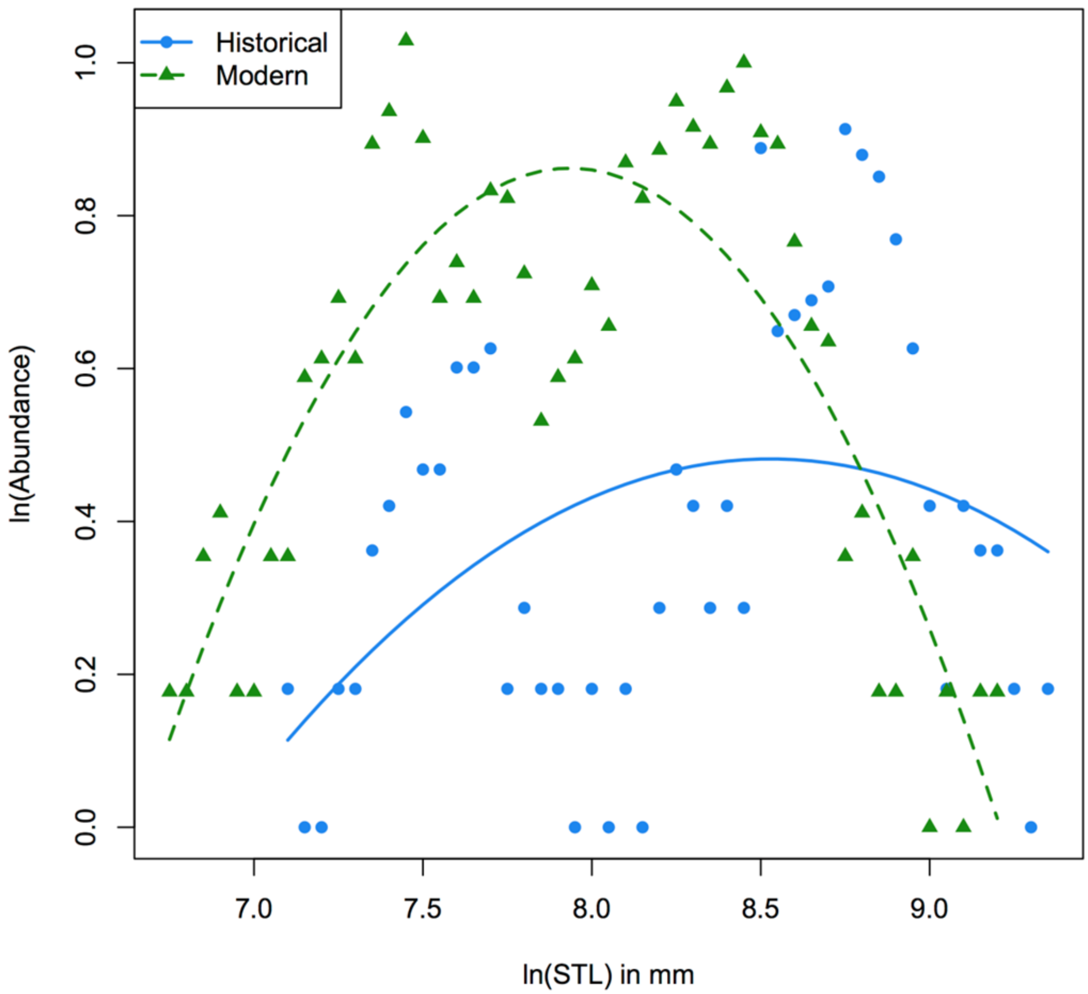


Figure 1.11 Density histogram of the frequency of lengths of Blacktip Sharks caught.

This plot compares historical (blue) to modern (green) shark catch. The stretch total length in mm of sharks caught is on the abscissa. The ordinate is the density of the frequency of that size class caught.

A)



Historical
Modern
ln(Abundance)
ln(STL) in mm
0.0
0.2
0.4
0.6
0.8
1.0
7.0
7.5
8.0
8.5
9.0

B)

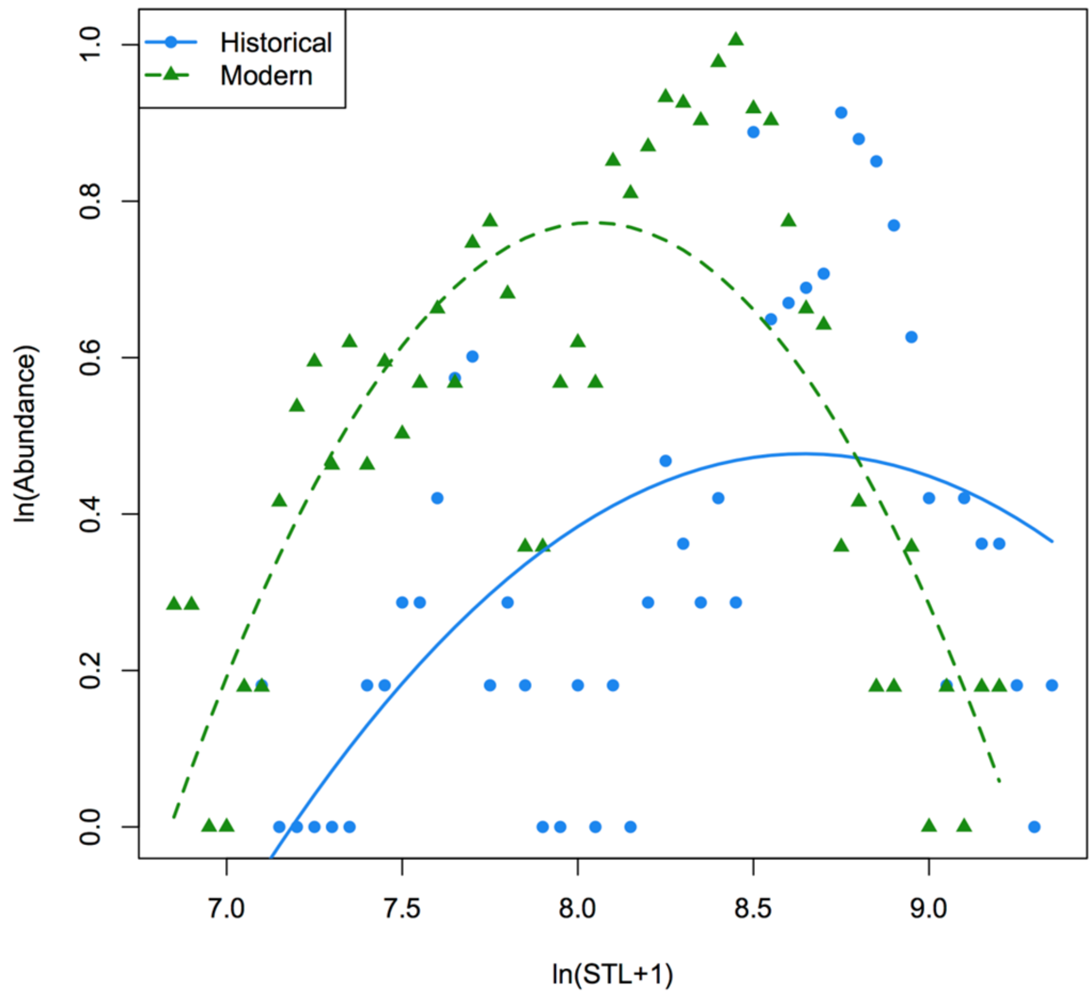


Figure 1.12 Size spectra analysis of (A) all sharks caught and (B) only the LCS in historical and modern data sets.
The curvature of the quadratic regression line was smaller for the modern data set in both analyses.

Discussion

Analysis of sex ratio - Female sharks occurred more frequently than male sharks in the recreational shark fishery, outnumbering males over 2:1. These data suggest female sharks use nearshore habitat more than males and sexual segregation may be occurring. Further examination showed this ratio does not hold true across all species or age classes. Therefore it is important to assess species and age class when investigating the sex ratio of nearshore sharks. These results are similar to other studies examining sex ratio of the nearshore shark community.

The overall sex ratio for Atlantic sharpnose in this study was 1:1. However, adult males outnumbered adult females 4:1 in the nearshore environment. Other life stages exhibited 1:1 sex ratios. These ratios suggest that adult male Sharpnose Sharks use nearshore habitat more than adult females but that juveniles and YOY do not exhibit similar sexual segregation. Previous studies have found male Atlantic Sharpnose Sharks are more common in nearshore shallow waters while females are more common in deeper waters (Drymon et al. 2010). Females may use deeper water to pup and the neonate sharks migrate back into nearshore habitats (Drymon et al. 2010). Although, deep-water habitats were not sampled, the results in this study suggest similar segregation in this species occurs along Texas.

This study found female Blacktip Sharks were more commonly encountered in nearshore habitat, outnumbering males 4:1. However, YOY sharks occurred in the expected 1:1 ratio. These results suggest that an ontogenetic shift may occur in Blacktip Sharks as they mature, with males moving out of nearshore waters along the Texas coast. Greater nearshore habitat use by females Blacktip Sharks has been demonstrated in other areas of the Gulf of Mexico (Drymon et al. 2010, Carlson et al. 2006, Branstetter 1987). Blacktips were commonly encountered during summer and fall in Texas, but absent in winter. Studies have shown Blacktip Sharks experience high residency during summer before embarking on southern migration during the fall (Heupel & Heuter 2001, Heupel et al. 2005). Blacktip Sharks in the nearshore Texas environment may be undertaking similar seasonal migrations.

Bull Sharks occurred in the expected 1:1 ratio in all seasons except for fall, when female sharks outnumbered male sharks. Bull Sharks were most abundant in fall and this data provides evidence that female sharks are responsible for the increase in abundance. These data suggest that seasonal sex segregation may occur in this species in Texas. No YOY Bull Sharks were encountered in this study, but numerous older juvenile sharks were found to inhabit nearshore waters. Bull Sharks are found throughout coastal waters with inshore bays serving as primary nursery areas (Froeschke et al. 2010, Curtis et al. 2011). Froeschke et al. (2010) found salinity to be a strong predictor for Bull Shark occurrence, with juveniles often found in moderate to low salinities, particularly around central Texas bay systems. These results in conjunction with previous findings suggest that the nearshore habitat along barrier islands is not suitable as primary nursery habitat for the YOY for Bull Sharks. However, the high frequency of juveniles suggests that nearshore barrier islands may serve as secondary nursery habitat for this species.

Characteristics of sharks caught in the modern fishery - Blacktip Sharks were the most abundant species in the nearshore habitat followed by Bull, Atlantic sharpnose, and Bonnethead Sharks. The suite of shark species encountered in the recreational fishery is similar to a previous survey of shark species in the nearshore habitat of the Gulf of Mexico that used fisheries independent data (Drymon et al. 2010). Blacktip, Bull, and Bonnethead Shark occurrence has been strongly correlated to moderate salinities along the Texas coast that are often found near tidal inlets (Froeschke et al. 2010). Many of these inlets in Texas are popular fishing spots, often with a major pier or jetty nearby. The high effort at these tidal inlets may account for the high abundance of these species in the recreational fishery.

Trends in the recreational shark fishery of Texas - Similar seasonal trends were found in historical and modern recreational shark fisheries. Spring and fall community assemblages were the most similar with Bull and Blacktip Shark comprising the majority of sharks caught. Winter was the most dissimilar season with Sandbar Sharks being caught almost exclusively. These trends also closely matched those found by Drymon et al. (2010) with the exception of the Atlantic Sharpnose Sharks in the modern fishery. Previous studies found this species peaked in fall in the northern Gulf of Mexico (Drymon et al. 2010, Parsons & Hoffmayer 2005), while this study found Sharpnose Sharks peaked in early summer for the modern dataset. Parsons and Hoffmayer (2005) found adult Atlantic sharpnose appearance correlated with water temperature and that an egress of adult sharks from nearshore waters occurred in summer. The increase in adult sharks in summer along Texas may be evidence for migrations from the northern to western Gulf of Mexico. However, more tagging/genetics studies are needed to confirm migration along the Texas coast.

Multivariate analysis statistically demonstrated distinct differences in shark community assemblages across seasons. Bray-Curtis cluster analysis and MDS ordination showed that winter was the most different season. A SIMPER analysis revealed Sandbar Sharks were the primary contributor to the winter species assemblage and was not a major contributor to the other seasons. Conrath and Musick (2008) found Sandbar Sharks overwinter in warm shallow waters in the northwest Atlantic off North Carolina. The nearshore Texas habitat, particularly along the southern barrier islands where concentrated effort occurs, fits these characteristics during winter months relative to the northern Gulf of Mexico. Sea surface temperatures along the southern barrier islands are significantly warmer than those along the coast of the northern Gulf of Mexico during winter months (www.nodc.noaa.gov). Sandbar Sharks are present in the nearshore habitat in the northern Gulf of Mexico from April to November, but their status from December to February in this area is unknown because those months were not sampled (Drymon et al. 2010). However, the relative abundance of Sandbar Sharks in the northern Gulf of Mexico and scarcity along Texas from April to November in addition to the sharks' arrival in Texas waters in December suggest the nearshore habitat along the southern Texas coast may serve as overwintering habitat for some Sandbar Sharks in the Gulf of Mexico. Further investigations on Sandbar abundance and tracking studies of this species during winter months in the northern Gulf of Mexico are required to determine connectivity between the northern Gulf of Mexico and Texas nearshore waters.

ANOSIM of historical and modern datasets showed similar species assemblages always occurred in fall and spring. SIMPER analysis showed this similarity was driven largely by Bull and Blacktip Shark. Previous studies found Bull Sharks exhibited high site fidelity and large-scale migratory movements were uncommon behavior (Carlson et al. 2010, Heupel et al. 2010). Blacktip Sharks have been documented to undertake seasonal migrations, leaving nursery habitat or moving along the east coast of the United States (Castro 1996, Swinsburg et al. 2012, Ulrich et al. 2007). The results of this study suggest that the Texas nearshore environment may serve as a migratory corridor for these species and possibly other species of sharks during transitional seasons such as spring and fall.

Species assemblage changed from the historical data set to the modern dataset. Bray-Curtis cluster analysis and MDS ordination of the yearly centroids showed 2 major groupings that separated predominately across data set classification. Only the 1984 and 1985 grouped with the modern years, and these were the two latest years in the historical data set. SIMPER analysis revealed Bull and Blacktip Shark largely affected the disparity in species assemblage between the data sets. In the historical data set, large coastal species, such as Bull, Lemon, Blacktip, Tiger, and Scalloped hammerhead sharks, contributed the most to the species assemblage. Many large coastal species that contributed to the historical dataset were replaced with smaller species. For instance Atlantic sharpnose, Bonnethead, and Finetooth sharks were more prevalent in the modern dataset while contribution from Lemon and Scalloped hammerhead sharks was minimal. Bull Sharks contributed most to the historical species assemblage followed by Blacktip. In the modern data set, this relationship was reversed with Blacktip becoming the dominant species. Although Blacktip are part of the LCS, they are a smaller species relative to Bull Sharks. These data suggest a general shift in community structure to smaller species over time. Furthermore, the similarity in species assemblage of later historical years with the modern dataset coincide with the opening of the commercial shark fishery and increased demand in shark fins in the 1980s. An increase in fishing pressure and targeting of larger sharks historically may explain the increase in smaller sharks due to a release in predation pressure and competition.

A decrease in size of species and communities can be an indication of overfishing (Graham et al. 2005). Bull Sharks decreased significantly in size ($p < 0.01$) over time while Blacktip Sharks showed a slight and non-significant, increase ($p = 0.655$). A decline in the size of top predators may have caused a trophic cascade that released smaller shark species from predation, resulting in the increase in the abundance and size of these species. Another explanation for the increase of small sharks in the modern data set is increased reporting by the recreational fishery. Shark anglers typically target the largest individuals and these smaller sharks may not have been considered “worth” recording in catch logs. Size spectra analysis was conducted to determine if shark stocks experienced overfishing. Overall size spectra analysis of the shark community showed a steeper slope of the regression line in the modern data set compared to the historic data set. This indicates that the shark community experienced exploitation and possibly historical overfishing (Graham et al. 2005). However, since an increase in smaller sharks in the modern data set due to improved reporting may have skewed the analysis, the size spectra analysis on only the large coastal species was performed. This test also returned similar results with the modern data set having a smaller curvature of the regression curve. Thus, it is likely that the decline in shark size is a result of exploitation and not improved reporting.

Assessment of the recreational shark fishery in Texas showed distinct temporal patterns in community assemblage and size. Seasonal patterns exist, driven largely by Bull and Blacktip Sharks in the fall and spring and Sandbar Sharks in the winter. The nearshore Texas habitat may be a migratory pathway for some shark species and serve as overwintering grounds for others. A shift in community assemblage from larger species to smaller species over time along with a decline in the size of sharks found in the nearshore community suggests these species have experienced high rates of exploitation and possibly overfishing. As shark stocks are rebuilt, greater attention should be given to shark communities as a whole to ensure rebuilt stocks reflect historical species assemblages. Until recently, the Texas nearshore habitat was not previously sampled for sharks. However, in 2009 Texas Parks and Wildlife began a bottom longline survey. My study provides a first attempt to characterize the shark species assemblage in the nearshore environment along Texas and can be used for comparison to later fishery independent studies.

Chapter 2 - Movement patterns of sharks along the Texas coast

ABSTRACT

Large sharks are apex predators that play a key role in structuring marine ecosystems. Studies have shown declining shark populations worldwide, increasing the need for the population trends and habitat data necessary to manage these species appropriately. To date, meta-analyses have used limited fishery-independent data and have neglected nearshore coastal habitats. In Texas, nearshore habitat along barrier islands was not scientifically sampled until 2009 when Texas Parks and Wildlife began a bottom longline survey. I employed traditional and electronic tags to monitor movement and habitat use of sharks in the nearshore environment. Traditional mark and recapture studies revealed a general trend of southward movement for sharks tagged south of Matagorda Bay, TX and northward movement for sharks tagged north of Matagorda Bay, TX. A total of 29 sharks were fitted with acoustic tags and 5 visited the array after tagging. Acoustically tagged sharks exhibited affinity for the nearshore habitat along north Padre and Mustang Islands with some individuals using the Aransas Channel repeatedly over time. Long absences from this area were punctuated with multiple brief visits over a short time span by sharks. Pop-up archival transmitting (PAT) satellite tags revealed interconnectivity between the nearshore and continental shelf edge habitats and a general southward movement. Sharks demonstrated depth selection from 10 m to 50 m and temperature selection around 27°C. This study also documented interconnectivity between nearshore and offshore habitat. Future management decisions should account for this connectivity of habitats when rebuilding shark stocks.

Introduction

Apex predators, such as large sharks, are an important element in coastal marine ecosystems, making them a key component in Ecosystem Based Fisheries Management (EBFM). Removal of these predators has cascading effects on coastal ecosystems through density-dependent and indirect behavioral interactions within an ecosystem (Myers et al. 2007, Frid et al. 2008, Heithaus et al. 2008, Christensen et al. 2003). This ability to affect other trophic levels renders shark species a principle component of ecosystems where they naturally occur.

Since the 1960s, shark populations have declined along with many other global fisheries (Baum et al. 2003, Baum & Myers 2004, Burgess et al. 2005). In the North Atlantic, shark populations have declined more than 50% between 1986 and 2003, with Tiger Sharks and hammerheads being some of the most affected species (65% and 89%, respectively) (Baum et al. 2003). Global declines in shark populations are due in part to overexploitation related to 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 movement of many shark species create unique challenges for managers working to manage and rebuild declining shark populations (Speed et al. 2010).

The nearshore environment is highly productive and provides habitat for a variety of shark species (Knip et al. 2010). This habitat is often proximal to high densities of human populations, making it economically valuable but also susceptible to perturbations (Knip et al. 2010). As such, a primary goal of Texas Parks & Wildlife Department (TPWD) fisheries management is to "create optimally sustainable fisheries populations" and healthy ecosystems along the Texas coast (tpwd.texas.gov). This environment has not been previously investigated as shark habitat in Texas and until recently (2009) no fishery independent data were available when TPWD began a bottom longline survey for sharks. Sharks are a popular recreational fish in Texas and understanding movement and nearshore habitat use will provide valuable insight into the management of shark stocks in Texas.

Traditional tagging and telemetry studies are useful tools in understanding habitat use and movement patterns of highly mobile marine species. Traditional tagging uses small plastic dart-type tags inserted into the musculature of a shark with a unique identification number to conduct a mark and recapture type study. Telemetry studies allow researchers to track animals without requiring the animal to be recaptured and can uncover linkages between distant ecosystems, making this type of study particularly suited for studying highly mobile species (Cooke et al. 2004). Acoustic and Pop-up archival transmitting (PAT) satellite tags are technology employed to track sharks. Acoustic transmitters emit a signal that is recorded and interpreted by stationary receivers in an acoustic array network. These tags provide presence/absence data of individual sharks at specific locations. PAT tags use daily light levels to estimate location while also recording water temperature and depth. These tags provide large-scale movement data and are not constrained by placement of a stationary acoustic array. Long-term habitat use can be determined from telemetry studies and provide finer resolution of large-scale movements than traditional mark and recapture studies.

The combined use of traditional tagging with telemetry will provide information on seasonal use and movement patterns of sharks in the nearshore environment of Texas.

Horizontal movement will be investigated using traditional tagging, acoustic tagging, and PAT tagging. Strategically placed acoustic receivers will monitor inshore and nearshore habitat use, particularly at tidal inlets, front beaches, and nearshore reef structures. While PAT tags will be employed to assess offshore habitat use. This study will investigate seasonal movement of sharks in the nearshore environment and determine connectivity between inshore, nearshore, and offshore habitats.

Materials and methods

Acoustic Tagging - Sharks were captured by hook and line and fitted with VEMCO brand acoustic transmitter tags from 2010-2013. A total of 29 sharks were fitted with transmitters and released in Texas waters (Table 2.1). Ten sharks were fitted with external tags, 5 V-13 and 5 V-16. The external transmitter tags were attached to M-type dart tags using superglue, gluing the length of the tags. The transmitters were further secured to the dart tags using 2 cable ties and heat-shrink tubing wrapped around the tags and cable ties. VEMCO brand V-16 tags were surgically implanted into the other 19 sharks, 10 of which included temperature and pressure (depth) sensors. A small incision (approximately 4cm) was made slightly off center from the ventral midline, posterior to the pectoral fins. The tag was inserted into the peritoneal cavity and the incision was closed with two Vicryl sutures using a basic surgeon's knot with three throws and treated with an antibiotic wash. During surgery, sharks were manually restrained, and the gills were aerated by pouring water over the gill slits (IAUCU #09-12). Post-surgery sharks were returned to the water and their condition was evaluated on a numeric scale: 0=Unknown; 1=Healthy; 2=Lethargic; 3=Requiring help; 4=Dead. Fish condition was used to determine a relative likelihood of post-surgical survival and inform data analysis to rule out detections that may be from sharks that did not survive the procedure.

A network of VEMCO brand VR2w receivers were deployed beginning in June 2011 and remained deployed for other projects. Monitoring of sharks for this project ended in December 2013. The network was deployed in three phases with three types of mounting systems (Figure 2.1). The first phase of the project overlapped with a previous fish tagging project and used the same receivers at major inlets along the South Texas coast that had been deployed before 2011 (Figure 2.1). This included Aransas Pass (Aransas North and Aransas South stations), Packery Channel (Packery East and Packery West stations), and Mansfield Cut (Mansfield East and Mansfield West). These receivers were attached to channel marker pilings and secured with a rope tied to an eye loop screwed into the piling. The second phase involved deploying three receivers at a near shore reef adjacent to Padre Island National Seashore (PINS), 7.5 Fathom Reef, in June 2011 (Figure 2.1D). These receivers were attached to a galvanized steel chain with cable ties and secured with a stainless steel cable crimped into a loop, shackled to the main chain. The chain was attached at one end to Quick-crete brand cement block (approximately 100 lbs) using a stainless steel shackle through a u-bolt sunk into the block while the cement was curing. A 25 pound float was attached to the other end of the chain to keep the receiver vertical in the water column. The entire apparatus was deployed on the top of the reef in three locations from a large metal hulled catamaran. The GPS locations were recorded for recovery. Two more receivers were deployed in this same fashion at “Porkchop’s Spot” and the “Mudflat,” locations north of the reef known to be anecdotal hot spots for sharks of varying species and age (Figure 2.1D). The final phase of receiver deployment occurred in spring 2012 and involved placing receivers at two popular fishing piers north of PINS: Bob Hall Pier (BHP) and Horace Caldwell Pier (HCP) (Figure 2.1). These receivers were attached to the outermost pier support using cable ties strung together and secured with a crimped stainless steel wire shackled to a tie out stake screwed into the substrate. Furthermore, previous receivers were upgraded to a new mounting system that did not require a swimmer to maintain. Receivers on pilings were attached to a galvanized steel pole using 3/8” x 5” bolts and cable ties. The poles were attached to a piece of angle iron above the water line by three 3/8” x 3” bolts. The angle iron was attached to the wood pilings with ½” x 6” lag bolts, with the receiver end of the pole submerged in the water. This allowed maintenance of the receivers from the deck of a small boat, requiring only the removal of the three exposed bolts to remove the pole and attached receiver from the water. Receivers at both piers and all inlets were replaced and data uploaded every 6-8 months. The receivers at the reef were replaced and data uploaded after 12-15 months. All receiver data were uploaded to a database in VEMCO’s proprietary VUE software. These data were then exported as a CSV file and imported into Microsoft Excel 2010 for further analysis.

Tag detections were filtered to ensure all detections used for analysis were from live sharks. Tag detections were compared to deploy date (i.e. the date the tag was implanted and shark released) and detection date to remove any detections that occurred previous to deployment. Detections were removed in this process, and it is hypothesized that the receivers detected tags that were being tested while in close proximity prior to deployment in the field. If detections from a single tag only occurred on a single receiver (or in the case of 7.5 Fathom Reef, receiver set) throughout the study and occurred at regular intervals closely matching the expected random interval from their programming over the course of 24 hours they were flagged as possible mortality or shedding events. Tags that appeared not to leave a receiver site and that transmitted continuously throughout the study were interpreted as a cessation of movement by the shark (i.e. death) or expulsion of the tag. Shedding of internally implanted tags either from transintestinal (Baras and Westerloppe 1999) or transabdominal (Daniel et al. 2009) expulsion has been previously documented, however not in sharks to date (Barnett et al. 2012). Tags that fulfilled these criteria were removed from the study. The remaining tags were used for analysis to examine site fidelity, residency, and migratory behavior.

Detections from verified tags were plotted using the ggplot2 package in R (Wickham 2009). Abacus plots were created with time along the abscissa and individual shark as the ordinate. Each receiver location was assigned a different color. Plots from a subset of the data were also created to highlight times of high activity of individuals in the receiver network. Time was plotted along the abscissa and receiver location as the ordinate. The receiver locations were ordered north to south from top to bottom and more clearly showed movement between locations over time of individual sharks.

The plots were examined for patterns in movement and habitat use. Visitation to a station was determined from individual time-stamped records, and any relocation occurring in a 24 hour period calculated as a single daily visitation (Dewar et al. 2008). Duration of visit and interval between visits was calculated for each shark and station within the array (Table 2.2). Receiver stations were assigned two habitat types based on location, front beach and inlet. Habitat use was examined by comparing the number of cumulative days in which a shark visited the network for each habitat type (Figure 2.7). Furthermore, the number of days with a visiting shark at each station for each habitat type was examined (Figure 2.8).

Satellite Tagging - Two sharks were tagged with Wildlife Computers MK-10 pop up archival transmitting satellite tags in 2010 and 2011. Archival data was binned in 8-hour bins in 2009 and 6-hour bins in all other years. Tags were programmed to release after 180 days or 192 consecutive hours at the same depth (±1 m) at which point they float to the surface and begin transmitting data to the ARGOS satellite system for download. Once data were downloaded, they were imported into Wildlife Computers DAP processor (3.0) software and geolocation was estimated using functions built into the DAP processor. Initial geolocation was estimated using the proprietary GPE2 software after poor data points were rejected. Horizontal movements were estimated using a state space Kalman filter (Kftrack and UKFSST). The Kftrack model calculates a most probable track using population specific parameters to create a random walk assuming geolocations are estimates (Sibert et al. 2003). The UKFSST model performs a similar calculation, but uses an unscented Kalman filter along with sea surface temperature to calculate a most probable track (Lam et al. 2008). The unscented Kalman filter is a more recent estimation technique that is both simpler to implement and more accurate (Lam et al. 2008). In instances where a model could not calculate a track with UKFSST, only KFtrack was used.

Location, depth, and temperature data was exported from the WC-DAP program to Microsoft Excel where it was quality checked and formatted for importation to R statistical software. Data from tags that released early were examined to determine the most likely date that meaningful data were recorded. Horizontal and vertical movements were compared by examining daily movement patterns. A lack of significant movement in both axes was interpreted as a tag that detached from a living shark or a mortality event. The first day a tag met these criteria was determined to be the last meaningful day of data. All data was used to create daily depth and temperature profiles in the R environment using the ggplot2 and akima packages (R Core Team 2014, Wickham 2009, Akima et al. 2013). A heatmap was interpolated for each shark indicating the frequency of use for depth bins programmed into the tag for each day. Daily minimum and maximum temperature and depth profiles were plotted to examine vertical movement and temperature selection. Lines were added to the plots to indicate the day a tag release was initiated as well as the most likely final day of meaningful data. An overall profile of depth and temperature selection was created for each shark using the ggplot2 package in R (R Core Team 2014, Wickham 2009). This analysis only included data that occurred prior to the last meaningful day before tag detachment. General trends in vertical movement, depth selection, and temperature selection for each shark were determined from these data. Locations estimated with the state space Kalman filters were imported into R for each shark. Tracks were created from these points using the ggplot2 package and mapped using ggmap, pacakge in R . A function for the scale bar was modified from script provided by Google groups user Osmo Salomaa (2011). Tracks of individual sharks were compared to patterns and trends in movement.

Passive Tagging - Sharks were caught using hook and line along the Texas coast from 2008 to 2013. An external dart tag was inserted into the shark's dorsal musculature after a small initial incision was made to penetrate the top dermal layer. Small sharks were fitted with plastic tipped Hallprint brand dart tags and larger sharks were fitted with Floy brand stainless steel M-type anchor dart tags. Rate of tag shedding is unknown, but at least one instance occurred during the study. Each tag had a unique identification number along with researcher contact information. Upon recapture, instructions on the tag directed anglers to report the location and date of the recapture shark to receive a reward.

The majority of sharks were tagged by recreational anglers participating in a volunteer network of anglers maintained by the Center of Sportfish Science & Conservation in conjunction with the shark tagging program since 2007. These anglers fished in waters along the Texas coast and generally targeted large sharks. The majority of effort occurred along the barrier islands of South Texas, Matagorda Bay, and San Luis Pass at the West end of Galveston Island, TX. Anglers were provided with M-type dart tags, tag applicators, and data cards to record pertinent information including date, location, size, species, and sex. Upon tagging a shark, the cards were either returned to researchers or the data was submitted via an online form (http://www.harteresearchinstitute.org/shark-tags). Data were compiled in a Microsoft Access 2010 database file, quality checked, and exported to Microsoft Excel 2010 file for importation into statistical programs for analysis.

Original tagging location and recapture location data were mapped using R with the ggmap package (Figure 2.15) (R Core Team 2014, Kahle and Wickham 2013). Each shark was assigned a movement vector by drawing a straight line between its original tagging location and recapture location. Total days at liberty were calculated for each shark along with Euclidian distance traveled and an average daily distance travelled (Table 2.3).

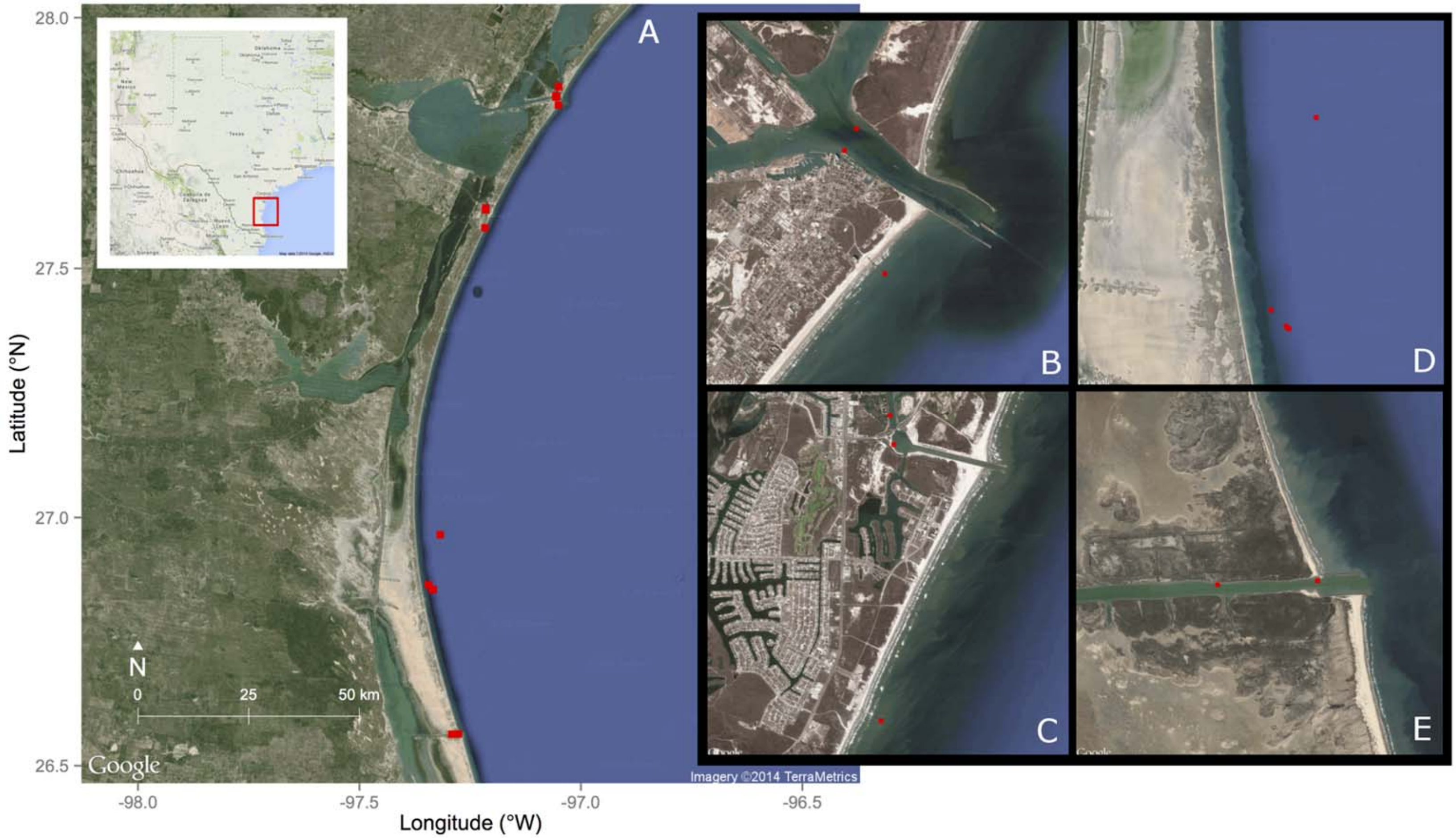


Figure 2.1 Locations of receiver stations in acoustic array, 2011 to 2013.
Receiver stations are marked by red boxes in each map, including (A) the entire array, (B) The Aransas Pass, (C) Packery Channel, (D) 7.5 Fathom Reef, and (E) Mansfield Pass. Stations from north to south are (B) Aransas North, Aransas South, HCP, (C) Packery West, Packery East, BHP, (D) Porchop's spot, Mudflat, 7.5 Fathom 1, 7.5 Fathom 2, 7.5 Fathom 3, and (E) Mansfield East and West (respectively).

Results

Acoustic tagging - Sharks fitted with acoustic transmitters demonstrated both large-scale movement and site fidelity. Of the 29 sharks tagged, 5 sharks returned to the array (sharks BT-152, BU-184, BT-297, BU-324, BU-371) (Figure 2.2). Shark BT-354 was present for an extended time after surgery and release. However, the frequency of detection, the poor release condition, and a lack of detections at other nearby stations was interpreted as a mortality event or a shed tag. This shark was removed from the dataset before analyses were conducted. Sharks were detected more frequently at beachfront stations than at inlet stations (Figure 2.7). Of the beachfront stations, 4 of the 7 received at least a single detection. Those stations were HCP, BHP, Porkchop's Spot, and Mudflat. No detections were recorded on receivers at 7.5 Fathom Reef. The only inlet stations that recorded detections were located inside Aransas Channel. Other stations located inside tidal inlets (Packery Channel and Mansfield Cut) did not receive detections. The majority of detections occurred at stations on the Gulf side of barrier islands, and only stations inside Aransas Pass received detections (Figure 2.8). Sharks were only detected during the summer and fall, with most detections occurring in fall (Figure 2.7).

Bull Sharks were the most commonly returning shark (n = 3) followed by Blacktip (n=2). Sharks demonstrated site fidelity by returning to stations after extended absences (Figure 2.3); 3 sharks returned to their original tagging location (BT-297, BU-324) or the station closest to their original tagging location (BU-184). A fourth shark (BT-152) was tagged along the beachfront in the northern portion of the array and returned to beachfront habitat along the southern portion of the array after more than 1 year (Figure 2.3). The fifth shark (BU-371) was tagged on the beachfront in the southern portion of the array and was detected over four months later at a southern beachfront array station, Porkchop's Spot (Figure 2.3). Both shark BT-297 and BU-324 use the areas near the piers most, returning after absences over 3 months and remaining in the area for several weeks. Shark BT-297 also used the Aransas Channel, moving north to south between BHP and Aransas Channel numerous times (Figure 2.5). Shark BU-324 exhibited the longest residency time in the array at 10 days (Figure 2.6). During this time, the shark was primarily detected at BHP. Shark BU-324 was visited the Aransas Channel, but never visited receivers placed further in the bay system for a concurrent study. Shark BU-184 was capture and tagged north of Aransas Channel along the barrier island known as St. Joe's Island (San Jose Island). This shark was never detected on any receiver south of Aransas Channel. The shark demonstrated short visitation duration times (<2 days), but high site fidelity by returning to the area over the span of three years. Shark BU-184 returned annually to the Aransas Channel area in August or September. In 2013, this individual was detected by a receiver for a concurrent study in the Lydia Ann Channel (Figure 2.4).

Five sharks were detected in the array after 24 hours of tagging and were present on multiple stations. Three sharks returned to the array within a year; two sharks were at liberty for longer than a year before returning. One shark, a large female Bull Shark, returned to the same area three times over a three year span. Shark BT-354 was present in the array, but it was presumed to have shed its tag or senesced due to lack of movement within the array and the intervals between detections.

Table 2.1 Detection distribution and morphological characteristics of sharks tagged.
"X" marks locations where an individual was detected and the bold represents release locations.

ID	Tag Type	Mounting	Species	Age Class	Sex	Date Tagged	STL(mm)	Location	Season	Condition	SJI	LAC	AN	AS	HCP	BHP	PINS	PCS	MF
BT-148	v16TP	internal	*Carcharhinus limbatus*	YOY	F	6/9/2011	581	Bob Hall Pier	Summer	0						**X**			
BT-151	v16TP	internal	*Carcharhinus limbatus*	YOY	M	6/9/2011	598	Bob Hall Pier	Summer	0						**X**			
BT-152	v16TP	internal	*Carcharhinus limbatus*	YOY	M	6/9/2011	560	Bob Hall Pier	Summer	0						**X**		X	X
BU-184	v16	internal	*Carcharhinus leucas*	Juvenile	F	9/22/2011	1770	St Joe Island	Fall	1	**X**	X	X						
BT-185	v16	internal	*Carcharhinus limbatus*	Adult	F	9/29/2011	1651	PINS 5	Fall	3							**X**		
BT-248	v16	internal	*Carcharhinus limbatus*	YOY	M	6/6/2012	570	Bob Hall Pier	Summer	1						**X**			
BT-265	v16	internal	*Carcharhinus limbatus*	Adult	M	6/8/2012	1314	Bob Hall Pier	Summer	1						**X**			
BT-267	v16	internal	*Carcharhinus limbatus*	Juvenile	F	6/9/2012	656	Bob Hall Pier	Summer	1						**X**			
BT-297	v16	internal	*Carcharhinus limbatus*	Adult	M	5/27/2012	1397	Bob Hall Pier	Spring	1			X	X	X	**X**			
BT-299	v16	internal	*Carcharhinus limbatus*	YOY	F	5/27/2012	650	Bob Hall Pier	Spring	2						**X**			
FT-304	v16	internal	*Carcharhinus isodon*	Juvenile	F	5/27/2012	1165	Bob Hall Pier	Spring	2						**X**			
BU-324	v16TP	internal	*Carcharhinus leucas*	Juvenile	M	6/2/2012	1702	Bob Hall Pier	Summer	1					X	**X**			
BT-332	v16	internal	*Carcharhinus limbatus*	Adult	F	6/9/2012	1310	Bob Hall Pier	Summer	1						**X**			
BT-338	v16	internal	*Carcharhinus limbatus*	Juvenile	M	6/19/2012	664	Bob Hall Pier	Summer	3						**X**			
BT-351	v16TP	internal	*Carcharhinus limbatus*	Juvenile	M	6/23/2012	666	Bob Hall Pier	Summer	1						**X**			
BT-354	v16TP	internal	*Carcharhinus limbatus*	Adult	F	6/23/2012	1280	Bob Hall Pier	Summer	2						**X**			
BT-355	v16TP	internal	*Carcharhinus limbatus*	Juvenile	F	6/23/2012	1240	Bob Hall Pier	Summer	1						**X**			
BU-369	v16TP	external	*Carcharhinus leucas*	Juvenile	F	6/27/2012	1956	PINS B	Summer	1							**X**		
BU-370	v16	external	*Carcharhinus leucas*	Juvenile	M	6/27/2012	1905	PINS B	Summer	1							**X**		
BU-371	v16TP	external	*Carcharhinus leucas*	Juvenile	M	6/28/2012	1981	PINS B	Summer	1							**X**	X	
BU-381	v16TP	internal	*Carcharhinus leucas*	Juvenile	M	6/23/2012	1733	Bob Hall Pier	Summer	1						**X**			
GC-383	v16	external	*Galeocerdo cuvier*	Unknown	F	6/23/2012	2915	Bob Hall Pier	Summer	3						**X**			
GC-385	v16	external	*Galeocerdo cuvier*	Unknown	F	6/23/2012	1918	Bob Hall Pier	Summer	0						**X**			
BT-386	v16	internal	*Carcharhinus limbatus*	Adult	F	6/23/2012	1403	Bob Hall Pier	Summer	0						**X**			
BU-455	v13	external	*Carcharhinus leucas*	Juvenile	F	10/31/2012	1956	PINS 39	Fall	1							**X**		
BU-460	v13	external	*Carcharhinus leucas*	Adult	F	11/1/2012	2261	PINS 39	Fall	1							**X**		
BU-501	v13	external	*Carcharhinus leucas*	Juvenile	F	8/30/2012	1676	PINS 40	Summer	1							**X**		
BT-503	v13	external	*Carcharhinus limbatus*	Adult	F	9/18/2012	1600	PINS 29	Fall	1							**X**		
BU-504	v13	external	*Carcharhinus leucas*	Juvenile	F	9/18/2012	1880	PINS 29	Fall	1							**X**		

Table 2.2 Summary of acoustic tag deployment along Texas from 2011 to 2013. Sharks in bold visited the array after initial tagging. Shark 354 was excluded because detection pattern indicated a mortality or tag shedding event. Information included on table is Date of tagging, the number of days between tagging a visiting the array, the number of visits, the number of days a shark visited, the minimum and maximum duration of a visit and interval between visits.

Shark ID	Date	Days 1st Visit	Visits	Days	Min Duration	Max Duration	Min Interval	Max Interval
BT-148	6/9/2011	-	0	0	0	0	0	0
BT-151	6/9/2011	-	0	0	0	0	0	0
BT-152	**6/9/2011**	**3**	**2**	**2**	**1**	**1**	**3**	**517**
BU-184	**9/22/2011**	**368**	**4**	**4**	**1**	**2**	**18**	**368**
BT-185	9/29/2011	-	0	0	0	0	0	0
BT-248	6/6/2012	-	0	0	0	0	0	0
BT-265	6/8/2012	-	0	0	0	0	0	0
BT-267	6/9/2012	-	0	0	0	0	0	0
BT-297	**5/27/2012**	**5**	**8**	**3**	**1**	**6**	**2**	**108**
BT-299	5/27/2012	-	0	0	0	0	0	0
FT-304	5/27/2012	-	0	0	0	0	0	0
BU-324	**6/2/2012**	**125**	**23**	**4**	**2**	**10**	**3**	**125**
BT-332	6/9/2012	-	0	0	0	0	0	0
BT-338	6/19/2012	-	0	0	0	0	0	0
BT-351	6/23/2012	-	0	0	0	0	0	0
BT-354	6/23/2012	-	-	-	-	-	-	-
BT-355	6/23/2012	-	0	0	0	0	0	0
BU-369	6/27/2012	-	0	0	0	0	0	0
BU-370	6/27/2012	-	0	0	0	0	0	0
BU-371	**6/28/2012**	**135**	**1**	**1**	**1**	**1**	**135**	**135**
BU-381	6/23/2012	-	0	0	0	0	0	0
GC-383	6/23/2012	-	0	0	0	0	0	0
GC-385	6/23/2012	-	0	0	0	0	0	0
BT-386	6/23/2012	-	0	0	0	0	0	0
BU-455	10/31/2012	-	0	0	0	0	0	0
BU-460	11/1/2012	-	0	0	0	0	0	0
BU-501	8/30/2012	-	0	0	0	0	0	0
BT-503	9/18/2012	-	0	0	0	0	0	0
BU-504	9/18/2012	-	0	0	0	0	0	0

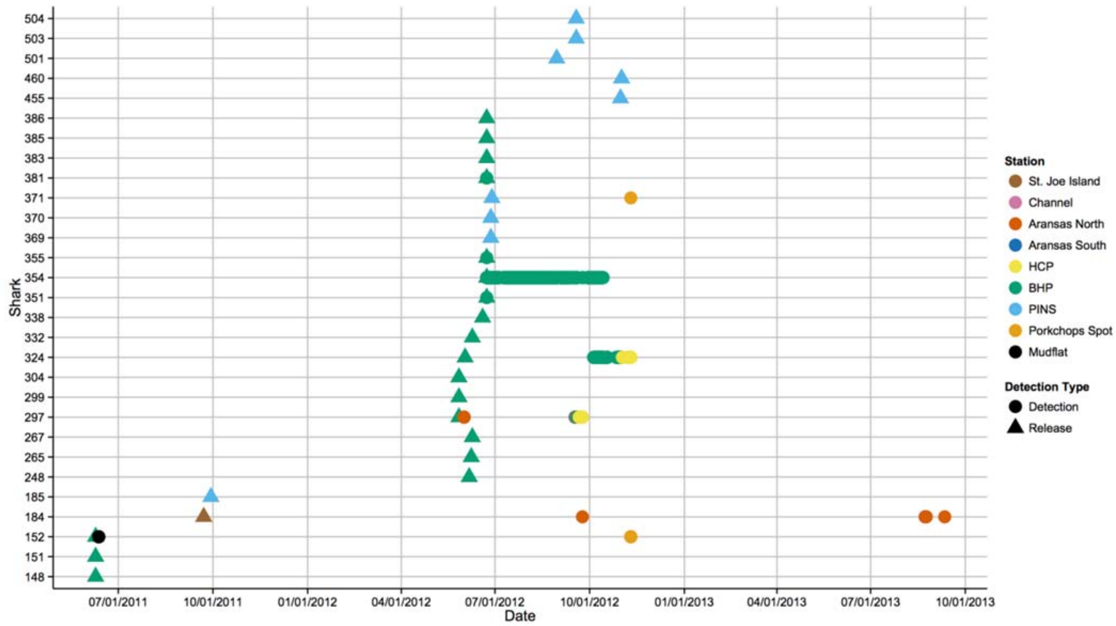


Figure 2.2 Abacus plot of detection history of sharks acoustically tagged in Texas. Detection history displayed over time from 2011 to 2013. Circles indicate detections in the acoustic array and triangles indicate original capture and tagging. Location of detection and tagging are indicated by color.

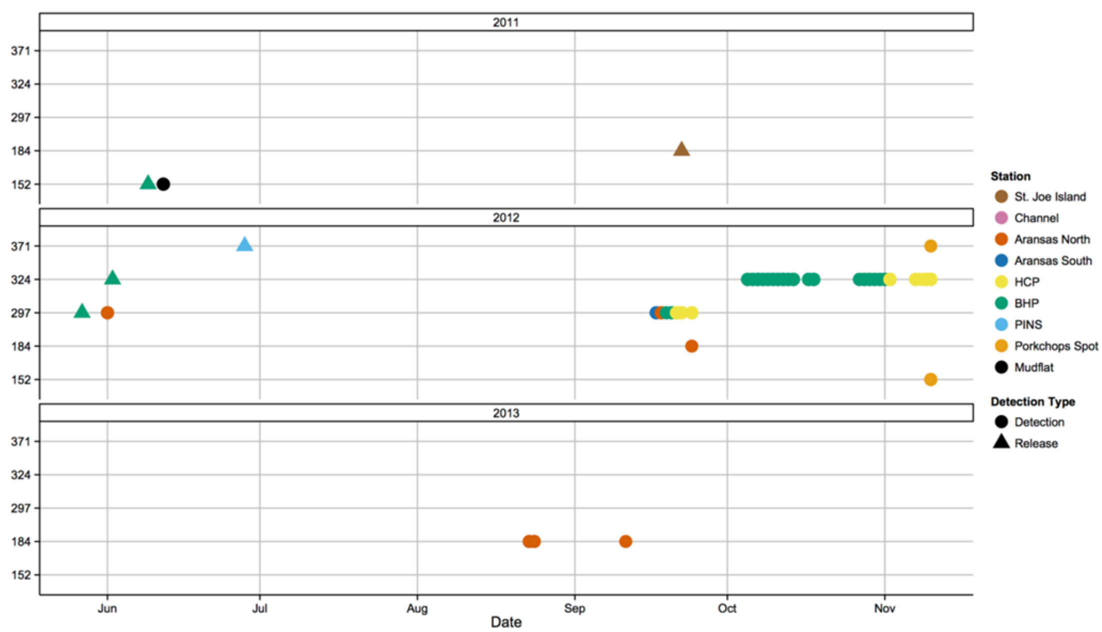


Figure 2.3 Abacus plot of detection history of sharks that returned to acoustic array. Detection history displayed over time from 2011 to 2013. Circles indicate detections in the acoustic array and triangles indicate original capture and tagging. Location of detection and tagging are indicated by color.

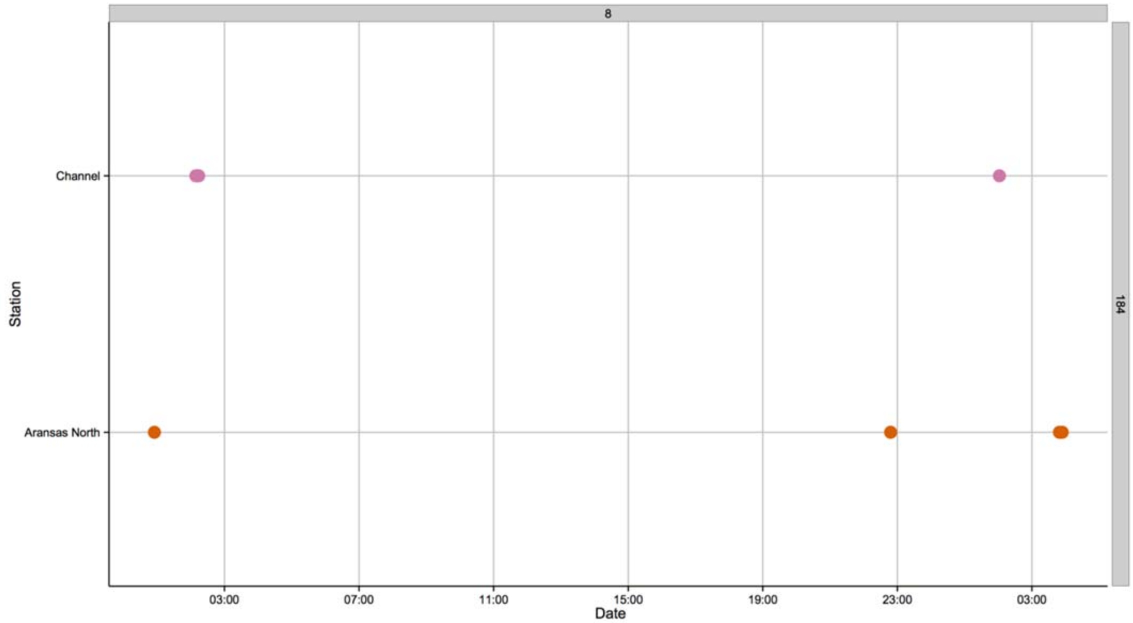


Figure 2.4 Abacus plot of detection history of BU-184 from 8/23 to 8/24/2013. Points indicate a detection or hit of the shark in the acoustic array. Stations are indicated by color and ordered on the ordinate by latitude. Time is plotted on the abscissa.

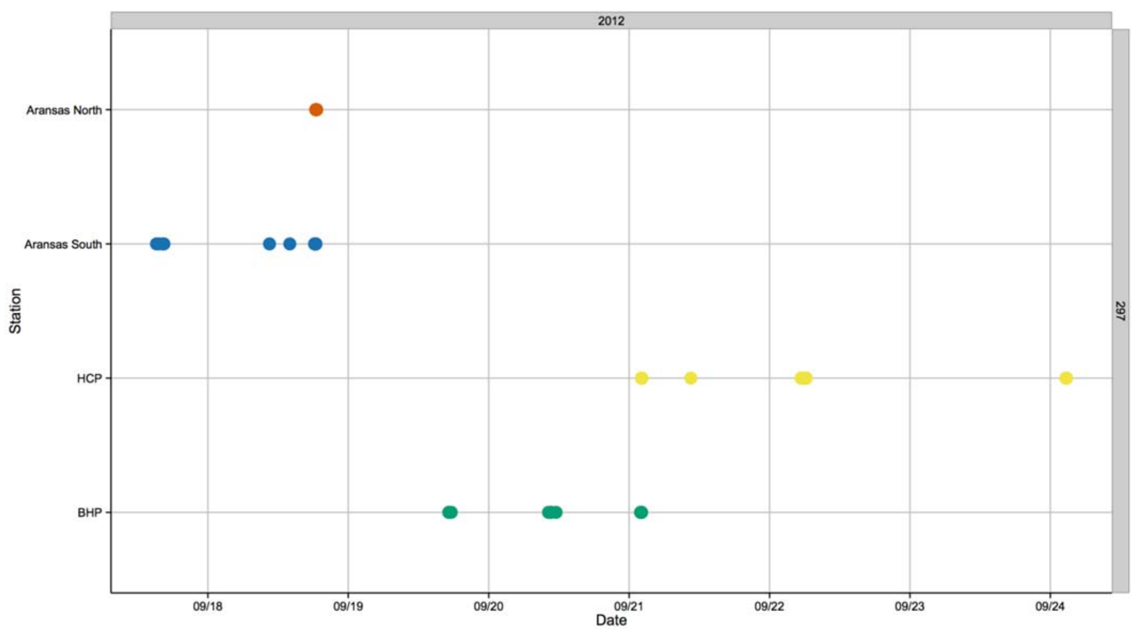


Figure 2.5 Abacus plot of detection history of shark BT-297 from 9/17 to 9/24/2012. Points indicate a detection or hit of the shark in the acoustic array. Stations are indicated by color and ordered on the ordinate by latitude. Time is plotted on the abscissa.

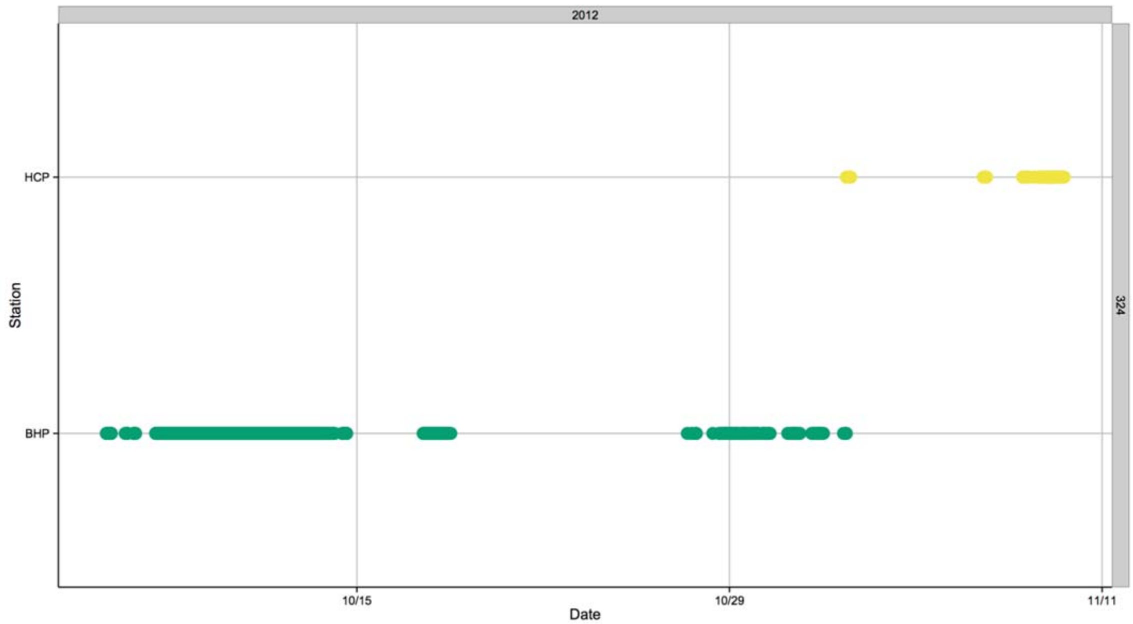


Figure 2.6 Abacus plot of detection history of BU-324 from Oct. to Nov. 2012. Points indicate a detection or hit of the shark in the acoustic array. Stations are indicated by color and ordered on the ordinate by latitude. Time is plotted on the abscissa.

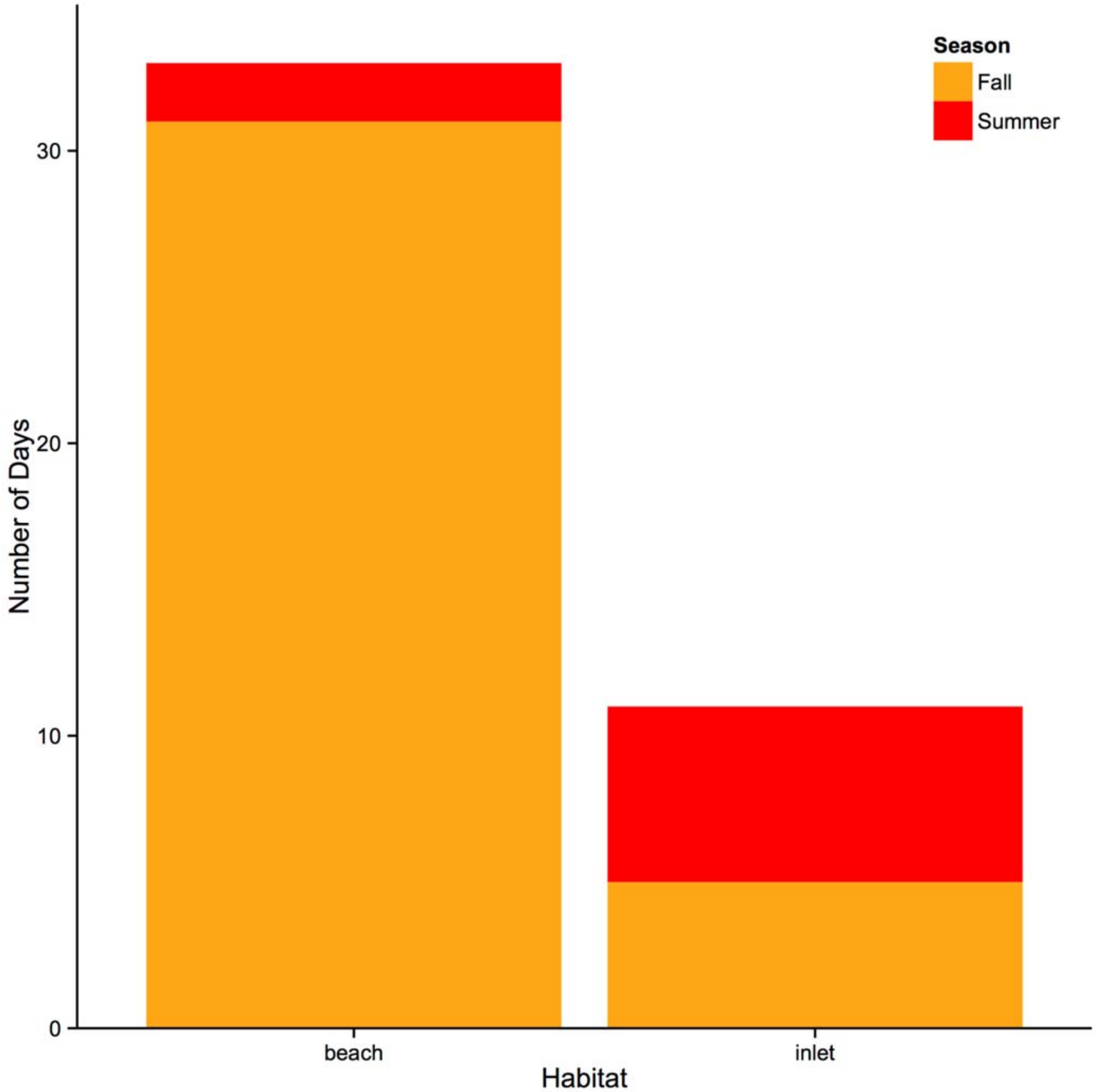


Figure 2.7 Barplot of days a shark visited each habitat type by season.
A visit was determined by detections on receivers located in inlets and along front beach areas of Texas. Color represents subgrouping of days within each habitat by season.

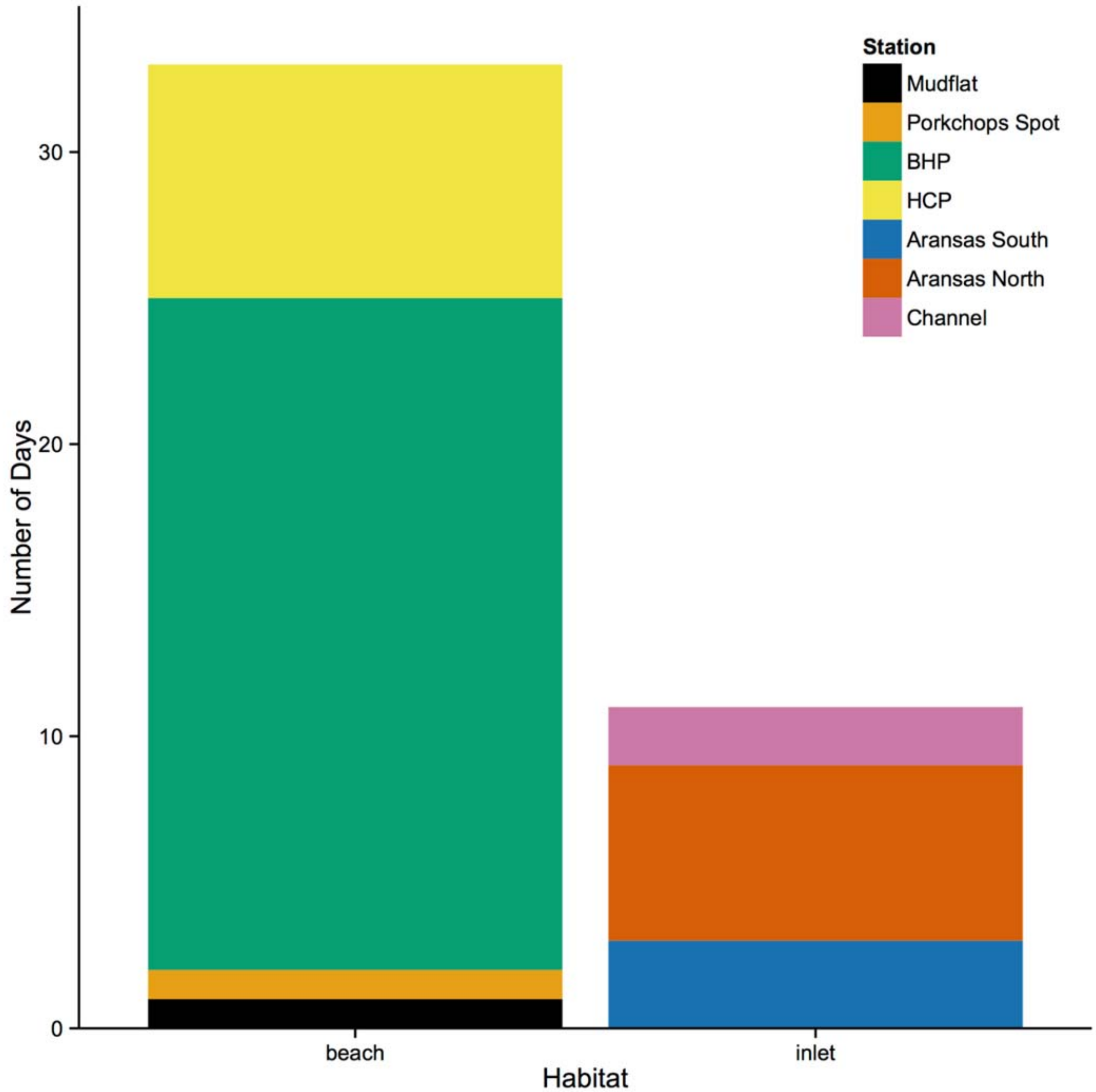


Figure 2.8 Barplot of days a shark was visited each habitat divided by station. A visit was determined by detections on receivers located in inlets and along front beach areas of Texas. Color represents subgrouping of days within each habitat by station

Satellite tagging - Two sharks were fitted with satellite tags. In 2010 a 2591 mm female Bull Shark was tagged and in 2011 a 2844.8 mm female Dusky Shark was tagged. Both sharks were tagged during summer months. Satellite-tagged sharks demonstrated an affinity for the continental shelf in the northwestern Gulf of Mexico as well as connectivity between the nearshore waters and the shelf slope interface. Both tracks appeared to follow the interface of the continental shelf and slope southward (Figures 2.9 and 2.10). The Bull Shark moved from nearshore waters to the shelf slope interface before a large horizontal movement south. The Dusky moved away from the nearshore habitat, followed the shelf slope interface north, and then moved into the slope after which it moved south and returned to the nearshore shelf before one final excursion onto the slope (Figure 2.10). Overall, both sharks displayed a general southward movement for the duration of tagging.

These satellite-tagged sharks spent the majority of time between 10 m and 100 m of depth and in waters between 24°C and 30°C (Figure 2.11 and Figure 2.12). The Bull Shark selected 10 m depths while the Dusky spent almost 50% of the tracking period at 50 m depths. Multiple depths were generally used throughout the day for individual sharks (Figures 2.13 to 2.14). Temperature profiles closely matched depth profiles, with warm temperatures encountered in shallow waters. Sharks remained in waters between 24°C and 30°C. The Bull Shark spent the majority of time in 27°C compared to 24°C for the Dusky. Both sharks occurred in waters above 20°C and never above 30°C except for very brief periods in 18°C water by the Bull Shark.

All satellite tags popped off prematurely. In the case of the Bull Shark, the tag released after spending the preprogrammed 192 hours at the same depth (Figure 2.11).

This shark demonstrated vertical movement in the water column until 6/20/2010 at which point it dropped to depths of 300 m and remained there exclusively (Figure 2.11). The track estimated for the shark in the 8 days following this event showed little movement of the individual. This was interpreted as a mortality event. The satellite tag attached to the Dusky Shark released on 8/20/2011. However, during the 192 hours preceding tag release the depth of the tag was almost exclusively at the surface and the temperature also rose above 33°C on several occasions (Figure 2.12). This was interpreted as the tag detaching from the shark and floating to the surface. After remaining at the same depth for the pre-programmed amount of time the tag release was initiated and the tag began transmitting.

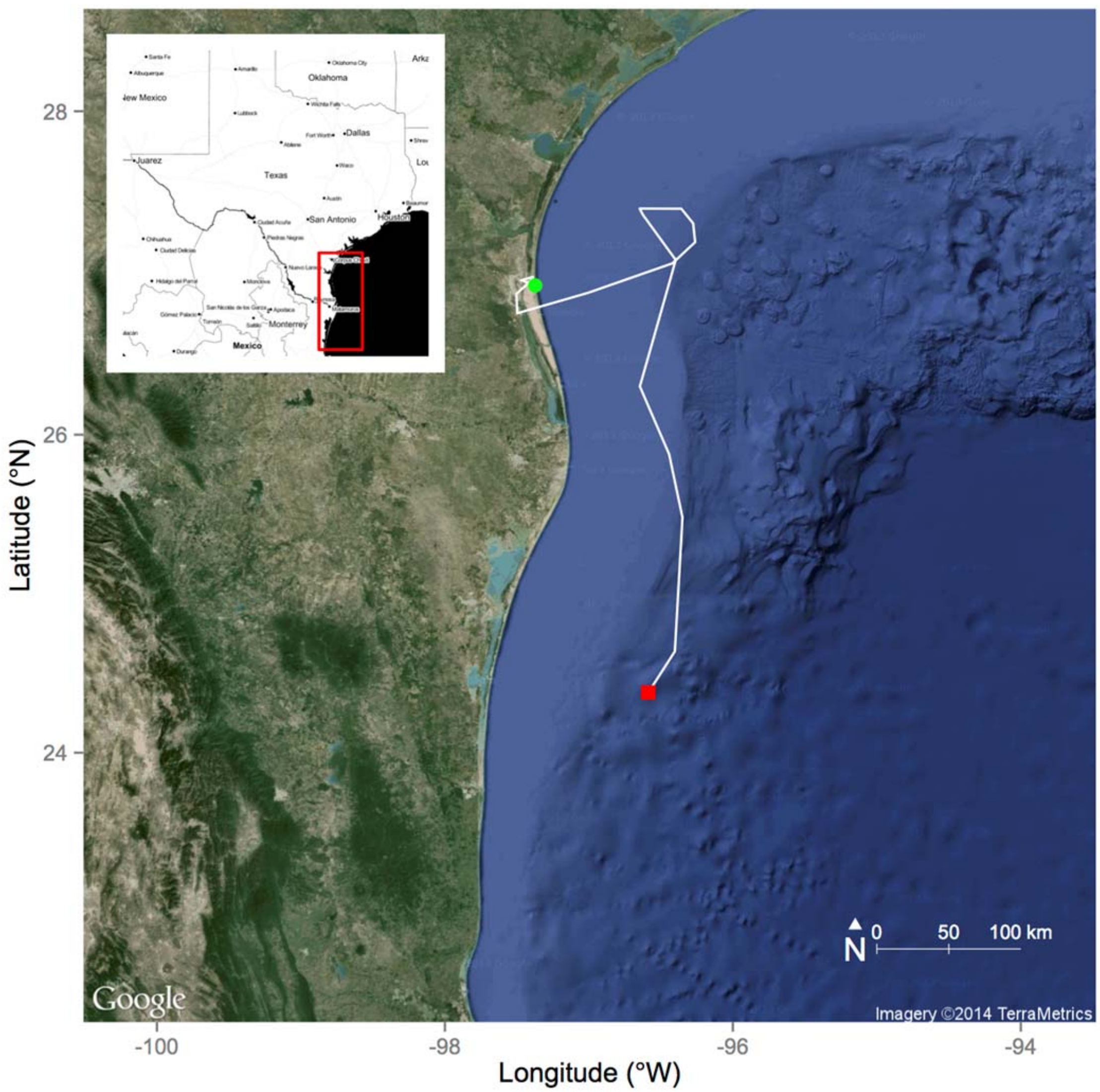


Figure 2.9 Most probable track of the Bull Shark using state space Kalman filter
This track was estimated using the KFtrack model state space Kalman filter. The green dot indicates the origin of the track and red box indicates the location the tag released from the shark. This shark was tagged from 5/29/2010 to 6/28/2010.

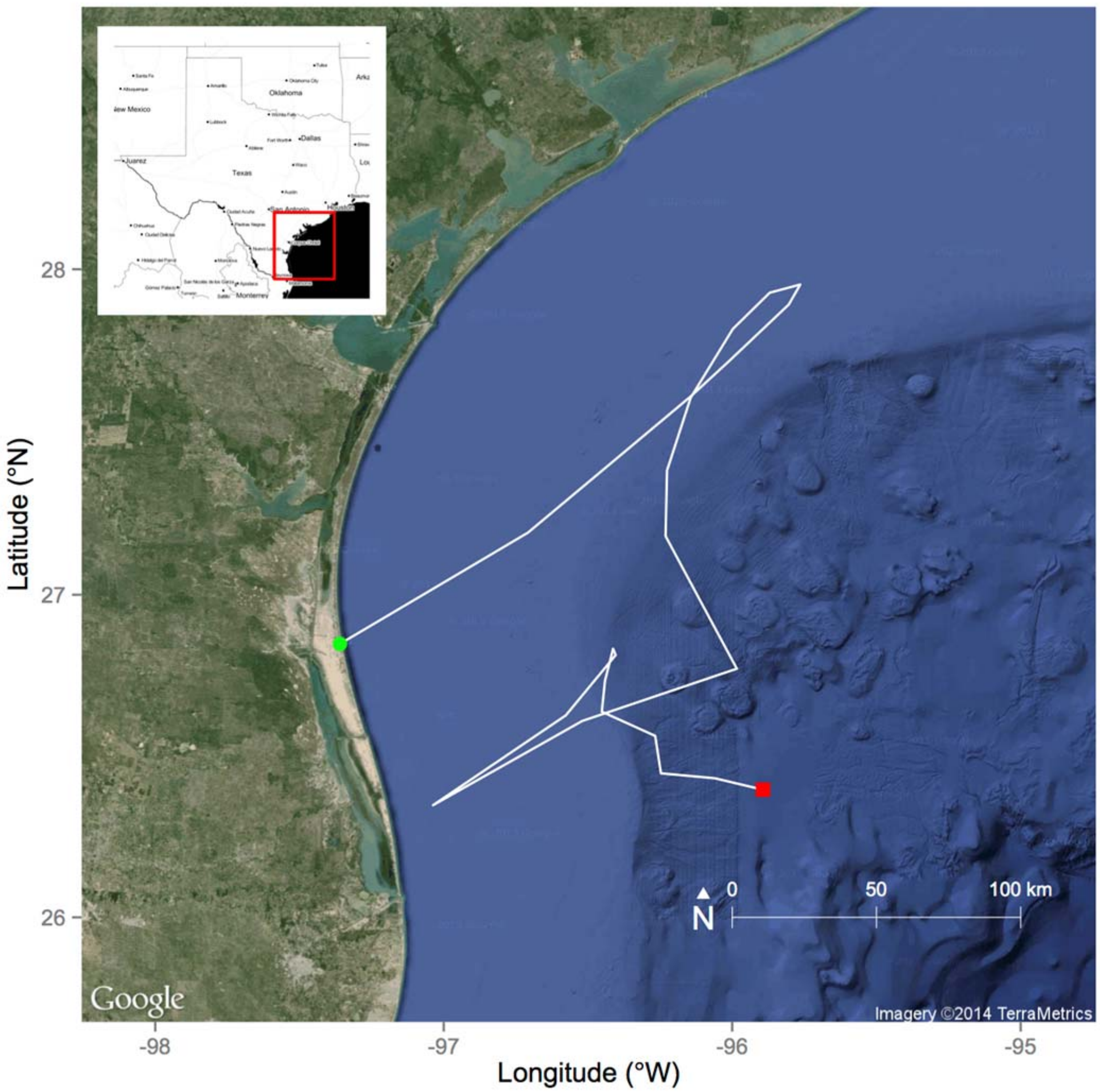
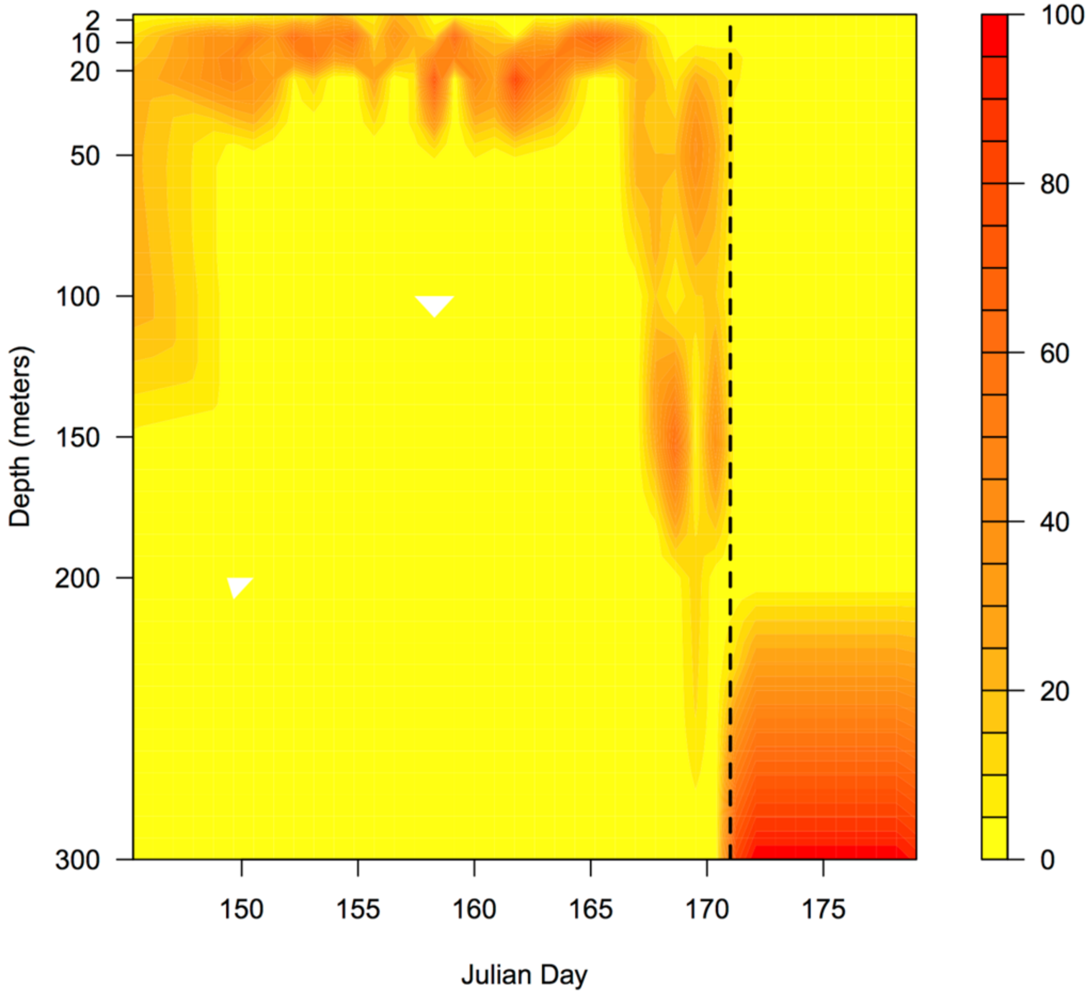


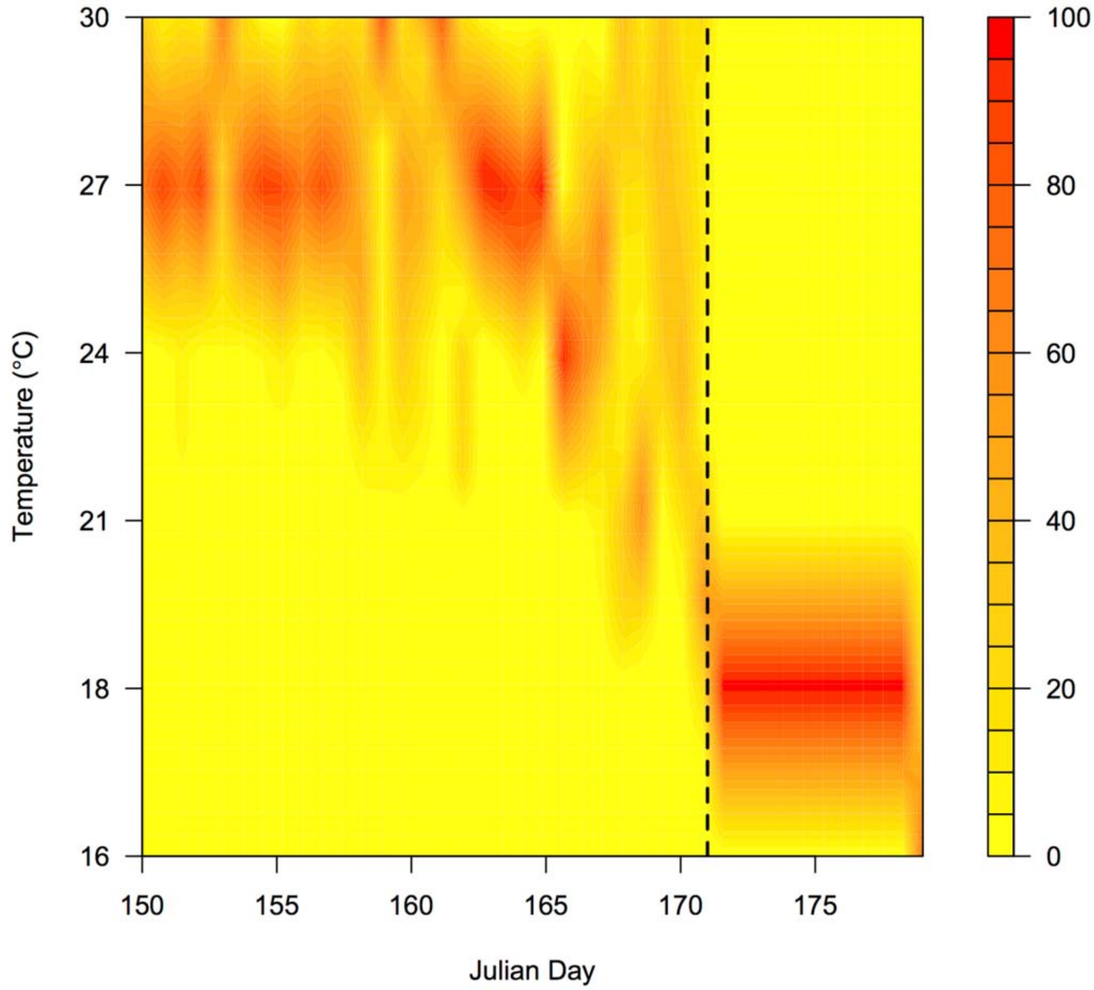
Figure 2.10 Most probable track of the Dusky Shark using state space Kalman filter
This track was estimated using the UKFSST model state space Kalman filter. The green dot indicates the origin of the track and red box indicates the location the tag released from the shark. This shark was tagged from 7/20/2011 to 8/20/2011.

A



Depth (meters)
2
10
20
50
100
150
200
300
150
155
160
165
170
175
Julian Day
100
80
60
40
20
0

B


30
27
24
21
18
16
Temperature (°C)
150
155
160
165
170
175
Julian Day
100
80
60
40
20
0

C

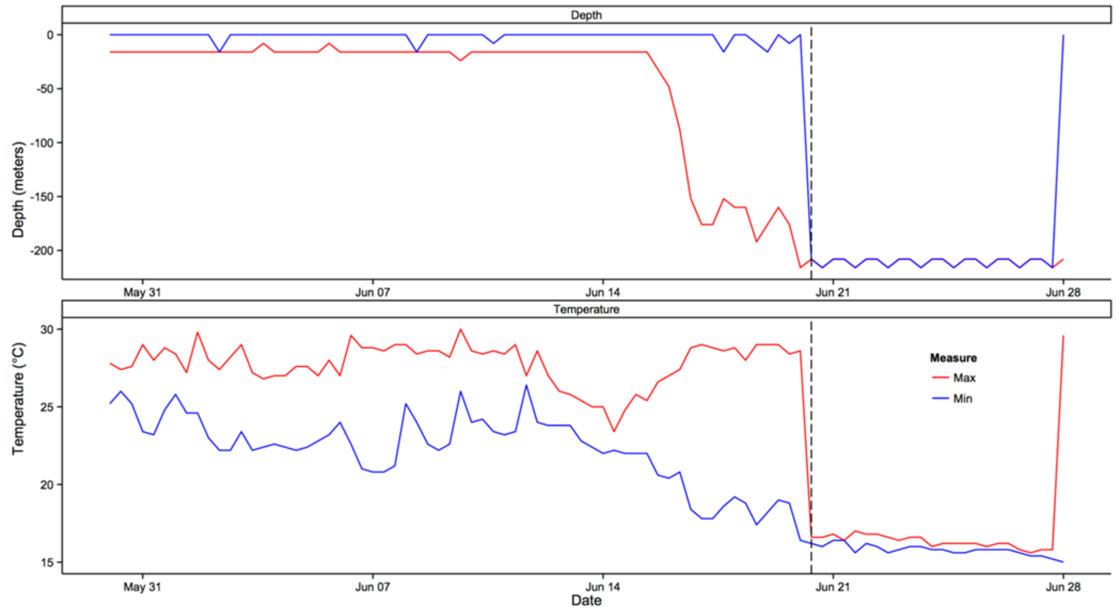
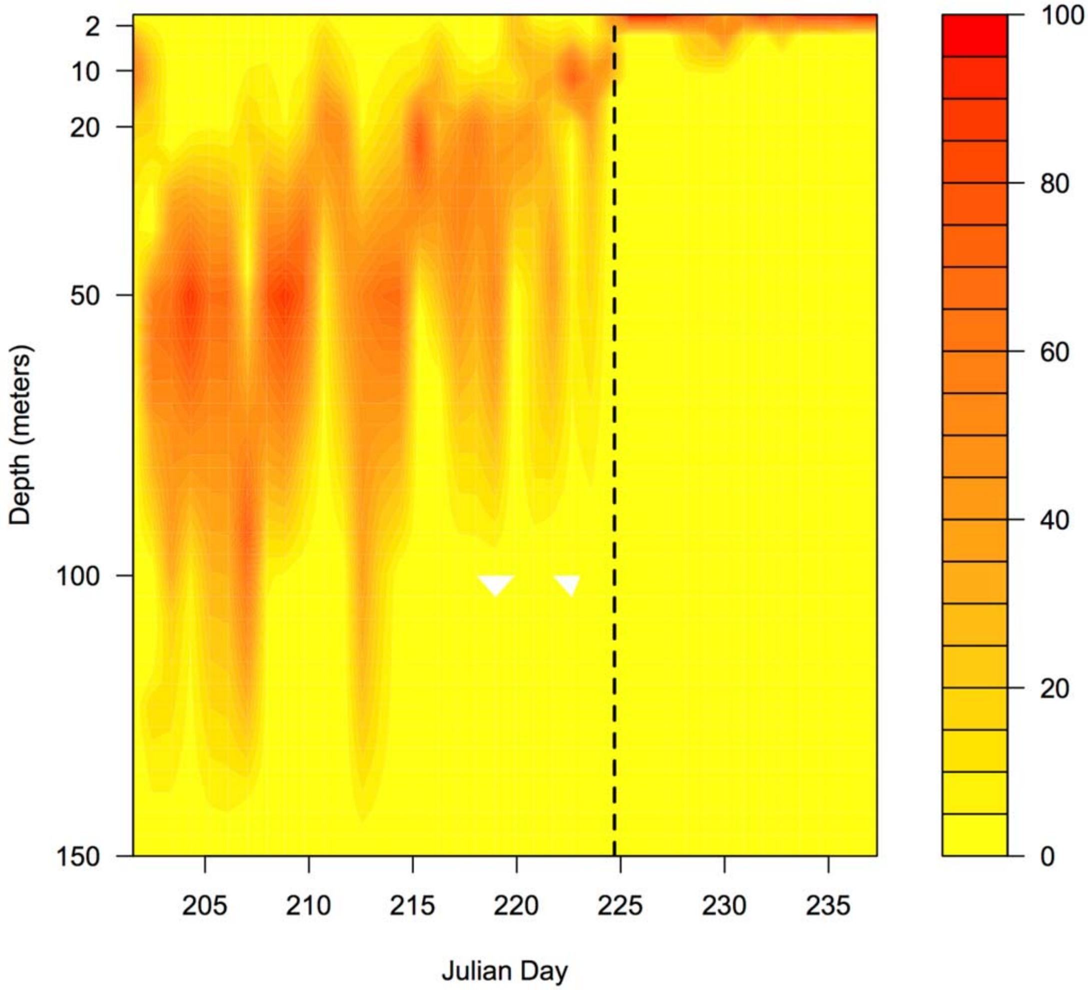


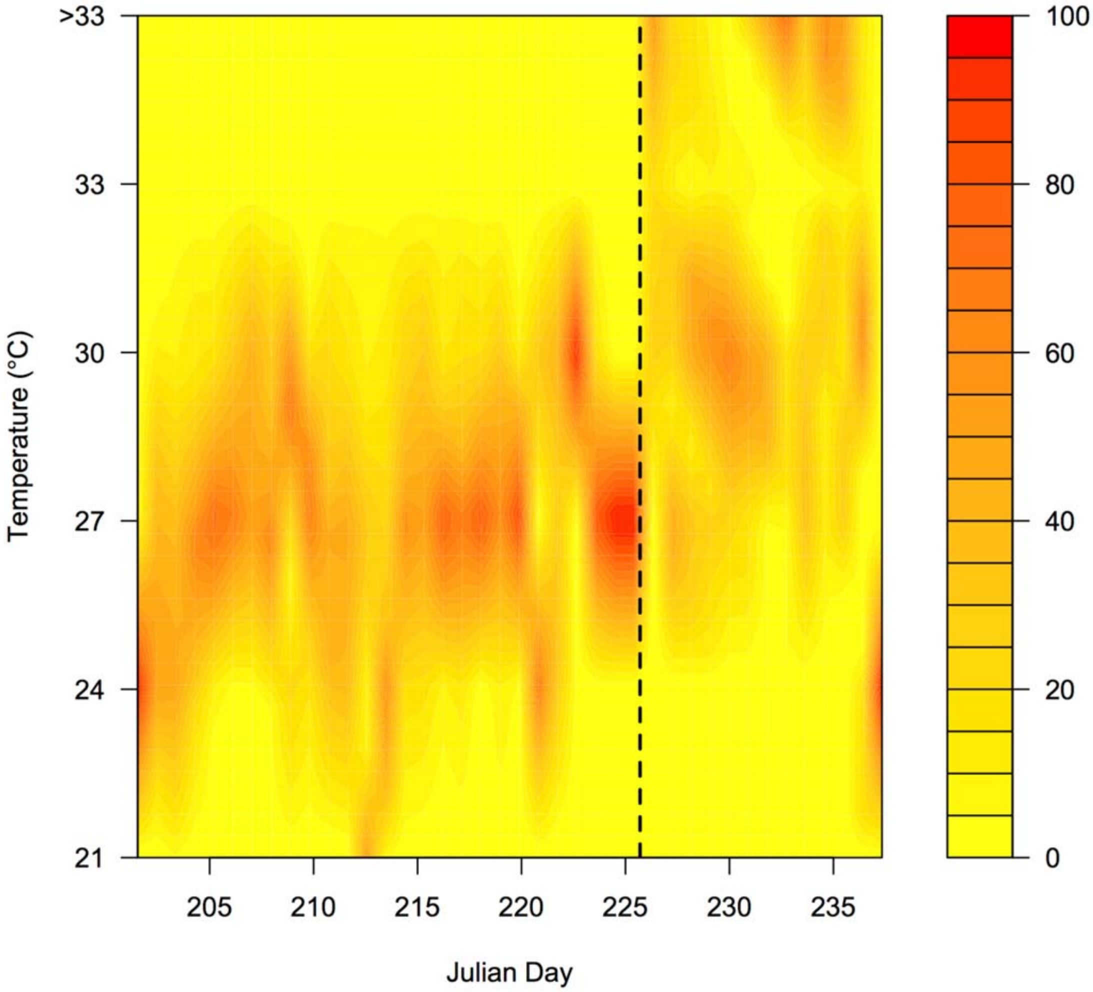
Figure 2.11 Depth and temperature profile of the Bull Shark
Heatmaps indicate amount of time spent at a (A) depth or (B) temperature while tagged interpolated from binned archival data. Daily minimum and maximum (C) Depth and temperature recorded by PAT tag. The black dotted line indicates the time when the PAT tag was estimated to have detached from the shark.

A



Depth (meters)
2
10
20
50
100
150
205
210
215
220
225
230
235
Julian Day
100
80
60
40
20
0

B



>33
33
30
27
24
21
Temperature (°C)
205
210
215
220
225
230
235
Julian Day
100
80
60
40
20
0

C

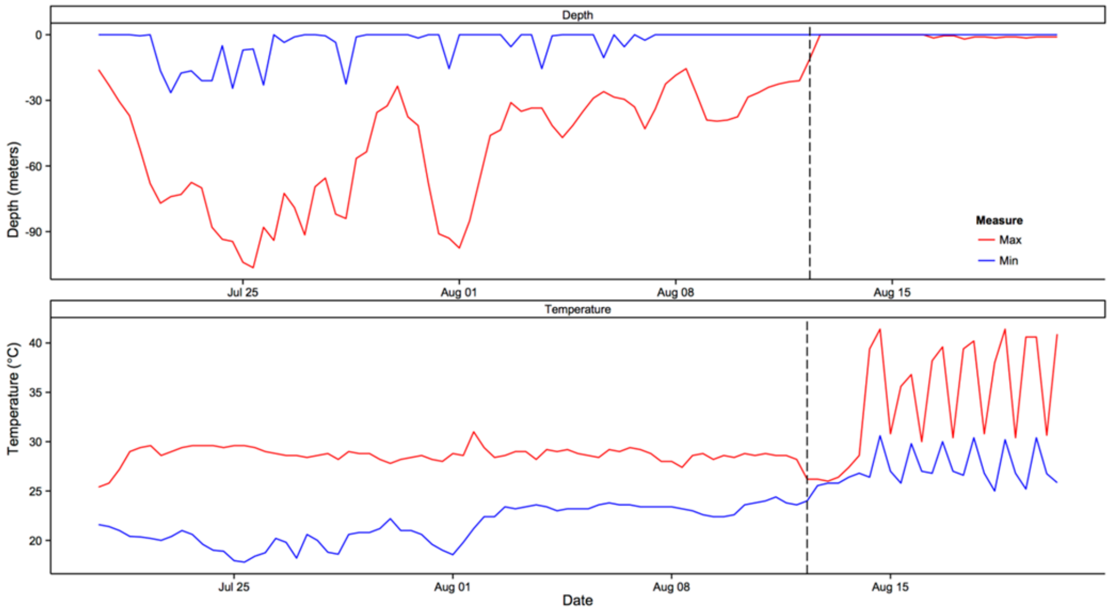


Figure 2.12 Depth and temperature profile of the Dusky Shark.
Heatmaps indicate amount of time spent at a (A) depth or (B) temperature while tagged interpolated from binned archival data. Daily minimum and maximum (C) Depth and temperature recorded by PAT tag. The black dotted line indicates the time when the PAT tag was estimated to have detached from the shark.

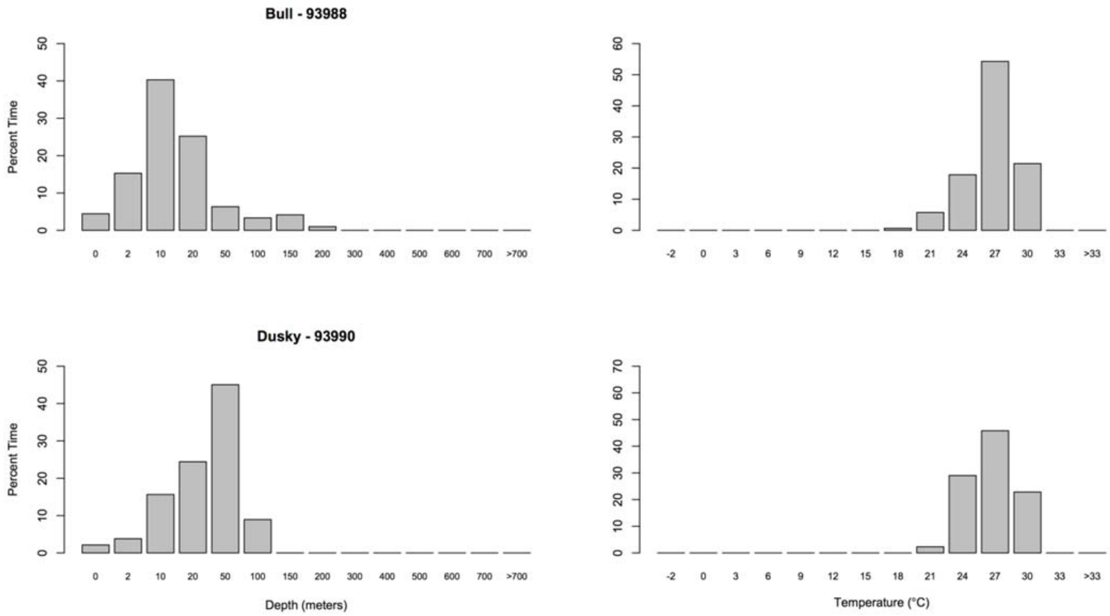


Figure 2.13 Depth and temperature histograms of satellite tagged sharks off Texas. Plots in the top row are for the Bull Shark and plots on the bottom row for the Dusky. The left column is depth and the right column is temperature.

Passive Tagging - The volunteer angler network along with researchers cooperatively tagged 801 sharks from 14 species from 2008 to 2013. A total of 12 recaptures were reported on 10 unique sharks for a 1.5% return rate (Figure 2.15). Shark 2721, a YOY Blacktip Shark, was recaptured multiple times (n = 3). Of the recaptures, 5 were reported from the southern part of the Texas coast and 7 were reported from the northern part of the Texas coast. The species most commonly recaptured was Blacktip Sharks (n = 10), with one recapture each for Sandbar and Bonnethead Sharks. All sharks were caught within a year of their initial tagging, with 9 sharks recaptured within 30 days. The longest time at liberty was by a Blacktip Shark that was tagged along PINS and recaptured 235 days later approximately 17 km south of its original tagging location.

Recaptured sharks fitted with dart tags demonstrated two geographical patterns of movement. Sharks tagged north of Matagorda Bay, TX generally moved north and associated with tidal inlets (Figure 2.15). Furthermore their average daily horizontal movement of 1.48 km/day was shorter than that of sharks tagged in the south at 2.30 km/day (Table 2.3). Sharks tagged south of Matagorda Bay, TX moved south (Figure 2.15) and generally had larger average daily horizontal movements (Table 2.3). Size of shark did not affect distance travelled; however YOY sharks were caught in proximity to tidal inlets. For instance, Shark 2721 was a YOY Blacktip caught numerous times near the inlet at San Luis Pass, TX.

Bob Hall pier Pier recorded the highest catch at over 412 individuals. Padre Island National Seashore also recorded a high catch. However, because of its size, the catch was distributed across multiple locations along the seashore. These two locations provided the greatest abundance of catch data due to high shark fishing activity (Figure 2.14).

Table 2.3 Recaptures of sharks tagged along the Texas coast from 2008 to 2013.

Tag	Species	STL (mm)	Age class	Sex	Tagged on date	Recapture date	Total Distance (km)	Distance since last capture (km)	Days at Liberty	Movement Rate (km/day)
807	Sandbar	1828.8	Adult	Female	10/12/2009	5/28/2010	110	109.87	228	0.482
778	Blacktip	1282.7	Adult	Female	10/2/2010	5/25/2011	18	17.62	235	0.075
1542	Bonnethead	700	Juvenile	Female	6/9/2011	7/6/2011	115	114.96	27	4.258
2485	Blacktip	1549.4	Adult	Female	11/3/2012	11/4/2012	0	0	1	0.000492
2771	Blacktip	558.8	YOY	Female	6/1/2013	6/10/2013	5	4.8	9	0.534
2841	Blacktip	1778	Adult	Female	4/6/2013	8/11/2013	29	28.82	127	0.227
2820	Blacktip	1803.4	Adult	Female	6/6/2013	6/7/2013	7	6.68	1	6.684
2437	Blacktip	1524	Adult	Female	6/22/2013	7/12/2013	40	40.01	20	2.000
2467	Blacktip	1625.6	Adult	Female	6/22/2013	7/15/2013	94	94.26	23	4.098
2721	Blacktip	584.2	YOY	Female	6/1/2013	6/6/2013	5	4.8	5	0.960
						6/7/2013	5	0	6	0
						6/9/2013	10	5.07	8	2.535

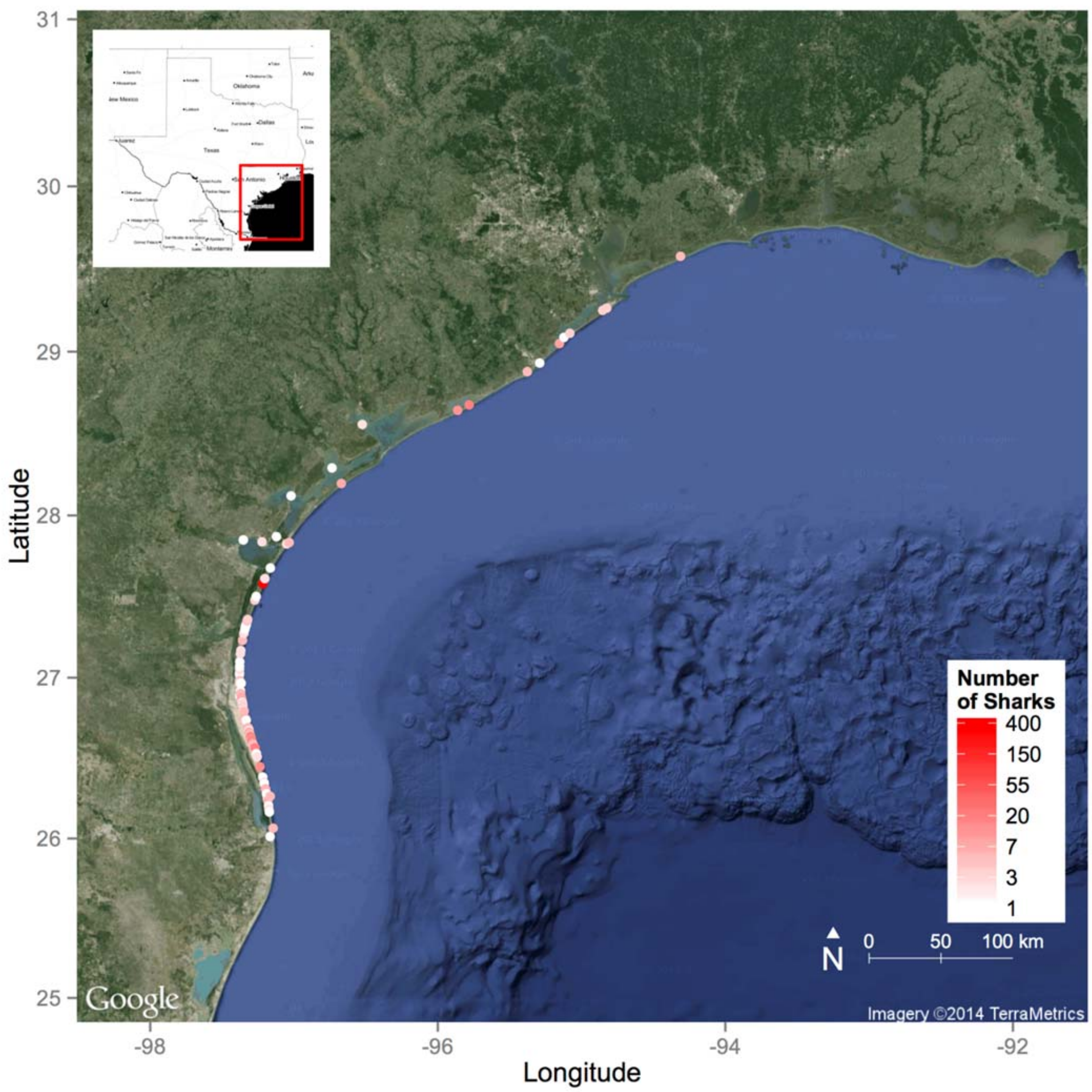


Figure 2.14 Density map of shark catch along the Texas coast, 2008 to 2013. Locations marked in red had higher catch totals than locations in white.

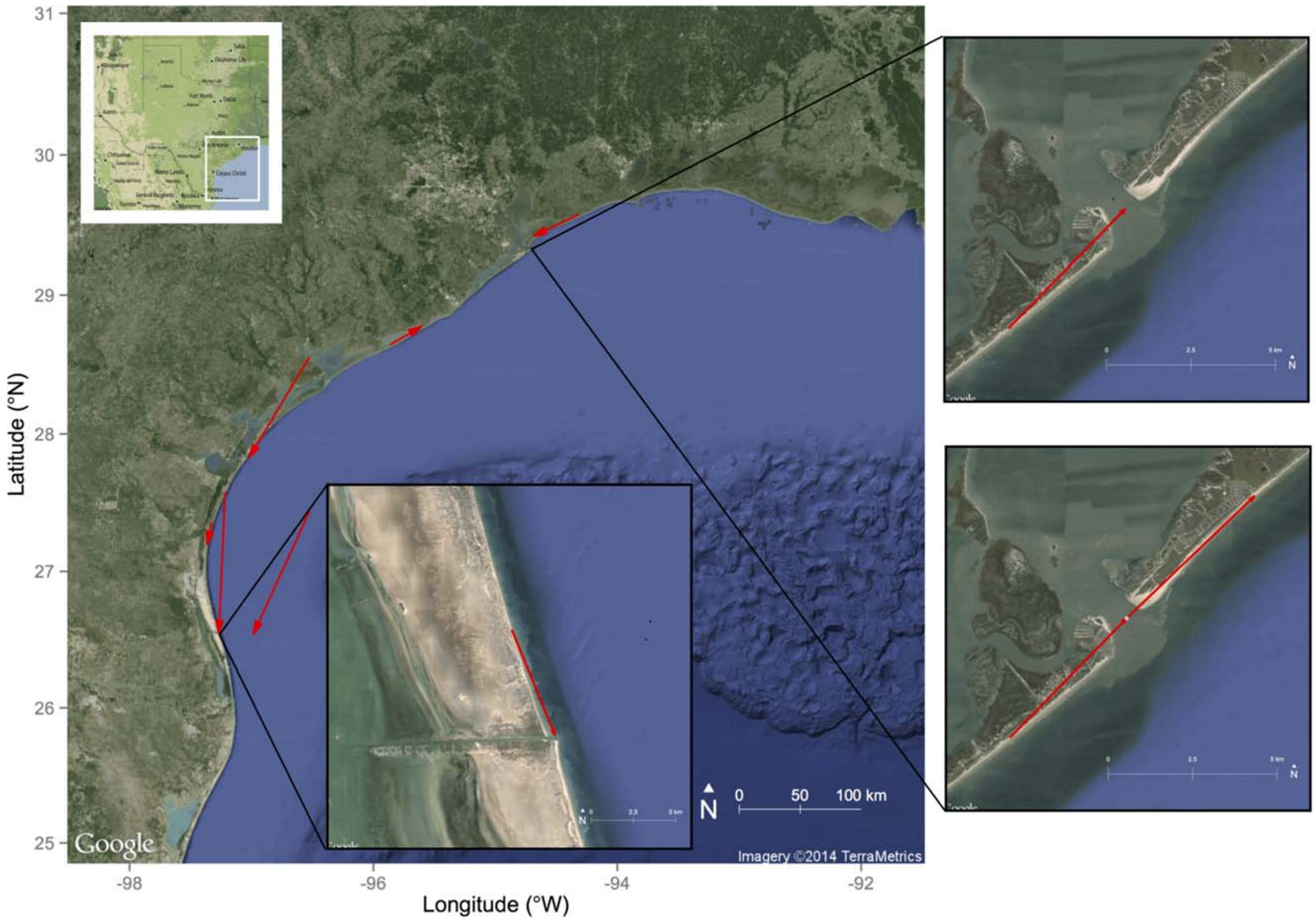


Figure 2.15 Mark and recapture locations of sharks in Texas, 2008 to 2013.
Movement patterns of sharks tagged with dart tags along the Texas coast illustrated with red arrows. The direction of movement is indicated by the arrowhead. Larger movements are shown in A, while small scale movements are shown in B, C, and D. The white asterisk in B indicates consecutive recaptures of the same shark at the same location.

Discussion

Acoustic Tagging - Detections were more frequent at northern stations compared to southern stations. The northern stations were in close proximity to or inside tidal inlets (Packery Channel and Aransas Channel) that connects to bay and estuary systems associated with sharks and have moderate salinities (Froeschke et al. 2010). The southern stations were not located near tidal inlets that received freshwater input. The closest inlet was Port Mansfield, a channel that connects the hypersaline Laguna Madre to the Gulf of Mexico. Salinity has been shown to influence shark habitat use in Texas, with many species preferring moderate salinities (Froeschke et al. 2010). Of the three channels with stations, only Aransas Channel recorded detections. Salinity increases as latitude decreases along the Texas coast and Depth may also play a role in inlet use. Aransas Channel is the deepest of the three channels ranging in depth from 7 m to 14 m and is used as the primary shipping lane to the Port of Corpus Christi. Both Packery Channel and Port Mansfield Channel are relatively shallow channels, not exceeding 5 m in depth. Shallow depths may affect signal transmission by deflecting sound waves and causing signal collisions. However, this was determined to be an unlikely factor because other acoustically tagged fish were detected at these stations. It is most likely that sharks in southern Texas select deeper channels with higher freshwater influence.

Sharks spent long durations away from the acoustic array and returned seasonally. Sharks generally returned in late summer and continued to return throughout the fall. Previous studies have shown numerous shark species migrate seasonally, usually moving south or offshore during fall and winter (Hueter & Tyminski 2002, Parsons & Hoffmayer 2005). Heupel et al. (2003) determined juvenile Blacktip Sharks often share similar seasonal movement patterns, with the highest associations occurring in early summer. Although the array did not allow calculate the same association metric calculations as Heupel et al. (2003), sharks had consistent patterns in temporal and spatial habitat use. Correlations with specific environmental cues for these movements were not possible because environmental data was not available for all locations. It is likely that season is a component of these coinciding movements into and out of the array.

Site fidelity has been described for numerous shark species and includes natal homing, nursery philopatry, and repeated habitat use over long periods of time (Keeney et al. 2003, Hueter et al. 2005, DiBattista et al. 2008, Chapman et al. 2009, Carlson et al. 2010, Karl et al. 2010, Kneebone et al. 2012, Knip et al. 2012). Sharks along the Texas coast demonstrated visitation patterns indicative of site fidelity. Four of the five sharks that returned to the array demonstrated repeated habitat use over long time periods. These sharks were detected at specific stations within the array after extended absences, indicating site fidelity for these areas. Receivers located along the front beaches and near the Aransas Channel received the most repeated use and these areas are likely important habitat for coastal sharks. A large sub-adult female Bull Shark returned to the Aransas Channel area over a three-year span. This individual demonstrated site fidelity to the Aransas Channel always arriving in late summer or early fall. Furthermore, this shark was not present in the channel for extended periods of time, indicating the channel served as a movement corridor. In 2013, this shark was detected in the Lydia Ann Channel which connects Aransas Channel with Aransas Bay and San Antonio Bay; the latter Froeschke et al. (2010) determined served as nursery habitat for Bull Sharks. Because this shark was not mature, there are two possible explanations for this behavior. The first is that this area is a migratory corridor to secondary nursery habitat and this Bull Shark is exhibiting natal homing. Another explanation is that this shark is demonstrating behavior characteristic of mature females. If this is the case, then it is possible this shark is returning to a nursery for parturition. Karl et al. (2010) found that genetic population structure at mitochondrial and nuclear markers suggested female Bull Sharks display high natal site fidelity and philopatric behaviors resulting from use of natal nurseries for parturition as adults. Although this shark was not mature, it is possible these are instinctual behaviors expressed as female sharks near maturity. Regardless of the impetus for this behavior, this shark demonstrated strong ties to the tidal inlets and repeated use over long periods of time. Future genetic studies should be conducted on Bull Sharks in this area to determine if natal homing occurs in Bull Sharks born in Texas.

One YOY Blacktip Shark demonstrated large-scale movements along the Texas coast and was detected in the southern portion of the array. This shark was tagged at BHP before being detected at the Mudflats station, a straight line Euclidean distance of 105 km to the south of the pier. Blacktip Sharks are thought to use inshore bays as nursery habitat in Texas, leaving these protected areas in October to migrate south into warmer waters (Hueter & Tyminski 2007). This shark demonstrated a southern migration along the Gulf side of barrier islands in June 2010 and returned to the southern portion of the array (Porkchop's spot) in November of 2011. The large number of YOY sharks encountered at BHP (see Chapter 1) and the lack of acoustic detection of tagged Blacktips inside nearby tidal inlets suggests that the front beaches of barrier islands is habitat used by YOY Blacktip Sharks. Froeschke et al. (2010) found juvenile Blacktip Sharks had a strong affinity for tidal inlets along the central Texas coast characterized by warm water temperatures and moderate salinities. Blacktip Sharks selected against the hyposaline bays (Sabine Lake and Galveston Bay) and the hypersaline Laguna Madre along the north and south Texas coast, respectively (Froeschke et al. 2010). All YOY Blacktip Sharks in this study were tagged along the beachfront but were never detected inside tidal inlets along the south Texas coast, supporting previous work by Froeschke et al. (2010). This pattern is most likely explained by the high salinities of south Texas bay systems, which were found to negatively influence habitat selection by this species (Froeschke et al. 2010). These data suggest that YOY Blacktip Sharks do not use tidal inlets along the south Texas coast and that beachfront habitat is more important in this region. Further studies are required to determine fine-scale front beach habitat use by YOY Blacktip Sharks.

Satellite Tagging - Coastal sharks of Texas fitted with satellite tags exhibited similar patterns of habitat use. Both sharks spent time on the continental shelf in the nearshore habitat and moved offshore to the shelf slope interface before moving south and did not enter the estuaries nor interact with tidal inlets. The Bull Shark remained in the nearshore habitat for a short period before moving offshore and following the shelf slope interface south. A previous study of Bull Shark movements in the Gulf of Mexico found similar movement with a Bull Shark using offshore habitat for long migrations with forays into nearshore areas (Carlson et al. 2010). However, Bull Sharks more frequently exhibited relatively small horizontal movement in the study (Carlson et al. 2010). The Dusky Shark in this study occurred on the continental shelf and slope, moving in an overall southward direction while making forays into nearshore waters before moving offshore. This horizontal movement and use of the interface of the shelf and slope is similar to previous findings for this species (Hoffmayer et al. 2014). Furthermore, Dusky Sharks are well known for their long migrations, many moving from the Eastern Seaboard to Campeche Bay, Mexico (Kohler et al. 1998). These movement patterns show connectivity between nearshore shelf and offshore slope waters along Texas. It is likely that these sharks follow the shelf slope interface around the northern Gulf of Mexico into Texas waters before moving south to Mexico. These patterns in long migrations highlight the need for international conservation efforts in both nearshore and offshore habitats for sharks.

Each shark demonstrated a unique depth selection pattern, ranging from shallow (10 m) to deeper waters (50 m). The Bull Shark spent 65% of its time tagged in shallow water between 10 and 20 m, of which 40% was spent at 10 m. Carlson et al. (2010) found similar depth selection in Bull Sharks. The maximum depth for the Bull Shark was 150 m. Greater depths were recorded by the PAT tag, but these depths coincided with cessation of movement of the shark and were determined to not be a result of shark behavior. The Dusky selected a depth range from 20 to 50 m, spending 70% of its time at these depths. The Dusky Shark spent 45% of its time at 50 m and had a maximum depth of 150 m. This depth selection is similar to those found by Hoffmayer et al. (2014). Both sharks exhibited similar temperature selection to those found in previous studies. The Bull Shark spent 75% of its time above 27°C but occurred in a range of temperatures from 18°C to 30°C. These results support previous findings that Bull Sharks in the Gulf of Mexico rarely occur below 20°C (Carlson et al. 2010, Drymon et al. 2014). The Dusky Shark occurred in temperatures between 21°C and 30°C, spending 75% of its time between 24°C and 27°C. These results support previous findings of Dusky depth selection

(Hoffmayer et al. 2014). Warming ocean temperatures from climate change have elicited ecological responses in marine organisms including alterations in distribution and depth (Walther et al. 2002, Perry et al. 2005). As ocean temperatures are predicted to continue to rise, the relatively small temperature selection for these sharks may play a role in ecological changes observed for these species in the future.

Passive Tagging - Sharks fitted with passive dart tags demonstrated geographically unique patterns along the coast of Texas. Sharks tagged south of Matagorda Bay generally moved south, while those tagged north of the bay tended to remain near the area where they were originally tagged. In addition to the directional difference, the southern group of tagged sharks averaged larger daily movement rates than their northern counterparts. Blacktip Sharks predominantly comprised each group; therefore, interspecific differences are not likely to have influenced the results. NOAA's cooperative apex predator tagging program found connectivity between the lower Texas coast and the southern Gulf of Mexico in Blacktip Sharks, with a large portion of the sharks moving south from Texas (Swinsburg et al. 2012). Blacktip movement patterns were similar in the current study with the exception that all sharks were recaptured in Texas waters. Both the NOAA Cooperative study and this study found little movement along the upper Texas coast. Recent studies have shown geographic differences in ocean currents along the Texas coast describing higher velocities along the mid and lower coast as compared to the upper coast (Ohlmann and Niiler 2005, Johnson 2008). Furthermore, currents along the mid and lower coast are directed south as opposed to the western direction of upper coast currents. These differences in currents may explain the movement of sharks along the coast. Sharks caught along the upper coast would remain in the area due to weaker currents, while sharks caught along the lower coast would use the currents to move south. This strategy in migration would maximize their energy expenditures. Many marine animal movements have been correlated to currents and it is theorized that this behavior minimizes physiological costs (Luschi et al. 2003, Brill et al. 1993, Akesson & Hedenstrom 2007). If sharks are migrating with currents, the lower Texas coast would be an important migratory pathway for sharks in the western Gulf of Mexico.

Summary - The nearshore Texas environment provides habitat for migrating sharks and may serve as movement corridor between the northern and southern Gulf of Mexico. Sharks demonstrated an affinity for the beachfront habitat, remaining in these areas for short periods and returning after long absences. In addition, sharks repeatedly used the Aransas Channel tidal inlet that connects protected bay systems with the Gulf of Mexico. Sharks used the nearshore shelf and shelf slope interface, moving between the two areas over time, while differences in depth and temperature selection. However, these differences occurred across species with each species exhibiting similar selection found in previous studies.

A diverse community assemblage occurs in spring through fall, with winter bringing a more homogenous shark assemblage. Furthermore, spring and fall share similar assemblages that indicate seasonal migrations of sharks along the Texas coast. During these seasonal movements, some sharks immigrated and emigrated between bay systems and the Gulf of Mexico. The lower Texas coast and the shelf slope interface along this area served as a pathway for southward movements by sharks. Two individuals of different species demonstrated an overall pattern of movement towards the southern Gulf of Mexico over relatively short time scales. This corroborates previous patterns described for sharks of the western Gulf of Mexico.

The trend for sharks to migrate south illustrates the migratory nature of these animals and the international movements they make. It also highlights the importance of international cooperation in shark conservation and management. Sharks moving south are likely moving into Mexican waters that include areas of heavy fishing pressure. Rebuilding shark stocks may be limited by their movement into areas where regulations are much less restrictive. Thus, a key component to shark conservation will be developing working relationships with other Gulf of Mexico countries to implement a coordinated shark recovery plan that includes protecting these species in heavily exploited areas.

Texas serves as nursery grounds for numerous shark species. This study found a large female Bull Shark returning to tidal inlets annually. This shark was also detected moving into protected bay systems thought to serve as a shark nursery. This behavior indicates that female sharks may be returning to the same nursery areas to pup. Further studies will need to be conducted to confirm this hypothesis. Genetic population analysis of large females and pups found in the bay systems could help answer this question. In addition, a more comprehensive acoustic network using choke points at entrances to bay systems can provide more insight into shark behavior near tidal inlets by elucidating connectivity between inshore and nearshore habitats. Both juveniles and mature females caught inside the bay systems should be targeted in future studies. Since it is likely that there is connectivity between nursery bays and the nearshore habitat of the Gulf of Mexico, management should consider a moratorium on harvesting female sharks during peak pupping seasons. This will maximize the number of sharks pupped which should result in higher recruitment and help rebuild shark stocks.

Management of the shark fishery in Texas is important to ensure that shark stocks are rebuilt after years of overfishing. The larger curvature of the historical data in the size spectra analysis from this study provides evidence of high historical fishing pressure that likely resulted in overfished shark stocks. Effects of this high exploitation rate persist today as large sharks have declined and small sharks have increased. The apparent community shift to smaller shark species from the historic large species dominated community is particularly important. Shark conservation goals generally focus on shark abundance and not a more holistic approach focused on the assemblage and composition of the shark community. Although increasing abundance of a single species is an important part of shark conservation, it does not meet EBFM goals of rebuilding marine communities and food webs. It is vital that managers not only examine historical abundance of a species, but include community assemblages in their rebuilding target plans.

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