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Movement patterns, habitat preferences, and fisheries biology of the common
thresher shark (*Alopias vulpinus*) in the Southern California Bight

A dissertation submitted in partial satisfaction of the
requirements for the degree Doctor of Philosophy

in

Marine Biology

by

Daniel Patrick Cartamil

Committee in charge:

Professor Jeffrey B. Graham, Chair

Professor David M. Checkley

Professor Philip A. Hastings

Professor Cleridy E. Lennert

Professor Richard H. Rosenblatt

Professor David S. Woodruff

2009

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University of California, San Diego

2009

EPIGRAPH

“The swordfish swimmes under the whale, and pricketh him
upward. The thresher keepeth above him, and with a mighty great thing
like unto a flail, hee so bangeth the whale, that hee will roare
as though it thundered, and doth give him such blowes with his weapon,
that you would think it to be the crake of a great shot”

Block Island fisherman, 1609

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ACKNOWLEDGEMENTS

In addition to the more cerebral tasks of data analysis and manuscript writing, studies such as the work described in this dissertation are the result of thousands of man-hours of field work. The success of each project was contingent upon an enormous amount of help from my fellow graduate students, co-authors from various institutions, and many volunteers and interns. I will not even attempt an exhaustive list; each chapter of the dissertation has an acknowledgements section that details the help of those involved and the various funding sources which made it all possible.

Special thanks are due to my advisor Dr. Jeffrey Graham. I have been privileged to be in Jeff's laboratory and benefit from his wisdom, accumulated over the course of a long and distinguished career. In addition, I would also like to thank the many members of the Graham Laboratory who were supportive and helpful over the years, particularly Nick Wegner.

At the deepest level, I am indebted to my parents George and Raquel Cartamil. Finally, I would like to dedicate this work to my wife Alisha, who has spent many sleepless nights wondering where I was and if I would survive to return home to her. So far so good...

DISSERTATION MATERIAL PUBLISHED, SUBMITTED, OR IN PREPARATION FOR PULICATION

Chapter 1, in full, was submitted for publication as:

Cartamil D, Wegner N, Aalbers S, Sepulveda C, Baquero A, Graham J. In review. Diel movement patterns and habitat preferences of subadult and adult thresher sharks (*Alopias vulpinus*) in the Southern California Bight. Journal of Marine and Freshwater Research. The dissertation author is the primary investigator and author of this paper.

Chapter 2, in full, is being prepared for submission for publication as:

Cartamil D, Sepulveda C, Wegner N, Baquero A, Aalbers S, Graham J. Archival tagging of subadult and adult thresher (*Alopias vulpinus*) off the coast of southern California. Journal to be determined. The dissertation author is the primary investigator and author of this paper.

Chapter 3, in full, was submitted for publication as:

Cartamil D, Wegner N, Kacev D, Ben-Aderet N, Kohin S, Graham JB. In review. Movement patterns and nursery habitat of the juvenile thresher shark (*Alopias vulpinus*) in the Southern California Bight. Marine Ecology Progress Series. The dissertation author is the primary investigator and author of this paper.

Chapter 2, in full, is being prepared for submission for publication as:

Cartamil D, Sosa-Nishizaki O, Graham JB. The artisanal elasmobranch fishery of the Pacific coast of Baja California, Mexico. Journal to be determined. The dissertation author is the primary investigator and author of this paper.

CURRICULUM VITAE

Daniel P. Cartamil

EDUCATION

- 1993 Bachelor of Science
 Biology
 State University of New York, Oneonta
- 2003 Master of Science
 Biology
 California State University, Long Beach
- 2009 Doctor of Philosophy
 Marine Biology
 Scripps Institution of Oceanography
 University of California, San Diego

PUBLICATIONS

C.G. Lowe, G. Moss, G. Hoisington, J. Vaudo, **D. Cartamil**, M. Marcotte & Y. Papastamatiou. 2007. Caudal spine shedding periodicity and site fidelity of round stingrays, *Urobatis halleri* (Cooper), at Seal Beach, California: implications for stingray-related injury management. *Bulletin of the Southern California Academy of Science* (106): 16-26.

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FIELDS OF STUDY

Fish movement patterns and habitat utilization
Shark Muscle Morphology
Artisanal shark fisheries
Fish ecology

ABSTRACT OF THE DISSERTATION

Movement patterns, habitat preferences, and fisheries biology of the common
thresher shark (*Alopias vulpinus*) in the Southern California Bight.

by

Daniel Patrick Cartamil

Doctor of Philosophy in Marine Biology

University of California, San Diego, 2009

Professor Jeffrey B. Graham, Chair

The common thresher shark (*Alopias vulpinus*) is a pelagic species that constitutes the largest commercial shark fishery in California waters. Despite its commercial value, little is known of thresher shark biology, nor is there adequate data on which to base fishery management decisions. This dissertation entails four studies dealing with the biology and fisheries interactions of common thresher shark in the Southern California Bight (SCB). Chapter 1 examines the movement patterns of adult and subadult thresher sharks using acoustic telemetry. These larger

threshers preferentially inhabit waters offshore of the continental shelf, inhabit shallow waters nocturnally, and may make extensive vertical excursions by day that are suggestive of foraging. In Chapter 2, movement patterns of larger threshers are further examined over extended time periods through the use of archival tagging. Archival data show that in addition to exhibiting diel periodicity in movement patterns, threshers undergo distinct modes of daytime depth distribution for extended periods that are interpreted as relating to regional differences in abundance of surface oriented prey and prey in deeper water. Chapter 3 investigates the habitat utilized by juvenile threshers and shows that they preferentially inhabit waters over the SCB continental shelf as a nursery area. Chapter 4 describes the artisanal fishery for threshers and other elasmobranchs along the Pacific coast of Baja California Norte, Mexico. It was found that 44 artisanal fishing camps are located in the region, of which at least 26 target elasmobranchs. In addition, the detailed species, size, and sex composition of elasmobranchs captured at the Laguna Manuela fishing camp is reported. Finally, Chapter 5 provides a synoptic view of the contributions made by this dissertation towards the current status of knowledge regarding thresher shark life history, ecology, and fisheries biology.

INTRODUCTION

The common thresher (*Alopias vulpinus*, Order Lamniformes) is a large migratory shark ranging in size from 0.6 m FL (fork length) at birth to over 3.0 m FL as adults. Despite the size attained by this species, they are known to feed primarily on small schooling fishes, such as the northern anchovy (*Engraulis mordax*) and the Pacific sardine (*Sardinops sagax*) (Prete et al. 2001, 2004). Although the common thresher inhabits subtropical and temperate seas worldwide (Compagno 2001), the eastern Pacific population is thought to be a single homogenous stock (Eitner 1995, Trejo 2005) ranging from Baja California, Mexico to British Columbia, Canada (Council 2003). Often referred to as a ‘coastal-pelagic’ species, abundance of *A. vulpinus* decreases rapidly beyond 30 km from the coast (Strasburg 1958, Hanan et al. 1993).

The highest concentration of common threshers in the eastern Pacific occurs within the Southern California Bight (SCB) (Hanan et al. 1993), an open embayment bounded on the west by the California Current and extending along the Pacific coast from southern California (Point Conception; 34°N) to Cabo Colonet (31°N) in northern Baja California. It is a transitional ecotone between cool- and warm-water species in the eastern Pacific Ocean and thus has a unique biotic assemblage (Carlucci et al. 1986). In addition to its importance as habitat for large threshers, the SCB is thought to be an important nursery area for juvenile threshers and other pelagic sharks,

including the mako (*Isurus oxyrinchus*) and the blue shark (*Prionace glauca*) (Compagno 2001).

The large size and relatively high market value of the common thresher shark have made this species a prime target for commercial exploitation. Currently, the major fishery targeting threshers is the California drift gillnet fishery (CA-DGN) (CDFG 1999), and effort is concentrated in the SCB. While the broadbill swordfish (*Xiphias gladius*) is the primary target of the CA-DGN, it actually constitutes only a small percentage of the total catch, and the common thresher shark (and to a lesser extent, the mako shark) is an important secondary target of the CA-DGN. However, it is has been well documented that without careful management targeted shark fisheries are often not sustainable (Walker 1998). Compared to other important fisheries species such as sardines or tunas, sharks grow slowly, require many years to reach sexual maturity, and have low reproductive rates (Walker 1998). Due to these life history traits, shark populations are far less resilient and recover far more slowly following over-fishing.

The history of the CA-DGF thresher catch provides evidence of over-fishing effects. Catch rates peaked in 1982 at over 1000 metric tons, only 5 years after the inception of the CA-DGN, and declined sharply thereafter (PFMC 2003). In comparison, commercial landings in 2004 totaled less than 100 metric tons (CDFG 1999). Nevertheless the drift gillnet fishery is of major economic importance in California waters, with a current annual value of approximately \$36 million and

involving close to 100 commercial vessels, and thresher shark constitute the largest commercial shark fishery in California waters.

Despite the commercial value of this species, very little is known about its biology. Indeed, the current status of knowledge regarding migratory patterns, depth distribution, and nursery habitat is indirectly inferred from CA-DGN catch records (PFMC 2003), rather than directed scientific studies. However, such studies have important implications for the CA-DGN as there is currently inadequate biological information upon which to base informed management decisions about many species taken in this fishery. In the case of pelagic sharks, age class and spatial and temporal movement patterns are major determinants of susceptibility to drift gillnet gear (Cartamil & Lowe 2004, Sepulveda et al. 2004). In addition, current thresher shark stock assessments fail to take into consideration mortality of threshers from fishery operations outside U.S. waters, despite the highly migratory nature of this species (PFMC 2003).

For these reasons, the dissertation research contained herein was initiated to obtain data on thresher shark biology and fisheries that can be used in the management of the CA-DGN. Specifically, the research questions addressed in this dissertation are: 1) What are the movement patterns and habitat preferences of larger (subadult and adult) common thresher shark, the size class targeted by the CA-DGN? 2) What is the nursery habitat of the common thresher? 3) To what extent are threshers and other elasmobranchs impacted by the artisanal shark fishery along the Pacific coast of Baja California?

This dissertation consists of four data chapters. Chapter One describes an acoustic telemetry tracking study of subadult and adult common thresher shark. The goal of this chapter was to collect movement pattern data and define essential fish habitat for thresher sharks within the SCB, and to interpret these data in terms of thresher shark behavior and their vulnerability to CA-DGN gear. Chapter 2 utilizes an alternate technology, archival tagging, in order to examine movement patterns of subadult and adult threshers over longer time scales and at higher temporal resolution. In Chapter 3, acoustic telemetry is again used to investigate the use of the SCB as a nursery area for thresher sharks. Chapter 4 is a survey of the artisanal elasmobranch fisheries of the Pacific coast of the Mexican state of Baja California. Finally, Chapter 5 combines the findings reported in the dissertation with the results of previous and ongoing studies to provide a synoptic view of thresher shark movement patterns and habitat preference in the SCB and adjacent waters. It also describes ongoing research in Mexico designed to gain a more complete understanding of thresher biology and management issues pertaining to this and other species having a binational occurrence.

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CHAPTER 1: DIEL MOVEMENT PATTERNS AND HABITAT PREFERENCES OF SUBADULT AND ADULT COMMON THRESHER SHARKS (*ALOPIAS VULPINUS*) IN THE SOUTHERN CALIFORNIA BIGHT

ABSTRACT

The thresher shark, *Alopias vulpinus*, is the basis of the largest commercial shark fishery in California waters. We used acoustic telemetry to determine the diel movement patterns and habitat preferences of this species in the Southern California Bight (SCB), where commercial and recreational fishing for thresher sharks is concentrated. Eight subadult and adult threshers (fork length: 122 to 203 cm) were tagged with temperature and depth sensing acoustic transmitters and tracked for periods ranging from 22 to 49 h. Tracked sharks preferentially utilized areas offshore of the continental shelf, and made highly linear movements, although there was no consistent overall directional trend. Mean rate of movement (ROM, \pm SD) was 2.15 ± 0.46 km h⁻¹. ROM and angular concentration (r , a measure of relative linearity) both showed a strong daytime pattern, peaking at dawn and then decreasing throughout the day. In contrast, nocturnal ROM and r were less variable. Daytime vertical movements consisted of either prolonged vertical excursions below the thermocline or relatively level swimming within the upper portion of the thermocline. Maximum dive depth was 217 m, and lowest temperature recorded at depth was 9.4°C. Nocturnally, all sharks remained within the mixed layer. In addition to suggesting that the thresher shark is primarily a daytime predator, these findings also have relevance for estimating

how the alteration of fishing-gear set depth could affect catch rates of this shark in the SCB.

INTRODUCTION

Shark fisheries have increased dramatically in scope in the past century, and sharks are now often harvested with the same high-capacity commercial gear that has reduced the populations of many teleosts. Unfortunately, most shark fisheries around the world have proven to be unsustainable at high levels of exploitation (Walker 1998). Because sharks are long lived, slow growing, and produce few offspring (Smith et al. 1998), over-harvested populations may take decades to recover, even under greatly reduced fishing pressure. The life history characteristics of sharks, along with an expanding human population and corresponding demand for sharks and shark products, pose a daunting problem for fisheries agencies charged with managing shark resources sustainably. In addition, the effectiveness of shark management strategies has been hampered by a paucity of basic biological data such as habitat utilization and movement patterns. This is particularly true for pelagic sharks, which are difficult to study due to their large size and offshore occurrence.

The thresher shark, *Alopias vulpinus*, is a large pelagic species with a cosmopolitan distribution in subtropical and temperate seas (Compagno 2001). Off the west coast of North America, threshers range from southern Baja California, Mexico to British Columbia, Canada (PFMC 2003). However, the highest concentrations occur in the Southern California Bight (SCB) (Hanan et al. 1993), a region extending

from Point Conception, California (34° N latitude) to Cabo Colonet, Mexico (31° N latitude) (Carlucci et al. 1986). As such, threshers are an important secondary target species for the California drift gillnet fishery (CA-DGN) for broadbill swordfish, *Xiphias gladius*, which operates primarily within the SCB.

Catch rates of threshers in the CA-DGN peaked in 1982 at over 1000 metric tons (mt) (Hanan et al. 1993); however, commercial landings in 2004 totaled only 67 mt (CDFG 2005). This marked decline in landings is partially attributable to a reduction in thresher shark population size following severe fishing pressure in the late 1970s and early 1980s. However, other factors affecting this discrepancy in landings include increased regulatory measures and a decrease in the CA-DGN fleet size. Nevertheless, threshers in the CA-DGN constitute the largest commercial shark fishery in California waters (CDFG 2005).

The objectives of the present study were to use acoustic telemetry to collect movement pattern data and define essential fish habitat for thresher sharks within the SCB, and to interpret these data in terms of thresher shark behavior and their vulnerability to DGN gear. These studies focused on the SCB, where the CA-DGN is concentrated, and on subadult (i.e., 120 cm < fork length [FL] < 166 cm) and adult threshers (FL > 166 cm), which are the size classes most commonly encountered in the fishery (PFMC 2003).

METHODS

Capture and tagging

Thresher sharks were captured offshore of San Diego County, California, on hook and line. Heavy tackle and 80 lb. (36 kg) test monofilament line were used to reduce the interval between hooking the shark and the time it was brought alongside the tagging vessel (range 10 - 20 min. Once the shark was brought alongside the tagging vessel, a temperature and depth-sensing acoustic transmitter (Vemco, Model V-22TP, 22 mm diameter x 100 mm length, frequencies 34 to 40 KHz) was attached to it using a stainless steel dart tag inserted into the radials at the base of the dorsal fin. Acoustic tags had a depth range of 680 m, and a transmitting range of approximately 1 km. After tagging, sharks were measured and sexed, the hook was removed, and tracking commenced immediately upon release. Handling time at the tagging vessel was 3 to 5 min.

Acoustic tracking was conducted aboard either the 5-m R/V 'Phoenix' or the 7.5-m R/V 'Saikhon'. Depth and temperature data encoded in the acoustic tag signal were acquired using a rotating Vemco V10 directional hydrophone mounted on the side and extending below the keel of the tracking vessel, and decoded with a Vemco VR60 receiver. These data, along with determinations of position (Garmin GPS 72), were recorded at 5-min intervals over the duration of each track. Water temperature profiles, down to a depth of 200 m, were determined at 2 to 3 hour intervals using a bathythermograph (Seabird Electronics, Model SBE39). The tracking vessel was kept at a constant distance of approximately 200 m from the shark during tracking; for purposes of analysis, this was assumed to be the shark's position.

Analysis

Shark movement data were plotted over a bathymetric chart of the study area using Arcview GIS Version 3.2. Distances between successive positions were determined with the Animal Movement Analyst Extension (Hooge and Eichenlaub 2000) for ArcView GIS. Rate of movement (ROM, or speed-over-ground) was calculated by dividing distances between successive positional fixes by the sampling interval. Distances traveled within 1-h periods were summed to provide hourly ROMs, and plotted against time of day. Fixed-effect analysis of covariance (ANCOVA), with a shark effect to account for differences among sharks in individual behavior and hour as a covariate, was used to investigate the relationship between ROM and time of day, and between linearity and time of day. Because linearity data were bounded by 0 and 1, the significance for the relationship between linearity and time of day was also evaluated using a randomization test (9,999 randomizations; Manly 2007).

Circular statistics were performed on each complete track, as well as on hourly segments of each track. For these analyses, Oriana Version 2.0 was used to calculate point-to-point bearings and angular concentration (r), a relative measure of linearity ranging from 0 to 1, with a value of 1 representing absolute linearity (Batschelet 1981). The equation for r is:

$$r = 1/n [(\sum \cos \phi_i)^2 + (\sum \sin \phi_i)^2]^{1/2}$$

where ϕ is each point-to-point bearing, and n is the number of bearings. Significance of r values (i.e., linearity of movement) was tested with Rayleigh's z test.

Vertical movements were examined by plotting the depth readings for each shark against time of day and a depth profile was constructed for each tracking period. Bathythermograph data were fitted over the depth profiles to evaluate the extent to which vertical movements of the shark were related to the thermal structure of the water column. Data obtained from the transmitter sensors were used to construct diel depth and temperature preference distribution histograms.

RESULTS

Eight thresher sharks (FL: 122 to 203 cm) were tracked for periods ranging from 22 to 49 h (Table 1). Most sharks exhibited a significant increase in ROM during the first 4-6 h of the track relative to ROM after 6 h (paired t -test, $P < 0.001$, see track ROM values below), and some sharks also made a deep dive immediately following release. These behaviors are consistent with short-term stress responses associated with capture and tagging that have been reported for other species (Carey and Scharold 1990, Klimley et al. 2002), and therefore data from the first 6 h of each track were not analyzed.

Thresher sharks tracked in this study were all caught offshore of the continental shelf edge, which occurs at a depth of approximately 110 m in the study area (Fig. 1). None of the tracked sharks moved inshore and over the continental shelf.

Rather, they frequented waters over the continental slope and offshore basins where depths ranged from 1000 to 1800 m.

The mean hourly ROM (\pm SD) for all eight sharks was 2.15 ± 0.46 km h⁻¹ (range: 0.99 to 4.42 km h⁻¹), which for an average shark FL of 167.1 cm is equivalent to 0.41 ± 0.09 FLs sec⁻¹. No relationship was found between shark size (FL) and mean hourly ROM (linear regression, $r^2 = 0.08$, $P = 0.42$). There was a significant daytime pattern in hourly ROM, which was highest at dawn, decreased throughout the day and reached lowest levels at sunset (ANCOVA, $P < 0.001$); a similar daytime pattern was found for linearity (ANCOVA, $P = 0.004$) (Fig. 2A). In contrast, nocturnal ROM remained relatively constant and was similar to the mean overall ROM. The maximum hourly ROM determined for an individual shark was 4.42 km h⁻¹.

Most shark movements were significantly linear over the entire track or for extended portions of it (Table 1); however, there was no consistent overall directional trend. Angular concentration (r) had a daytime trend similar to that observed for ROM; r typically peaked at dawn, decreased throughout the day and reached lowest levels at sunset (Fig. 2B).

Figures 3 and 4 detail diel effects on the depth of occurrence and ambient temperatures experienced by the tracked sharks. Nocturnally, threshers remained in the mixed layer 88.4% of the time with little variation in swimming depth. Based upon examination of the bathythermograph data, the lower limit of the mixed layer (and thus the upper limit of the thermocline) occurred at a depth of 15 to 20 m during tracks. Daytime movement patterns were more variable. Threshers 2,3,4 and 5 made

very few vertical movements during the day, but remained deeper than their nocturnal depths, typically residing within the thermocline. However, threshers 1,6,7 and 8 made extensive daytime vertical excursions below the thermocline; these excursions often commenced at first light and ranged in duration from several min to over 10 h. Maximum dive depth was 217 m, and minimum temperature experienced at depth was 9.4°C, corresponding to a differential of approximately 10°C from sea surface temperature.

DISCUSSION

The thresher shark is a highly migratory species and its range in the northeastern Pacific extends well into Mexican waters (Eitner 1995). It is thought that threshers overwinter offshore of Baja California, and migrate north to the SCB (or farther in the case of larger sharks) in the spring (Smith and Aseltine-Neilson 2001). This purported northward migration is strongly supported by fisheries data (Hanan et al. 1993), and the appearance of threshers in large numbers offshore of San Diego County beginning in early spring (typically April or May) is a phenomenon well known to commercial and sport fishermen. It is during this period that we used acoustic telemetry to track thresher sharks in the SCB, in order to describe fine-scale movement patterns within the overall context of a generally northward migration. However, the movements of threshers tracked in this study were generally not to the north. Rather, no consistent directional pattern in the movements was observed (Fig. 1). Therefore, while a northward trend on the seasonal scale is probable, fine-scale

movements appear to be more variable, and are likely influenced by local prey dynamics and oceanographic features (discussed below).

Despite variable directionality, thresher shark movements exhibited significant linearity for entire tracks (sharks 1,2,7,8; Table 1) or for extended portions of tracks. For example, the non-significant r -value (0.13) of track four was due to a reversal of direction after 31 h. If the track is viewed as being composed of two segments, 31 h and 12 h in duration, the respective r values of the two segments (0.64 and 0.80) are both significantly linear at $P < 0.001$. Such directed movements have now been documented in many acoustically tracked pelagic fish, including various pelagic sharks (Carey and Scharold 1990, Klimley 1993, Holland et al. 1999), blue marlin, *Makaira nigricans* (Block et al. 1992), ocean sunfish, *Mola mola* (Cartamil and Lowe 2004), and yellowfin tuna, *Thunnus albacares* (Holland et al. 1990). It has been suggested that pelagic fishes may orient to celestial, infrasound, or olfactory cues (Gruber et al. 1988, Hara 1994, Barbin 1998, Sand and Karlsen 2000), as well as electromagnetic fields in the case of elasmobranchs (Klimley 1993, Meyer et al. 2005). In view of the relative constancy of the open ocean environment, this capacity for directed navigation may play an important role in the migration of threshers.

Offshore habitat preference and prey availability

The thresher sharks tracked in this study showed a strong preference for waters over the continental slope, offshore basins and submarine canyons, although shallower inshore habitat over the continental shelf was readily accessible (Fig. 1). It is likely

that prey distribution, and to a lesser extent, physical habitat characteristics, may be an important driving mechanism for this preference.

Threshers can attain large sizes (to at least 5.7 m TL; Compagno 2001), on a diet consisting largely of small schooling fish. Dominant prey include northern anchovy, *Engraulis mordax*, Pacific sardine, *Sardinops sagax*, and Pacific mackerel, *Scomber japonicus* (Preti et al. 2001, 2004). These species are commonly observed in near-surface waters both offshore and over the continental shelf; however, turbidity is generally much higher in nearshore waters (Eganhouse and Venkatsen 1993) and this may be one factor affecting predatory efficiency in shelf waters.

Another factor that may influence the offshore habitat preference of threshers is an ontogenetic increase in dietary scope. Threshers appear to become more generalized predators as they increase in size, and demersal species can form a significant portion of the diet of larger threshers (Preti et al. 2001, 2004; A. Preti, Personal Communication). For example, Pacific hake, *Merluccius productus*, which commonly occur beyond the continental shelf at depths of up to 500 m (Ressler et al. 2007), were found to be an important food item of larger threshers by Preti et al. (2001). The daytime diving activity of some tracked sharks further suggests that subadult and adult threshers may exploit the increased availability of alternative prey in deeper waters.

Daytime movement patterns and foraging

Distinct diel patterns in vertical movement, swimming speed, and path linearity suggest that thresher sharks forage by day and are relatively quiescent at night. Evidence for daytime activity comes from the correlation between ROM and angular concentration (Fig. 2), both of which peaked at dawn, decreased throughout the day, and were lowest at sunset. The increased speed of sharks at first light, coupled with highly linear movement, suggests a foraging behavior that maximizes the probability of encountering patchily distributed prey (e.g., sardine schools). When an area of high prey density is encountered, ROM and r would be expected to decrease as the shark remained to feed in a relatively small area. Although this pattern was not observed during every daytime tracking period, our analysis (fixed effects ANCOVA) accounts for inter-shark variability, and provides robust statistical support for this interpretation of the observed movement patterns. Similarly, greater linearity was found to coincide with non-foraging migratory behavior and foraging was accompanied by convoluted (i.e., lower r value) movements for the white shark, *Carcharodon carcharias* (Weng et al. 2007), salmon shark, *Lamna ditropis* (Weng et al. 2008), narwhal, *Monodon monoceros* (Laidre et al. 2004) and wandering albatross, *Diomedea exulans* (Weimerskirch et al. 2002).

The supposition that foraging is predominantly a daytime activity for the thresher is further supported by diel vertical distribution patterns. Daytime movements often featured repeated dives below the thermocline, up to ten h in duration and occasionally reaching depths in excess of 200 m. Other sharks, such as the mako, have been shown to feed during diving episodes (Sepulveda et al. 2004). Carey and

Scharold (1990) suggested that vertical movement of blue sharks through the water column might increase prey encounter rates, and this could also be true for threshers, particularly on dives of short duration.

Some sharks did not dive by day, and instead remained in the upper portion of the thermocline (Fig. 3, 4), at depths of 15 to 40 m. A vantage point below the mixed layer might assist in location of schooling near-surface prey by silhouetting them against downwelling light. Alternatively, the thermocline may be an area of high prey density; however, little is known about the daytime depth distribution of schooling prey species.

Nocturnal movements

Thresher sharks utilize a mode of predation that is unique among elasmobranchs, wherein prey is struck with the elongate upper lobe of the caudal fin prior to capture (Gubanov 1972). Assuming that this behavior likely requires adequate light levels, it might be expected that the nocturnal behavior of threshers would reflect reduced foraging activity. The characteristic daytime high variability in movement patterns (suggestive of foraging behavior) is absent by night, and nocturnal movements were instead characterized by lower variability in all measured movement parameters. Specifically, both ROM and angular concentration, r , were more constant at night (nocturnal ROM usually ranged from 2.05 – 2.25 km h⁻¹ and r ranged from 0.8 to 0.9). In the presumed absence of feeding, this constancy of nocturnal ROM may be indicative of an optimal cruising speed (U_0) that would minimize the energy required

per unit distance traveled (Weihs 1984), while still maintaining ram-ventilatory efficiency. Indeed, the measured nocturnal ROM translates to approximately 0.6 m sec^{-1} , which falls within the uncertainty estimates of U_0 calculated by Weihs (1984) for the size class of sharks tracked in this study.

There was also little variation in swimming depth by night, and threshers were located above the thermocline (i.e., in the mixed layer) 88.4% of the time during nighttime hours. A nocturnal preference for the mixed layer after daytime predatory activity could be a form of post-feeding thermoregulation; threshers might benefit from warmer temperatures in the mixed layer by increased digestive rate and assimilation efficiency (Wurtsbaugh and Neverman 1988). It must be noted, however, that thresher sharks may be opportunistic feeders, and the possibility of nocturnal predation cannot be excluded. Feeding periodicity data are needed to validate these findings, and are a logical next step for thresher shark research.

Fishery management implications

Despite the crash in the eastern Pacific population of threshers in the 1980s caused by over-fishing (Hanan et al. 1993), there are signs that this population may be slowly recovering, such as increased catch-per-unit-effort (CPUE) and average fish size (Smith and Aseltine-Neilson 2001) in the CA-DGN. This is largely attributable to a seasonal closure (within 75 miles of the coast from 1 May to 14 July) enacted subsequent to the crash and designed to protect vulnerable aggregations of threshers during their spring migration northward along the California coast. Our tracking data

support this closure, in that they show the essential habitat of subadult and adult threshers during this period to include the area immediately offshore of the continental shelf.

In addition to seasonal and area closures, gear parameters (e.g., net dimensions, mesh size, and deployment time and depth) of drift gillnets can be manipulated for management purposes in the CA-DGN. For example, Sepulveda et al. (2004) stated that drift gillnet deployment depths in the CA-DGN likely lead to a reduced catch of juvenile mako shark. Typically, drift gillnet gear consists of a 2.2 km (length) x 30-40 m (depth) large-mesh (≥ 35.6 cm) gillnet that hangs vertically in the water column at a legally mandated minimum depth of 6 fathoms (approximately 11.0 m). Nets are set at dusk and retrieved before dawn, and therefore it is the nocturnal depth distribution of the thresher shark that is particularly important in determining its susceptibility to DGF gear. Based upon data shown in Fig. 4, 50.5 % of thresher shark nocturnal depth readings were found to be deeper than 6 fathoms, and threshers were thus within 'capture range' a substantial portion of the time. These data indicate that increasing the legally mandated minimum net depth would have the effect of decreasing catch rates of this species. For example, 63 % of nocturnal depth readings were shallower than the 7 fathom (12.8 m) depth. This indicates that a change in minimum set depth from 6 to 7 fathoms could decrease thresher shark catch rates by approximately 12.5 %. Conversely, increased catch rates would likely be achieved by deploying nets higher in the water column. According to the data in this study,

decreasing the minimum set depth from 6 to 5 fathoms could increase catch rates by approximately 17.5 %.

It appears that the depth of the thermocline has a strong influence on nocturnal vertical distribution of thresher sharks (Fig. 3,4), and has potential utility as a management parameter (as opposed to absolute depth or temperature preference). Thermocline depth is known to vary seasonally and spatially. In the SCB, thermocline depth generally increases from summer through fall, and decreases from winter through spring (Eber 1977). Our data, collected in spring and early summer, represent thresher shark vertical distribution when the SCB thermocline is at its shallowest, and therefore likely represent an underestimate of the amount of time threshers are within CA-DGN capture range. Assuming that the nocturnal vertical distribution - thermocline relationship remains constant, thresher sharks in a given area may become increasingly susceptible to CA-DGN capture over the course of the fishing season (typically August through January) as the thermocline moves progressively lower in the water column. Correspondingly, abundance estimates derived from drift gillnet fishery CPUE analyses will tend to overestimate the abundance of threshers in winter if thermocline depth is not taken into account. The incorporation of thermocline depth (among other oceanographic variables), habitat preferences and movement patterns into habitat-based fisheries models (e.g., Brill et al. 2005) could result in more efficient management of thresher sharks and other pelagic fishery resources in the SCB.

Table 1.1: Shark sex, length and track information for each of the eight thresher sharks tracked in this study. Angular concentration (r) values in ***bold italics*** denote movements that exhibit significant linearity over the entire track period (Rayleigh's z test, $P < 0.05$). U = sex unidentified. FL = fork length.

Thresher Shark #	Sex	FL (cm)	Track Start Date	Track duration (h)	Track Distance (km)	r
1	F	152	6 April 2005	35	57.9	<i>0.60</i>
2	F	179	20 April 2005	31	78.0	<i>0.88</i>
3	F	202	3 May 2005	40	81.4	0.23
4	F	200	11 May 2005	43	90.0	0.13
5	F	147	17 May 2005	49	94.2	0.12
6	M	132	22 May 2005	43	96.0	0.18
7	U	203	28 May 2005	26	68.9	<i>0.73</i>
8	F	122	5 June 2005	22	57.6	<i>0.73</i>

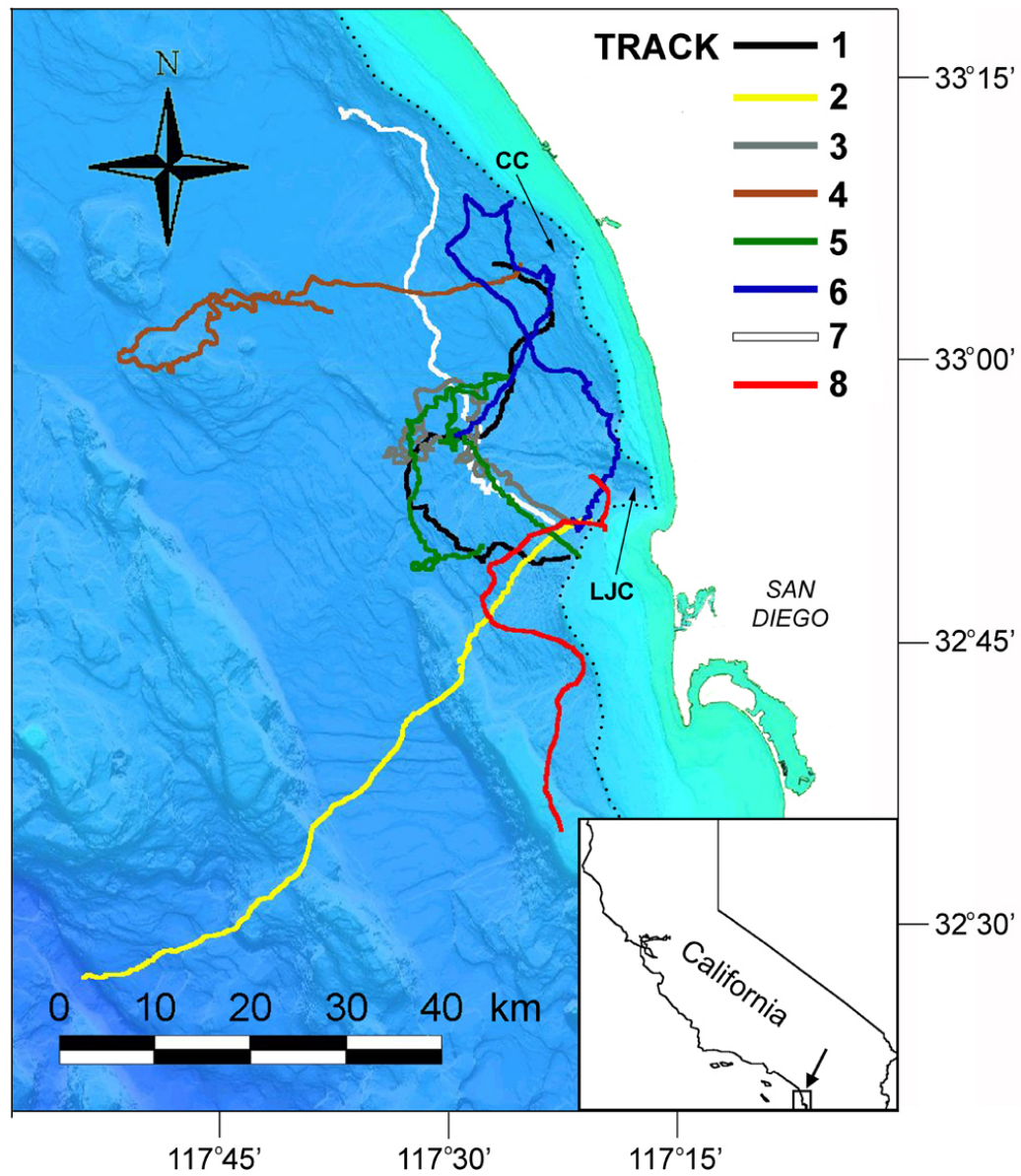


Figure 1.1: Latitude and longitude movement data for eight common thresher sharks tracked by acoustic telemetry off San Diego County, California. Inset shows the tracking area in relation to California. Darker blue indicates deeper water (max depth: ca. 1800 m), dotted line indicates the offshore edge of the continental shelf (light blue). LJC = La Jolla Canyon, CC = Carlsbad Canyon.

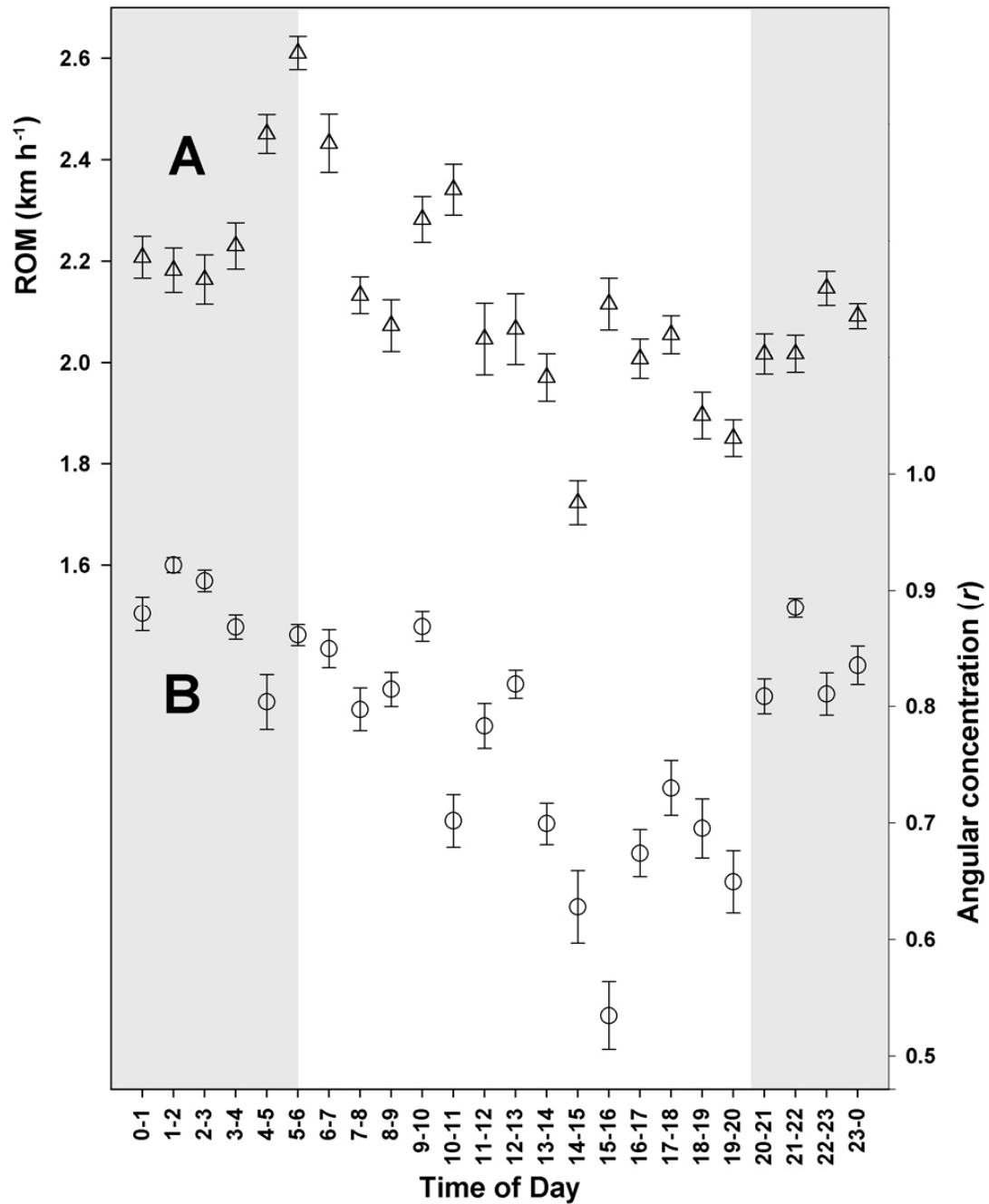


Figure 1.2: Open triangles: hourly rates of movement (ROM; km h⁻¹, mean \pm s.e.) of thresher sharks tracked over the diel cycle. Gray shaded areas are nocturnal hours, unshaded areas are daylight hours. **B.** Open triangles: corresponding hourly angular concentration (r) values.

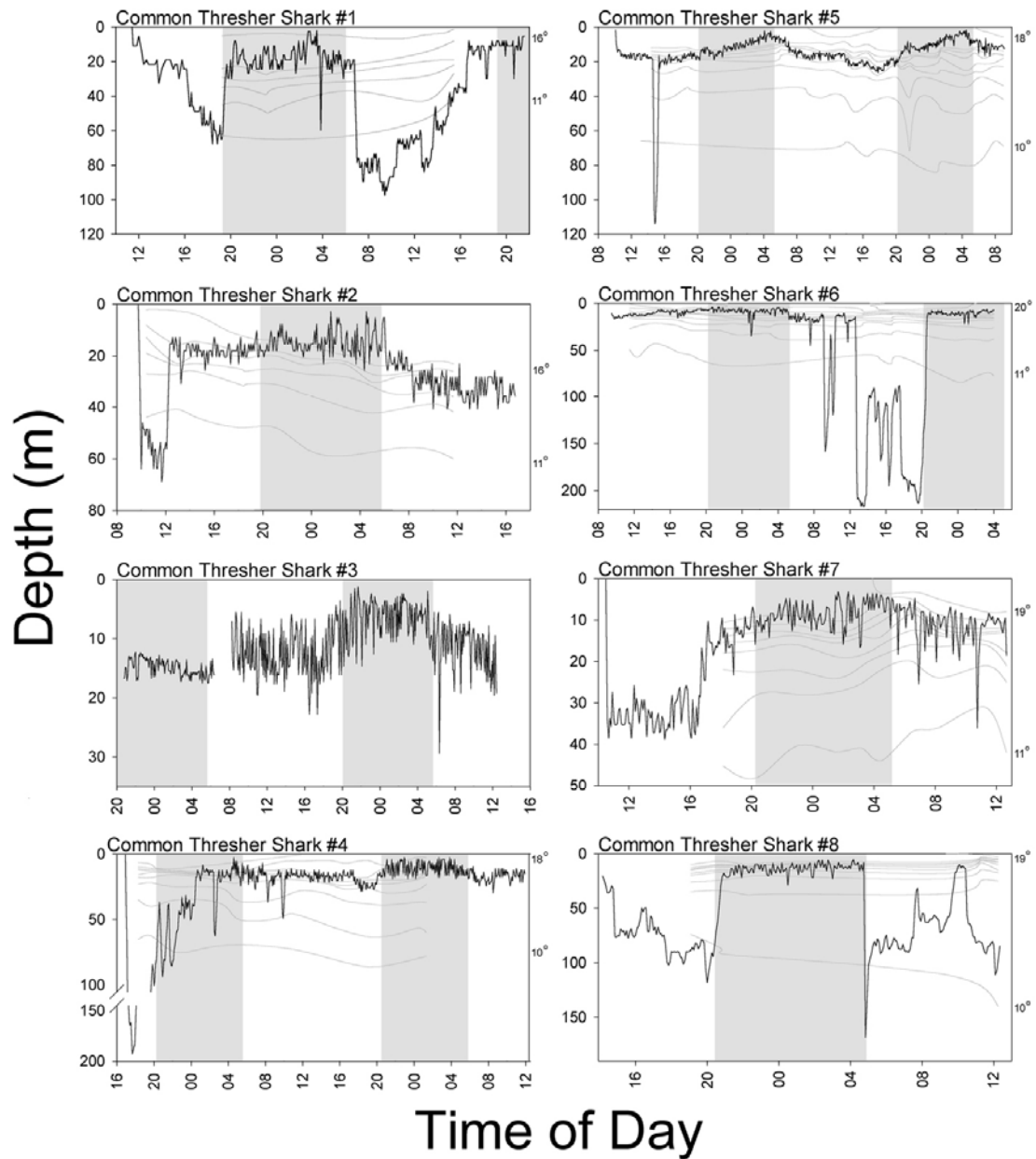


Figure 1.3: Dive profiles of common thresher sharks 1 through 8. Shaded areas indicate nighttime hours. Gray lines represent 1°C isotherms; maximum and minimum isotherm temperatures are given on the right. Water temperature data were not collected for shark #3. Data for first 6 h of track are shown, but were not used in analyses.

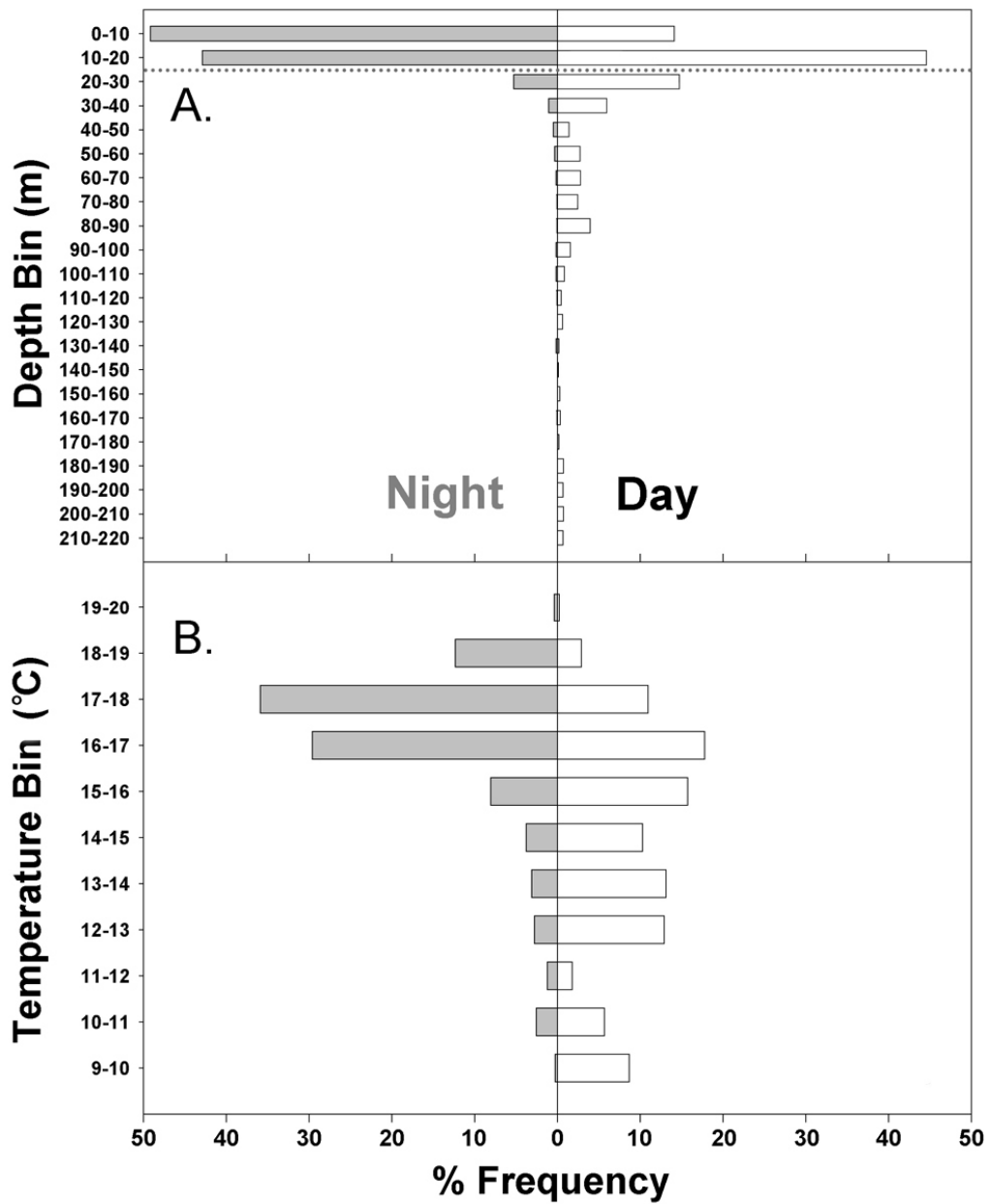


Figure 1.4: Pooled depth distributions (% frequency) for all tracked common thresher sharks in 10 m bins, during night (shaded bars) and day (unshaded bars). Dotted line represents the approximate depth of the thermocline. **B.** Pooled temperature distributions (% frequency) for all tracked common thresher sharks in 1°C bins.

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ACKNOWLEDGEMENTS

This work was supported by California Sea Grant (Grant # R/F-193), the William H. and Mattie Wattis Harris Foundation, the Tinker Foundation, the Moore Family Foundation, UC Mexus-CONACYT, J. Steinitz, and a gift from J. Bohn. D. Cartamil was supported by a fellowship from the Alliance for Graduate Education and the Professoriate, and the Tuna Industry Endowment Fund. We thank T. Thomas, L. Brammer, and K. Duff at the Scripps Institution of Oceanography Machine Science Development Center for custom construction of the acoustic tracking system, and J. Dufour and B. Jones for use of the tracking vessel ‘Saikhon’. D. Holts and the National Marine Fisheries Service provided the tracking vessel R/V ‘Phoenix’ and

essential tracking equipment. Thanks to E. Kisfaludy and the many volunteers who assisted in fishing and tracking operations. We also thank D. Checkley, P. Hastings, C. Lennert, R. Rosenblatt, and D. Woodruff for reviewing and commenting on this manuscript. All procedures were performed under the guidelines of the Institutional Animal Care and Use Committee of the University of California, San Diego (protocol S00080).

This chapter, in full, was submitted for publication as:

Cartamil D, Wegner N, Aalbers S, Sepulveda C, Baquero A, Graham JB. In review. Diel movement patterns and habitat preferences of subadult and adult thresher sharks (*Alopias vulpinus*) in the Southern California Bight. *Journal of Marine and Freshwater research*. The dissertation author is the primary investigator and author of this paper.

CHAPTER 2: ARCHIVAL TAGGING OF SUBADULT AND ADULT THRESHER SHARK (*ALOPIAS VULPINUS*) OFF THE COAST OF SOUTHERN CALIFORNIA

ABSTRACT

The common thresher shark, *Alopias vulpinus*, is a secondary target species of the California drift gillnet fishery (CA-DGN), which constitutes the largest commercial shark fishery in California waters. This study used archival tags to examine the movement patterns and habitat preferences of threshers for longer time periods than possible using manual tracking techniques. Depth and temperature-logging archival tags with 44 d memory capacities were deployed on 57 subadult and adult threshers in the SCB, and data were recovered from 4 tags. By night, sharks occupied depths of 5 to 13 m, and were confined to the mixed layer. Sharks were significantly deeper by day, and daytime vertical distribution consisted of two distinct modes; a 'shallow' mode (wherein sharks occupied only the upper 20 m of the water column), and a 'deep' mode (characterized by vertical excursions to depths of up to 320 m). This modal switch is interpreted as relating to regional differences in abundance of surface oriented prey and prey in deeper water. Maximum dive depth was 320 m, greatest dive duration was 712 min, and minimum temperature experienced during a dive was 9.1° C. In addition, dive descent rate was significantly greater than ascent rate. Sharks inhabited waters corresponding to a sea surface temperature range of 16 to 21° C. The nocturnal depth distribution of threshers has implications for management of drift gillnet deployment depths in the CA-DGN.

INTRODUCTION

The thresher shark, *Alopias vulpinus*, is a large pelagic species with a cosmopolitan distribution in subtropical and temperate seas (Compagno 2001). Along the west coast of North America, the thresher occurs from southern Baja California, Mexico to British Columbia, Canada (PFMC 2003) and is an important commercial species throughout this range. In Baja California waters, the thresher is a target of drift gillnet (Olvera 2009) and artisanal shark fisheries (Chapter 4 of this dissertation). In U.S. waters, it is an important secondary target species of the California drift gillnet fishery (CA-DGN) for broadbill swordfish, *Xiphias gladius*, and constitutes the largest commercial shark fishery in California waters (CDFG 2005). Analyses of CA-DGN catch patterns suggest that the thresher overwinters offshore of Baja California, and migrates north in the spring (Hanan et al. 1993, Smith & Aseltine-Neilsen 2001). The largest number of threshers occurs in the Southern California Bight (SCB), a region extending from Point Conception, California (34° N latitude) to Cabo Colonet, Mexico (31° N latitude) (Carlucci et al. 1986, Hanan et al. 1993).

Acoustic telemetry tracking in the SCB (Chapter 3 of this dissertation) has shown that juvenile thresher sharks utilize shallow waters over the continental shelf as a nursery area. By contrast, Chapter 1 of this dissertation showed that subadult and adult threshers [i.e., > 120 cm fork length (FL)] have a preference for deeper waters offshore of the continental shelf. Some of these larger sharks made vertical excursions by day of up to 220 m that were suggestive of foraging behavior, whereas nocturnal depths were generally limited to the upper 20 m of the water column, and appeared to

be strongly influenced by the depth of the thermocline. These results were used to estimate changes in CA-DGN thresher shark catch rate that might be achieved by varying the depth at which drift gillnets are deployed. However, logistical constraints generally limit acoustic telemetry studies to durations of < 75 h, and these relatively short periods may not encompass the full range of behaviors exhibited by a species. Thus there is a need for complementary studies utilizing technologies that yield longer time series, such as archival tagging.

Archival tags can record a range of high-resolution environmental data for periods ranging from days to years. They can be implanted or secured externally, and have been used extensively on pelagic fishes (Block et al. 1998, Ishida et al. 2001, West & Stevens 2001). The limitations of archival tags are that they cannot gather the full compliment of ambient data that can be collected during active acoustic telemetry tracking, and that the shark must be re-captured in order for the data to be extracted from the tag. However, these limitations are outweighed by a longer archived data stream.

The purpose of the present study was to use archival tags to examine the depth and temperature preferences and movement patterns of subadult and adult common thresher sharks in the SCB. Specific goals were to 1) determine whether behavioral trends identified through acoustic tracking persisted over longer time scales, 2) describe new behaviors that were not apparent from the acoustic tracks, 3) examine variability in thresher shark movement patterns over greater temporal scales, and 4)

more accurately quantify habitat preferences with respect to thresher shark vulnerability to CA-DGN fishing gear.

METHODS

Tagging

Tagging was accomplished between the periods 15 March - 10 August 2004, and 10 March - 22 June 2005. During these periods, 62 fishing days were needed to deploy 57 archival tags, with fishing effort concentrated offshore of La Jolla, CA (Fig. 1). Thresher sharks were captured on rod and reel, trolling live baits (Pacific mackerel, *Scomber japonicus* or Pacific sardine, *Sardinops sagax*) at depths of 15 to 20 m. After capture, sharks were allowed to swim on the line for 5 - 10 min in order to make them more docile for handling; they were then brought alongside the tagging vessel and restrained in an upright position. Lotek Inc. (Newfoundland, Canada) model LTD 1100 archival tags were mounted on the center of the dorsal fin, with a thin sheet of PVC (underlain by neoprene to minimize fin abrasion) on the side of the fin opposite the tag acting as a backing plate. The tag and backing plate thus 'sandwiched' the dorsal fin, and were held together by 1 mm diameter stainless steel wire. Data on sex, length, capture location, handling time and release condition were collected prior to release. Tagging was restricted to subadult and adult threshers, which are the size classes most commonly captured in the CA-DGN (PFMC 2003).

Tags were pre-programmed to collect ambient temperature and depth data at 1.88 min intervals (except tag 1: 0.94 min intervals), with a resolution of ~ 0.2 °C and

<2.0 m. Tags had dimensions of 8 mm X 16 mm X 27 mm, weighed 5 g in air (2 g in water), and had a memory storage capacity of approximately 44 d (except tag 1: 22 d memory capacity). Acquisition of archived data was dependent upon re-capture of the animal, and thus each tag had reward information and contact phone number displayed on the exterior. Recovered tags were downloaded via TagTalk1100 software, or sent to the manufacturer for download.

Analyses

An overview of each shark's vertical movements was constructed by plotting the depth readings of the shark against time of day. Vertical distribution was further illustrated by calculating aggregate time-at-depth distributions in 10-m bins, during both day and night periods. For each shark data set, the mean thermocline depth during the data acquisition period was estimated by determining the depth during dives at which the rate of temperature decrease was greater than 1°C per 5 m of vertical change. [These values were chosen based on previous bathythermograph thermocline determinations made by Cartamil et al. (Chapter 1 of this dissertation)]. Differences in depth between night and day, between periods of dissimilar diving behavior, and differences in nocturnal depths during full, new, and intermediate moons (full and new moons refer to the day of each full or new moon and the two days preceding and following it) were examined by fitting an ANOVA-type model to the data using weighted least squares. The weights were equal to the inverse of the variance of depth values for each data set tested, and are a conservative means of

incorporating variability in depth among periods into the analysis. The dependent variable for these models was the average depth during a specified period.

Independent variables were a shark effect, included to account for animal-specific differences in overall average depth, a mode effect, night/day effect, and lunar period.

To examine diving behavior of thresher sharks, individual dives were defined as vertical excursions that began in the upper 20 m of the water column, spanned a minimum depth of 15 m, and were followed by a return to the upper 20 m. These discrete diving periods were quantified in terms of total dive duration, maximum dive depth, and minimum dive temperature. Where dives were followed by a post-dive interval in the warmer waters of the mixed layer, fixed-effect analysis of covariance (ANCOVA) was used to investigate the relationship between post-dive interval and the above calculated dive parameters (as covariates) using each shark as a fixed effect. Descent and ascent rates were calculated for each dive, and compared with a general linear model using each shark as a fixed effect. For all statistical tests, results were considered significant at the $p < 0.05$ level.

To determine temperature preferences of the sharks, pooled temperature data were grouped into 1°C bins and expressed as percentage of time spent at each temperature bin during day and night periods. The sea surface temperature (SST) range corresponding to actual shark locations was estimated using tag temperature data collected when the shark was at a depth of < 2 m.

RESULTS

Fifty-seven thresher sharks were captured and released with archival tags offshore of San Diego County, California. Of these, five sharks were re-captured in the SCB (Fig. 1) and the tags recovered, corresponding to a tag return rate of 8.8%. Time at liberty between tagging and re-capture ranged from 76 to 1,277 d. Unfortunately, one of the tags (Shark 5) was damaged and the data could not be extracted. Full data sets were recovered from the remaining four tags. Complete shark size, sex, and tagging details are reported in Table 1.

All four sharks exhibited similar behavior immediately following release, consisting of a deep dive lasting several hours followed by a return to near-surface waters and behavior consistent with the remaining data set (Fig. 2). Because these immediate movements are likely a short-term response induced by capture and tagging stress, the first 12 h of data were not used for analyses.

Archivally tagged thresher sharks showed a clear diel pattern in vertical distribution which consisted of two distinct modes; throughout the remainder of this paper these are referred to as 'Shallow mode' and 'Deep mode'. During Shallow mode the majority of shark depth readings were located in the upper 20 meters of the water column, and sharks were slightly deeper by day than by night (Fig. 3, Table 2). Deep mode was very similar, but further characterized by diving activity during daytime hours only to depths that often exceeded 200 m (Fig. 3, 4) (whereas in Shallow mode the sharks rarely dove). All four sharks exhibited both modes at different times throughout tracks (Fig. 2, 3, 4), and a detailed view of the transition from Shallow to Deep mode for shark 1 is shown in Fig. 3. For further analyses, a shark was considered

to be in Shallow or Deep mode if it exhibited the characteristic depth distribution for that mode for two or more consecutive days, and dives were excluded from data sets prior to testing for differences between modes in order to more accurately describe the primary depth distribution during that period. During both Deep and Shallow modes, daytime depths were significantly greater than nocturnal depths. Moreover, for individual sharks, both daytime and nocturnal depths were greater in Deep mode than in Shallow Mode. The mean (\pm S.D.) depths of each shark in both modes (excluding dives) are given in Table 2, as is the estimated thermocline depth, which ranged from approximately 14 to 19 m. It is apparent from these data that the sharks spent the majority of their time above the thermocline, regardless of mode.

Analyses were conducted on 372 discrete dives. Dives were usually <200 m in depth, but maximum dive depth recorded was 320 m (Fig. 5). Most dives (57%) were < 20 min in duration, but maximum dive duration was 712 min (Fig. 6). Post-dive intervals were not significantly correlated to any of the calculated dive parameters. Rate of descent (21.1 ± 14.5 m min⁻¹; $\bar{X} \pm SD$) was significantly higher than rate of ascent (11.6 ± 6.5 m min⁻¹) (Fig. 7).

Archival tag data show similar temperature ranges, from 21.3 °C at the surface to a low of 9.1° C at maximum depth (Fig. 8). SSTs corresponding to thresher movements from June to July 2004 (sharks 1,3, and 4) ranged from 18.6 to 21.1° C. Shark 2, which was tagged in late April 2004, encountered SST as low as 15.5° C. Lunar phase had no effect on nocturnal depth distribution.

DISCUSSION

This paper describes movement patterns and habitat preferences of subadult and adult thresher shark using depth-and temperature sensing archival tags in the SCB. The results reported herein validate acoustic tracking studies by Cartamil et al. (Chapters 1 and 2 of this dissertation), showing that such previously reported behaviors as diel patterns in depth distribution persist over longer time periods. Cartamil et al. (Chapter 1 of this dissertation) reported that subadult and adult threshers preferentially utilize waters offshore of the continental shelf, and the off-shelf recapture locations of four of the five archivally tagged sharks support these findings. In addition, new facets of behavior were observed that would be difficult to accurately quantify using more temporally-limited acoustic telemetry, such as the Shallow and Deep modes of vertical distribution. Thus, the archival and acoustic telemetry studies each provide unique and complementary data sets that further our understanding of thresher shark biology.

Daytime Movements

Daytime depth distribution consisted of two distinct modes, a Shallow and a Deep mode. In both modes, the shark's vertical distributions were primarily within the upper 20 m of the water column. However, during Deep mode the sharks made from one to several vertical excursions by day to depths of up to 320 m. The archival records of each shark show both modes at different times, and the switch from one mode to the other was often abrupt. These modal shifts may be related to the vertical

distribution and abundance of prey. Small coastal pelagic fishes such as the northern anchovy, *Engraulis mordax*, Pacific sardine, and Pacific mackerel comprise the majority of thresher shark diet in the SCB (Preti et al. 2001, 2004), and typically occur in surface waters during daylight hours (Allen & DeMartini 1983). Sharks exhibiting Shallow mode behavior may be foraging near the surface when these species are abundant, and daytime Shallow mode depths of 8-20 m may be optimal for visual detection of small surface schooling prey silhouetted by downwelling light.

The switch to a Deep mode of vertical distribution may occur when surface prey are scarce and sharks commence deeper foraging excursions. The small coastal pelagics upon which the thresher shark preys are patchily distributed, and their abundance in near-surface waters varies spatially (Matsuura & Herwitt 1995, Nonacs et al. 1998, Emmett et al. 2005). An important component of the thresher shark's diet is the Pacific hake, *Merluccius productus* (Preti et al. 2001, 2004), which commonly occurs beyond the continental shelf at depths of up to 500 m (Ressler et al. 2007). Other thresher prey that are known to inhabit deeper waters include louvar, *Luvarus imperialis*, market squid, *Loligo opalescens*, and rockfishes, *Sebastes* sp. (Preti et al. 2001, 2004). In addition, species such as northern anchovy and Pacific sardine may also occur at depth by day. Diving activity for foraging has been described for several pelagic fish species such as the blue shark, *Prionace glauca* (Carey & Scharold 1990), Pacific bluefin tuna, *Thunnus thynnus orientalis* (Kitagawa et al. 2000), bigeye tuna, *Thunnus obesus* (Holland et al. 1990), mako shark, *Isurus oxyrinchus* (Sepulveda et al. 2004) and ocean sunfish, *Mola mola* (Cartamil & Lowe 2004).

An alternative explanation for the diving behavior of thresher sharks is that it provides an efficient mechanism for transportation. Weihs (1973) asserted that negatively buoyant fish might move from place to place with less energy expenditure by adopting a 'swim-glide' mode of locomotion, and vertical movements suggestive of this behavior have been reported for some tunas (Holland et al. 1990, Block et al. 1997). However, during an energy-saving glide, the shark would be expected to descend slowly and ascend at a faster rate, whereas the dive profiles of archivally tagged thresher sharks reveal the opposite tendency. Fast descents coupled with slower ascents have in fact been reported for several pelagic sharks (Carey & Scharold 1990, Nakano et al. 2003, Dewar et al. 2004, Sepulveda et al. 2004). Dewar et al. (2004) argue that because sharks tend to be only slightly negatively buoyant, this could preclude their use of 'swim-glide' as an energy saving mechanism. Although no data are available on the buoyancy of the thresher shark, pelagic elasmobranchs are generally more buoyant than benthic species (Bone & Roberts 1969, Baldrige 1970). Nakano et al. (2003) suggested that during prolonged ascents, the pelagic thresher *Alopias superciliosus* may take advantage of backlighting to spot potential prey, and this may be a foraging strategy for *A. vulpinus* as well. However, sharks occasionally spent several hours at maximum depth during dives, suggesting that predation occurred at these depths. During shorter dives, up and down swimming movements could be a hunting tactic to locate prey or olfactory cues indicating the proximity of prey (Carey & Scharold 1990).

Nocturnal Movements

Sharks were shallower by night than by day, at mean depths of 6 to 12 m. Although nocturnal depths in Deep mode were greater than in Shallow mode, this difference was small (< 2 m for two of the sharks, and negligible for the other two), and thus the distinction between the two modes nocturnally was less apparent than by day. As previously reported by Cartamil et al. (Chapter 1 of this dissertation), nocturnal depth preference appears to be strongly influenced by the depth of the thermocline, as over 90% of nocturnal depth readings were located above estimated thermocline depths. Why did thresher sharks inhabit such shallow waters by night? One possibility is that thresher sharks are foraging in the mixed layer. However, several factors argue against this. First, northern anchovy and Pacific sardine schools often disperse at night (Allen & DeMartini 1983), which could make predation more difficult. Secondly, the thresher shark utilizes a unique mode of predation, wherein prey is struck with the elongate upper lobe of the caudal fin prior to capture (Gubanov 1972), and this behavior may require light levels higher than those available nocturnally. Finally, Cartamil et al. (Chapter 1 of this dissertation) suggested that the lack of variability in swimming speed, linearity, and vertical movements of acoustically tracked threshers reflected reduced foraging activity nocturnally. A nocturnal preference for the mixed layer after daytime predatory activity could be a form of post-feeding thermoregulation; threshers might benefit from warmer temperatures in the mixed layer by increased digestive rate and assimilation efficiency (Wurtsbaugh & Neverman 1988). However, feeding periodicity has not been

investigated for this species, and the possibility of nocturnal feeding cannot be ruled out.

Lunar phase had no effect upon the nocturnal depth of tagged threshers. Previous studies have found greater nocturnal depths during the full moon for the blue shark, school shark, *Galeorhinus galeus*, and juvenile white shark, *Carcharodon carcharius*; these changes were attributed to foraging on prey species (e.g., squids, fishes, zooplankton) that undergo light-mediated vertical migrations (Carey & Scharold 1990, West & Stevens 2001, Weng et al. 2007). However, it must be noted that typical southern California Spring weather conditions [characterized by a dense and persistent marine cloud layer caused by the intrusion of warm Pacific air moving over colder waters (LaDochy & Brown 2003)] prevailed during May and June 2004 when most archival data were collected, and may have decreased lunar illumination sufficiently to prevent a light response. Alternatively, if thresher shark foraging is predominantly a daytime activity, nocturnal depth would not be expected to be influenced by changes in prey vertical distribution corresponding to lunar illumination.

Physiology

Temperatures at the maximum depths attained by threshers were up to 12 °C lower than those at the surface. Prolonged exposure to low temperatures during dives could impose various physiological stresses such as reduction of cardiovascular function (Blank et al. 2004), power output (Altringham & Block 1997), and temporal resolution of vision (Fritsches et al. 2005). The thresher shark possesses vascular retina

that enable it to elevate red muscle temperature above that of ambient water (Bone & Chubb 1983, Bernal & Sepulveda 2005), and this capability for regional endothermy may allow the thresher to withstand cold temperatures for longer durations than pelagic ectotherms of similar mass. For example, the blue shark (Carey & Scharold 1990), scalloped hammerhead shark, *Sphyrna lewini* (Klimley 1993), and ocean sunfish (Cartamil & Lowe 2004) dive through temperature gradients as severe as those encountered by the thresher, but do not usually remain at maximum depth for more than a few minutes; this is reflected in their 'yo-yo' dive patterns. By contrast, almost 40% of thresher dives were longer than 30 min and 11% were longer than 100 min, with a maximum dive duration was 712 min.

Thresher sharks often made several dives throughout the day that were punctuated by short surface intervals. Periodic returns to warmer surface waters may facilitate recovery from thermal stress incurred during dives, as suggested for the swordfish (Carey & Robison 1981) and the blue shark (Carey & Scharold 1990). Cartamil & Lowe (2004) found that the durations of post-dive surface intervals of ocean sunfishes increased significantly as a function of maximum dive depth, further supporting this hypothesis, and a similar relationship was found by Dewar et al. (2004) for one juvenile white shark. In the present study, no relationship was found between the depth, temperature or duration of dives and subsequent surface intervals for archivally tagged threshers. Therefore, while these intervals may be physiologically beneficial, their duration does not appear to be constrained by thermal stress incurred during the preceding dive. Taken as a whole, these results suggest that red muscle

endothermy may allow the thresher to more efficiently forage in cold, deep waters than other sympatric large pelagics. However, large endothermic sharks such as makos may have similar abilities.

Fisheries Implications

The SCB is an important habitat for the thresher shark, and most of the U.S. commercial and recreational catch of threshers occurs there (Hanan et al. 1993, Council 2003). This importance of this region is underscored by the fact that all tagged thresher shark re-captures took place in the SCB, with three sharks caught by the CA-DGN, and two by recreational fishers. A tag return rate of 8.8% is considered high for pelagic sharks (Kohler & Turner 2001) and reflects the fishing pressure on this species. Nevertheless, this rate likely underestimates the actual capture of tagged threshers due to the possibility of trans-boundary movements into Mexican waters, as has been documented through conventional and satellite tagging studies (Baquero 2006; D. Cartamil, unpublished data). Threshers are a target of drift gillnet (Olvera 2009) and artisanal shark fisheries (Chapter 4 of this dissertation) in Baja California; however, tags recovered in these fisheries are usually discarded at sea (D. Cartamil, personal observation). The possibility also exists that some tags were lost due to shedding, although the maximum time-at-liberty of 1,277 d suggests that the tag attachment method was successful.

Within U.S. waters, the primary fishery impacting the thresher is the CA-DGN. Typical drift gillnet gear consists of a 2.2 km (length) x 30-40 m (depth) large-mesh (\geq

35.6 cm) gillnet that hangs vertically in the water column at a legally mandated minimum depth of six fathoms (approximately 11.0 m). Nets are set at dusk and retrieved before dawn, and therefore it is the nocturnal depth distribution of the thresher shark that determines its susceptibility to CA-DGN gear. In the present study, 23% of thresher shark nocturnal depth readings were located below six fathoms, a similar depth distribution to that found for juvenile mako sharks in the SCB by Sepulveda et al. (2004). These data suggest that a further decrease in catch rates of the thresher could be achieved by deploying nets lower in the water column (i.e. at depths of > 6 fathoms).

These results differ from those of Cartamil et al. (Chapter 1 of this dissertation), who reported a higher percentage (50.5 %) of thresher shark nocturnal depth readings below the 6 fathom demarcation. However, the acoustic telemetry percentages were based upon a considerably smaller sample size. In addition, although the season was similar for both studies (acoustic tracking: April and May; archival tagging: May and June), they were done a year apart, and the oceanographic conditions influencing thresher depth distribution were likely different. For example, the average depth of the southern California thermocline was slightly shallower in 2004 than 2005, which could decrease the percentage of time sharks were below 6 fathoms nocturnally (Goericke et al. 2005, Peterson et al. 2006). Furthermore, the acoustic tracking data in Cartamil et al. (Chapter 1) were collected within 100 km of La Jolla, CA over maximum tracking periods of 49 h, whereas archivally tagged threshers likely traversed much larger areas during the 44 d data acquisition period and

encountered different conditions. Neither study was conducted during the CA-DGN fishing season (mid-August through mid-January) when thermocline depth is deeper in the water column, thus increasing the catchability of thresher sharks in this fishery. It is tempting to extrapolate from archival tag depth data the changes in thresher shark catch rates that might occur as a result of changes in drift gillnet set depths. However, depth values alone may not accurately predict the extent of thresher shark interactions with fishing gear of a set depth over time periods longer than that of the tagging study, and the incorporation of thermocline depth (among other oceanographic variables), habitat preferences and movement patterns into habitat-based fisheries models (Link 2002, Brill et al. 2005) could result in more efficient management of thresher sharks and other pelagic fishery resources in the SCB.

Table 2.1: Tag and recapture data for five thresher sharks released with archival tags in the SCB. FL = Fork Length. D.A.L. = Days at liberty.

Shark ID	Sex	FL	CAPTURE			RECAPTURE			D.A.L.
			Date	N. Latitude	W. Longitude	Date	N. Latitude	W. Longitude	
1	F	163	11 June 2004	32.89	117.27	17 Dec 2005	32.71	118.00	554
2	M	129	27 April 2004	32.90	117.27	5 July 2007	34.38	119.53	1164
3	M	160	31 May 2004	32.90	117.27	15 Nov 2004	33.47	117.78	168
4	F	140	15 June 2004	32.89	117.29	30 Aug 2004	34.03	118.63	76
5	F	135	23 June 2004	32.89	117.29	22 Dec 2007	34.32	119.97	1277

Table 2.2: Total number of days of archived data collected for each shark, the number of days each shark spent in shallow and deep mode, and the mean (\pm SD) depths occupied by the shark in each mode during day and night (excluding dives), relative to average thermocline depth.

Shark	Days Total	Days		Shallow Depths (m)		Deep Depths (m)		TC Depth (m)
		Shallow	Deep	Night	Day	Night	Day	
1	22	16	6	10.77 \pm 3.54	17.06 \pm 4.33	12.34 \pm 4.16	17.44 \pm 4.55	18.8 \pm 1.6
2	44	19	25	6.46 \pm 2.75	8.49 \pm 3.18	7.05 \pm 1.94	9.60 \pm 2.91	13.8 \pm 2.1
3	44	13	31	6.94 \pm 2.33	9.85 \pm 2.96	7.15 \pm 3.24	10.03 \pm 3.41	15.7 \pm 1.1
4	44	20	24	5.98 \pm 3.07	8.19 \pm 3.85	8.09 \pm 3.16	10.34 \pm 4.94	15.4 \pm 1.6

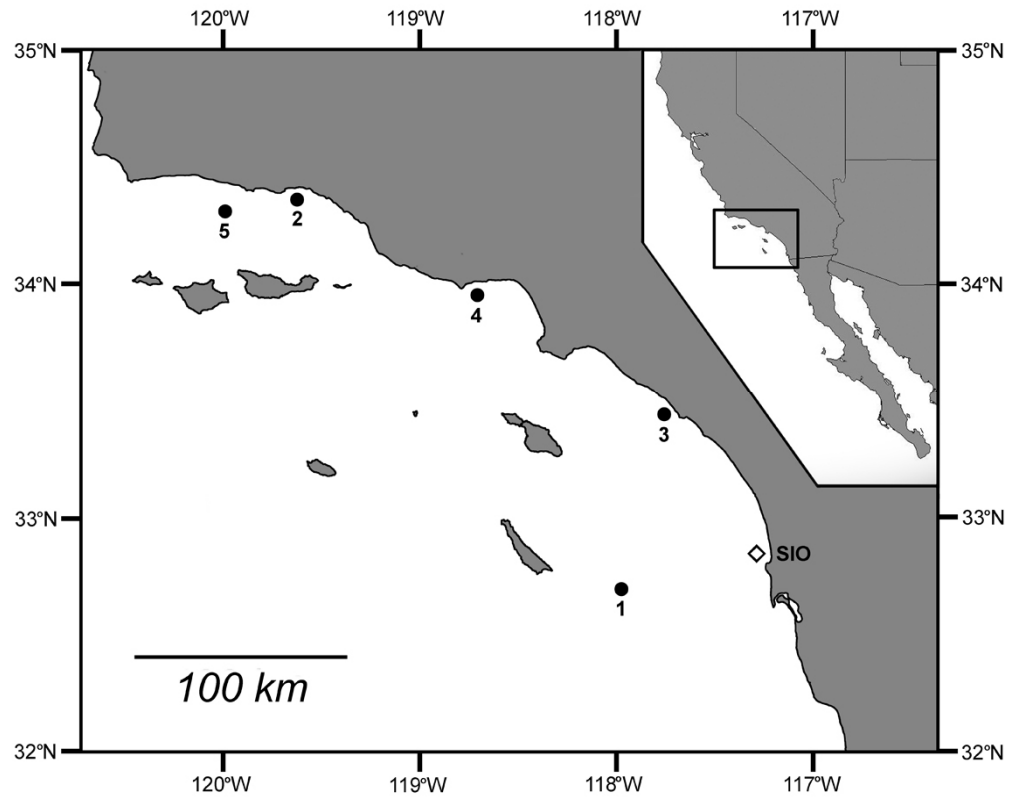


Figure 2.1: Tag and recapture locations of five thresher sharks in the SCB. Open diamonds: tagging location for all sharks. Black dots: recapture locations. Inset shows location of the SCB (in black box) in relation to California and Baja California, Mexico.

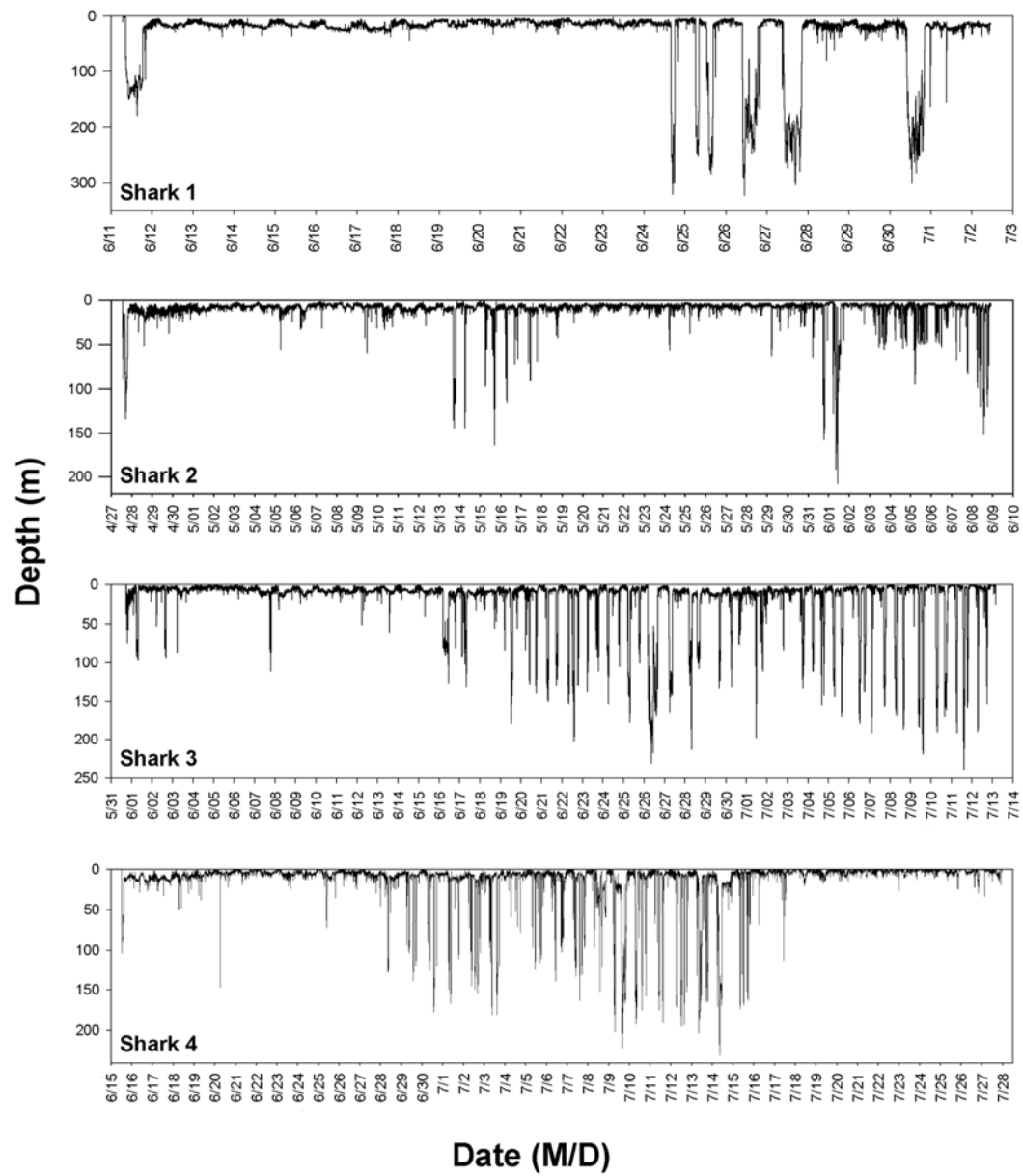


Figure 2.2: Dive profiles of four archivally tagged thresher sharks in 2004.

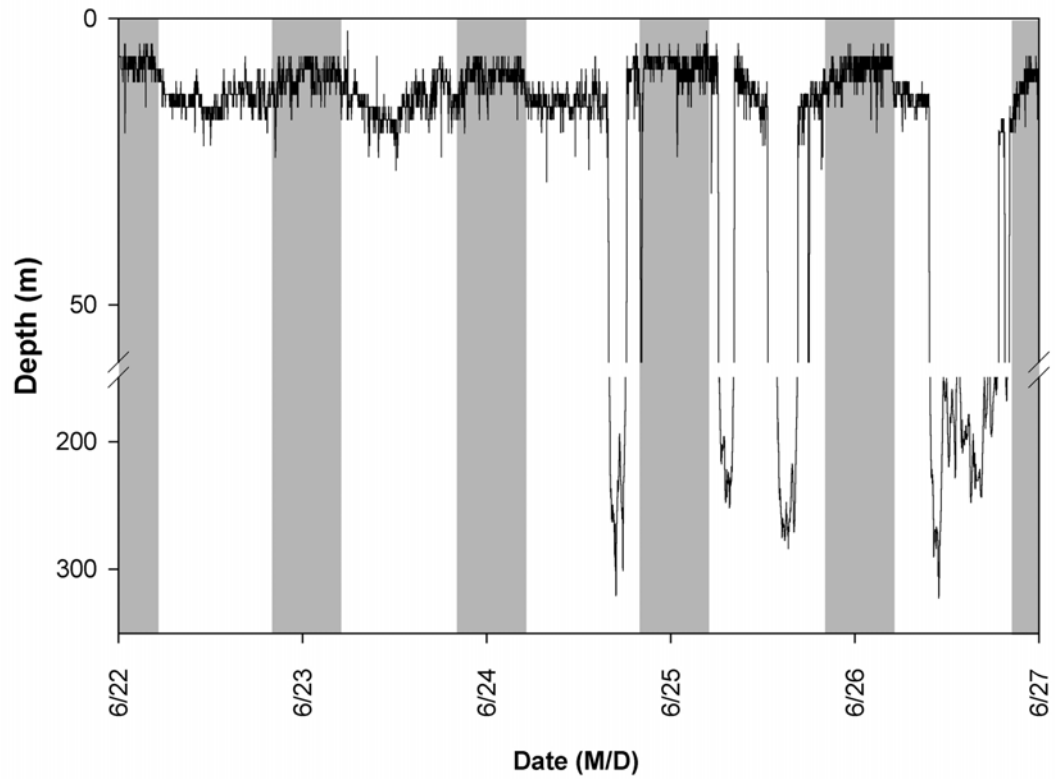


Figure 2.3: A representative five day section of archival data from Shark 1, showing the abrupt transition from Shallow to Deep mode of vertical distribution. Bars indicate night (grey) and day (white).

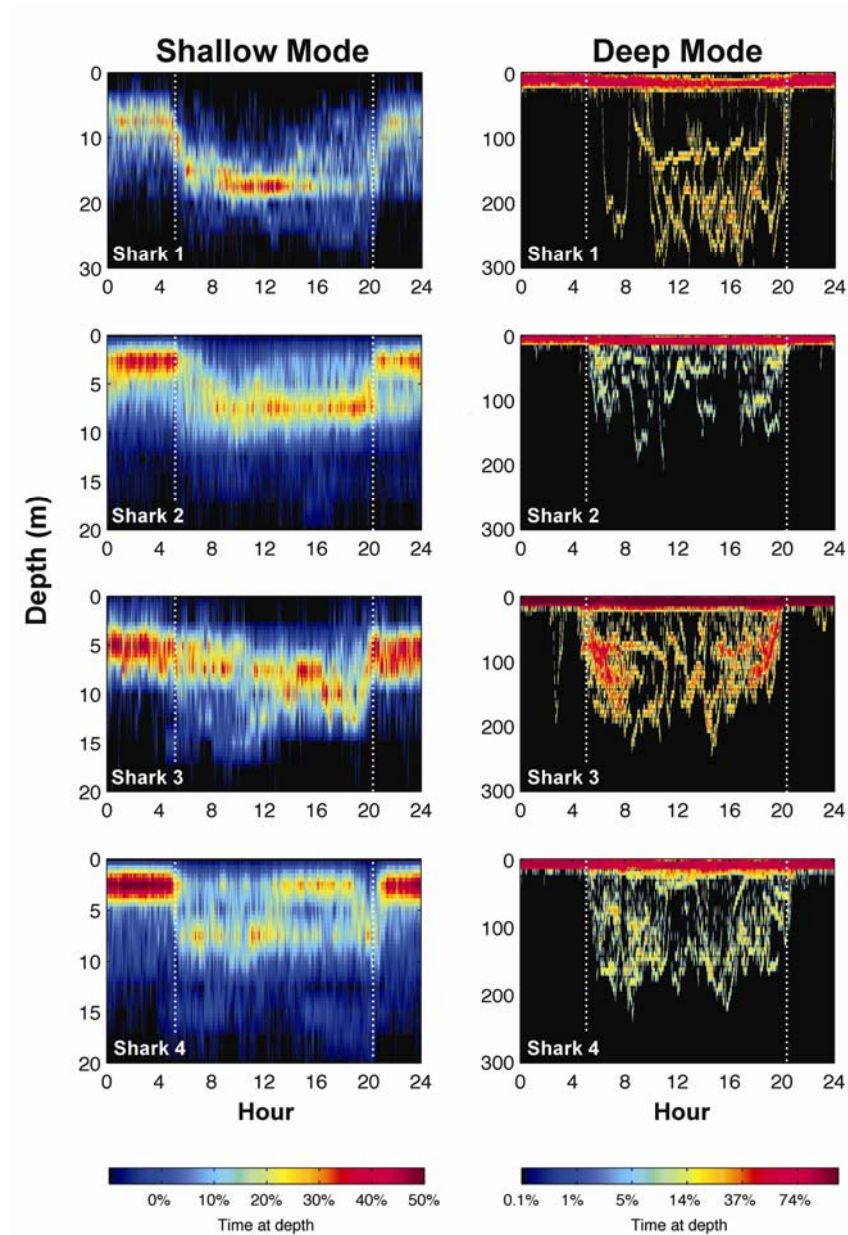


Figure 2.4: Depth distribution for each shark during Shallow (left) and Deep modes (right). Color scale denotes the percentage of time at given depths. Dotted white line shows time of sunrise and sunset (civil twilight).

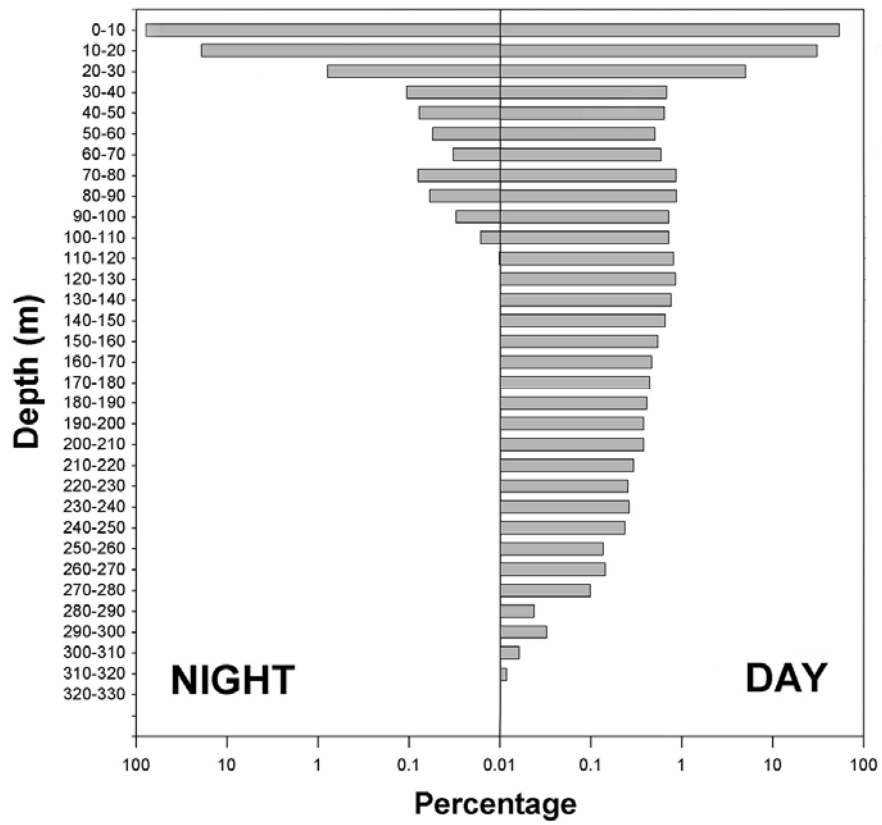


Figure 2.5: Swimming depth (10 m bins) histograms for archivally tagged thresher sharks during night and day.

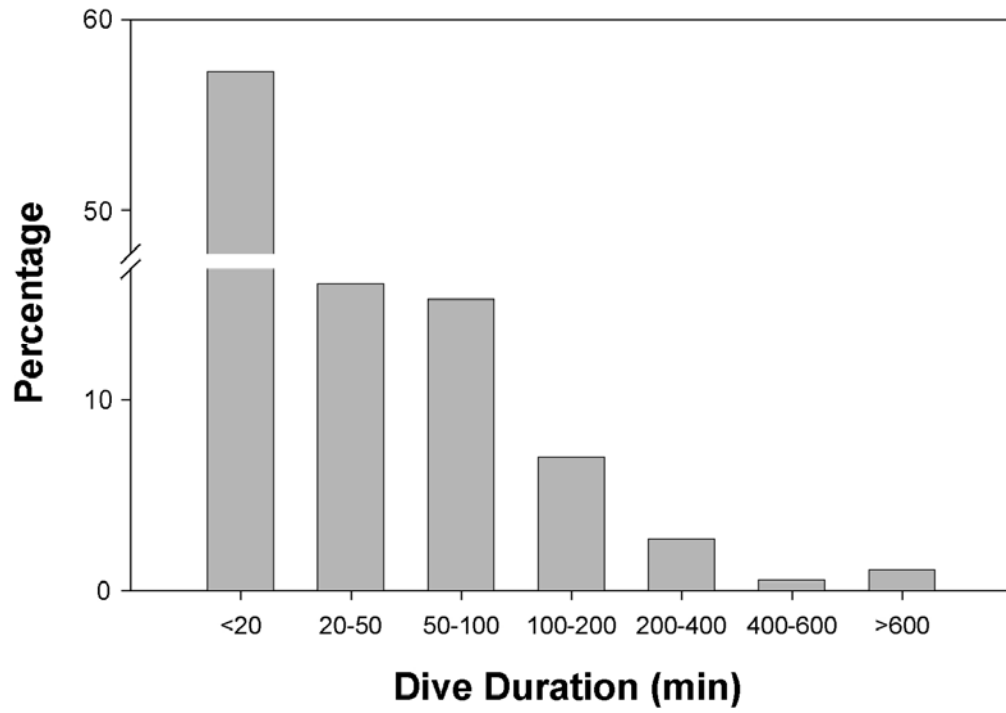


Figure 2.6: Dive duration histograms for archivally tagged sharks, showing percentage of time spent in each time

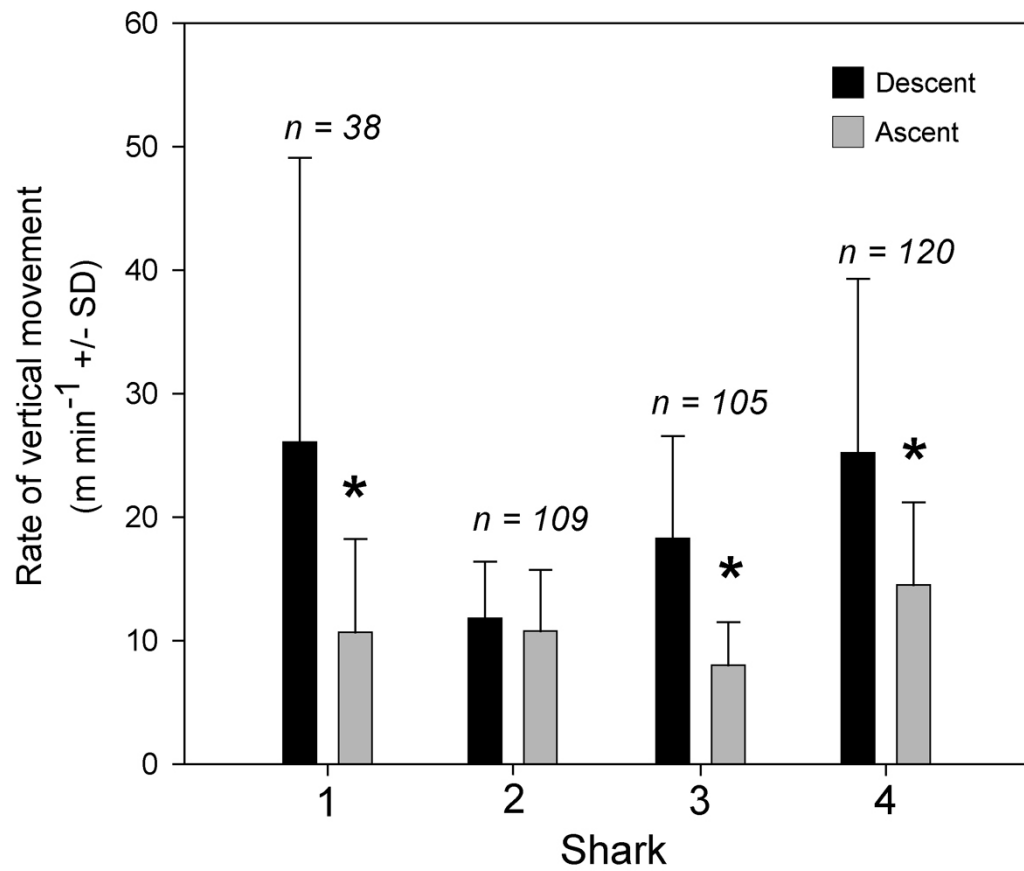


Figure 2.7: Mean descent and ascent rates for archivally tagged thresher sharks. Numbers indicate the total number of dives used for rate calculations. Asterisks indicate a significant difference between descent and ascent rate.

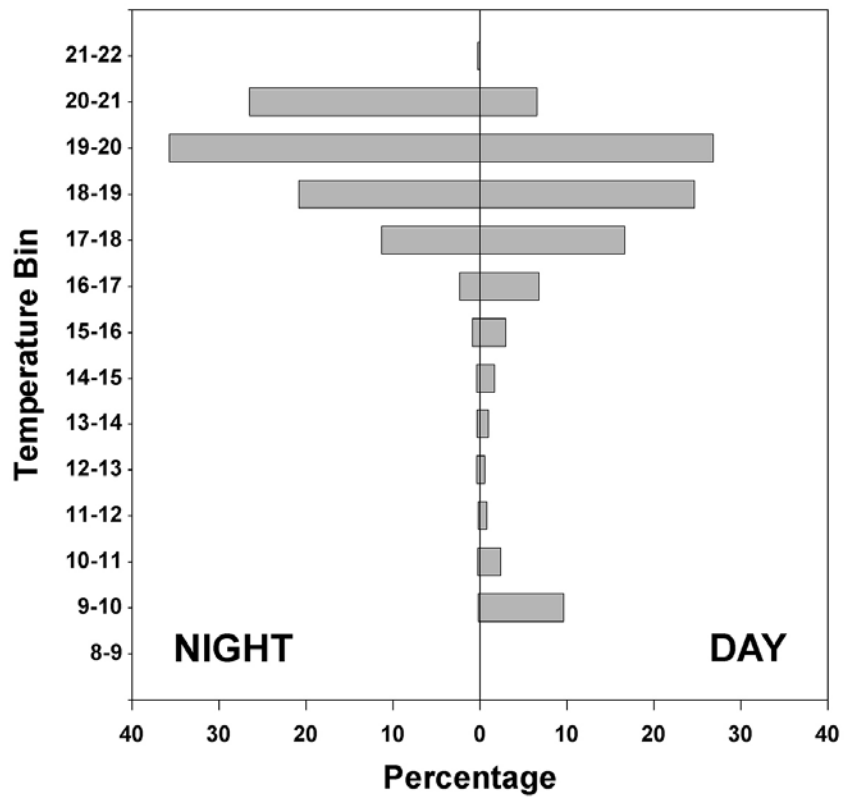


Figure 2.8: Temperature (1°C bins) histograms for archivally tagged thresher sharks during night and day.

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ACKNOWLEDGEMENTS

California Sea Grant (Grant # R/F-193) provided research funding and traineeship support for D. Cartamil, C. Sepulveda, and N. Wegner. D. Cartamil was also supported by a fellowship from the Alliance for Graduate Education and the Professoriate, and the Tuna Industry Endowment Fund. Additional funding was received by the William H. and Mattie Wattis Harris Foundation, the Tinker Foundation, the Moore Family Foundation, UC Mexus-CONACYT, and the Save Our Seas Foundation. Thank to J. Steinitz for help procuring funding. E. Kisfaludy was

instrumental in logistical support. C. Lennert provided valuable statistical assistance. Thanks to J. Blum for Matlab assistance. We wish to thank the following volunteers for their help with fishing and tagging: J. Schram, J. Gaeta, others. Thanks to NMFS for the use of the R/V 'Phoenix'. Thanks to D. Checkley, P. Hastings, C. Lennert, R. Rosenblatt, and D. Woodruff for reviewing and commenting on this manuscript. All procedures were performed under the guidelines of the Institutional Animal Care and Use Committee of the University of California, San Diego (protocol S00080).

CHAPTER 3: MOVEMENT PATTERNS AND NURSERY HABITAT OF THE JUVENILE THRESHER SHARK (*ALOPIAS VULPINUS*) IN THE SOUTHERN CALIFORNIA BIGHT

ABSTRACT

This study investigates the potential use of open coastal habitat over the continental shelf as a nursery area for the thresher shark *Alopias vulpinus*. Seven juvenile threshers were tracked using acoustic telemetry to determine their movement patterns and nursery habitat in the Southern California Bight. Tracked sharks occupied waters over the continental shelf 87% of the time. These waters had an average SST of $18.8 \pm 1.6^{\circ}\text{C}$, and chlorophyll concentrations that were an order of magnitude higher than in adjacent waters offshore of the continental shelf. Tracked sharks had a mean rate of movement (\pm SD) of $1.63 \pm 0.56 \text{ km h}^{-1}$, and some sharks exhibited high site fidelity. The vertical distribution of juvenile threshers was generally limited to the upper 20 m of the water, and most sharks showed a diel depth distribution patterns, with daytime depths significantly greater than nighttime depths. Juvenile thresher shark movement patterns are consistent with predation on northern anchovy *Engraulis mordax*. It appears that the SCB continental shelf provides juvenile threshers with ample food resources and reduced predation risk relative to adult habitat, and thus serves as a nursery area for this species.

INTRODUCTION

The young of many shark species spend the first few years of life in nursery areas that are discrete from the areas occupied by adult sharks. These nursery

areas appear beneficial in providing ample food resources and reduced predation risk at a vulnerable life stage (Clarke 1971, Castro 1993, Heupel et al. 2007), and are thus seen as critical to the survival of young sharks (Medved & Marshall 1983, Carrier & Pratt 1998, Gruber et al. 2001, Heupel & Simpfendorfer 2002). However, because nurseries are often located in shallow coastal environments, they are vulnerable to fisheries exploitation and other anthropogenic impacts. In view of worldwide declines in numbers of many shark species (Myers & Worm 2003), the identification of shark nursery areas and their inclusion into fishery management plans are important tools for the conservation and sustainable management of sharks (Heupel & Simpfendorfer 2005, Aires-da-Silva & Gallucci 2007, Heupel et al. 2007, McCandless et al. 2007).

Most of the documented shark nursery areas occur in bays, lagoons, and estuaries (Clarke 1971, Gruber et al. 1988, Holland et al. 1993, Heupel & Simpfendorfer 2005). Nevertheless, more open coastal habitats bordering waters along the continental shelf may also serve as nursery areas for some shark species (Hussey et al. 2009). A region containing such habitats is the Southern California Bight (SCB), an open embayment extending along the Pacific coast from Point Conception (34° N latitude) in southern California to Cabo Colonet (31° N latitude) in northern Baja California, Mexico, and offshore to a maximum width of 300 km (Fig. 1A). The SCB has been suggested as a nursery area for various pelagic shark species, including the shortfin mako shark, *Isurus oxyrinchus* (Sepulveda et al. 2004), blue shark, *Prionace glauca* (Ebert 2003), white shark, *Carcharodon carcharias* (Weng et al. 2007), and

thresher shark, *Alopias vulpinus* (Compagno 2001). However, no studies have addressed what nursery functions the SCB may actually provide for these species.

This paper reports investigations characterizing the nursery habitat of the thresher shark in the SCB. The thresher is a large, highly migratory pelagic shark with a cosmopolitan distribution in subtropical and temperate waters (Compagno 2001). Previous studies have shown that subadult and adult threshers [Fork length (FL) > 120 cm] generally inhabit waters offshore of the continental shelf (Cartamil et al., in review). In the SCB, the thresher shark is economically important as a secondary target of the California drift gillnet fishery (CA-DGN), and is the basis of the largest commercial shark fishery in California waters (CDFG 1999). Fisheries data suggest that threshers make a seasonal migration from a winter habitat south of the SCB off Baja California, Mexico, to the west coast of the United States, as far north as the state of Washington (PFMC 2003). In early spring, as adult threshers travel northward, pupping is thought to occur in SCB waters. Pups are born at 60-70 cm FL (Smith & Aseltine-Neilson 2001).

Although little is known about the movement patterns, distribution, or ecology of juvenile thresher sharks, preliminary evidence suggests that they utilize SCB continental shelf waters as a nursery habitat. Although the highest CA-DGN catch rate of larger threshers occurs in offshore (20 to 200 km from shore) waters in the SCB, juveniles (i.e., FL < 120 cm) constitute only a relatively small proportion (approx. 14 %; PFMC 2003) of this catch, suggesting that they do not consistently utilize the same habitat as adults. Further support for a distinct juvenile habitat distribution is provided

by CA halibut and white seabass coastal gillnet fisheries data (PFMC, 2003; NMFS Southwest Region Fishery Observer Program, unpublished data) and Mexican artisanal gillnet fisheries data (D. Cartamil, unpublished data), showing a higher proportion of juvenile threshers than adults occurring over the SCB continental shelf.

In this study acoustic telemetry tracking was used to test the hypothesis that the shallow, coastal waters over the continental shelf of the SCB function as a nursery area for juvenile thresher sharks. We describe the specific areas utilized by juvenile threshers, their habitat preferences, and their degree of short-term site specificity. We also examine the influence of physical, temporal, and environmental variables on the movement patterns of tracked sharks. These findings develop the nursery area concept for juvenile threshers, and have relevance for the management of thresher sharks in the SCB and adjacent waters.

METHODS

Tagging and tracking

Juvenile thresher sharks were captured by research longline or rod and reel at various coastal locations throughout the SCB (Fig. 1B). For sharks caught by rod and reel, fight time was less than 5 min. During longline operations, the line was checked hourly, and only sharks that were vigorously active and appeared free of injury when retrieved on the longline were tagged and tracked.

Captured sharks were brought alongside the capture vessel; a temperature and depth sensing acoustic transmitter (Vemco, Model V-13TP, 13 mm diameter x 45 mm

length, frequencies 60 to 75 KHz) was attached to the shark with a nylon dart (Floy Tag & Mfg. Inc., Model FIM-96) inserted into the radials at the base of the dorsal fin. Each shark was then measured and sexed, the hook was removed, and tracking commenced immediately upon release. Handling time at the tagging vessel was 3-5 min.

Sharks were tracked from a 5-m Boston Whaler equipped with a rotating Vemco V110 directional hydrophone mounted on the side of the tracking vessel that extended below the keel. Depth and temperature-calibrated signals from the acoustic tags were decoded with an onboard Vemco VR100 receiver. These data, along with determinations of position (Garmin GPS 72) and bottom depth (Hummingbird Matrix 10 depth sounder), were recorded at 5-min intervals over the duration of each track. A bathythermograph (Seabird Electronics, Model SBE39) was deployed every 2 to 3 h in order to determine the thermal structure of the water column. Acoustic tags had a depth range of 200 m, and a transmitting range of approximately 1 km. The tracking vessel was kept at a constant distance of approximately 100 m from the shark during tracking; for purposes of movement analyses, this was assumed to be the shark's position.

Analyses

Movement data were plotted over a bathymetric chart of the study area using Arcview GIS Version 3.2. Distances between successive positions were determined with the Animal Movement Analyst Extension (AMAE) (Hooge & Eichenlaub 1997).

Distances traveled over 1-h periods were summed to determine the hourly rate of movement (ROM), expressed in km h^{-1} .

Shark movements were mapped in relation to sea surface temperatures (SST) and chlorophyll concentrations (mg m^{-3}) (TerraFin software, www.terrafin.com). For each shark position for which a corresponding TerraFin satellite image was available, the SST and chlorophyll values were estimated, and these were used to calculate a mean for each track. In addition, a paired t-test was used to compare chlorophyll values for each shark position with chlorophyll values directly offshore of the continental shelf. To determine interaction with giant kelp *Macrocystis pyrifera* beds, location and extent of kelp beds were plotted from California Department of Fish and Game survey data for the appropriate year (http://www.dfg.ca.gov/biogeodata/gis/mr_nat_res.asp).

A site fidelity index (SFI; modified from Zeller 1997, Bellquist et al. 2008) ranging from 0 to 1 was calculated for each shark to assess the degree to which individuals exhibited short-term site fidelity. This was calculated as:

$$1 - \left(\frac{\text{distance from the first to last recorded position}}{\text{total distance traveled during the tracking period}} \right)$$

Small SFIs indicate unidirectional (linear) movements, while large SFIs indicate meandering movements over a relatively confined area (high site fidelity). Linear regression was used to determine if there was a relationship between SFI and habitat characteristics (i.e., mean SST and chlorophyll concentration) for each track.

Vertical movements were indicated by plotting the depth readings of each shark against time of day. These depth profiles were then fitted over bathythermograph data to evaluate the extent to which the shark's vertical movements were related to the thermal structure of the water column. Data obtained from the transmitter sensors were used to construct a diel depth-preference histogram, and data from the depth sounder were used to plot a histogram of bottom depths over which the shark swam.

RESULTS

Seven juvenile thresher sharks (FL: 66 to 108 cm) were tracked for periods ranging from 32 to 75 h, between 9 September 2005 and 11 September 2007 (Table 1). Based upon age and growth studies by Cailliet & Bedford (1983) and Smith et al. (2008), we estimate that the smallest sharks tracked (66 and 73 cm FL) were young-of-the-year, while larger sharks (101 to 108 cm FL) were from 1 to 2 y of age.

Mean hourly ROM for all sharks pooled during the first 6 h following release ($1.96 \pm 0.51 \text{ km h}^{-1}$) was significantly higher than ROM values recorded beyond 6 h ($1.63 \pm 0.56 \text{ km h}^{-1}$; paired t-test, $p < 0.001$). This increased ROM may reflect a short-term capture-induced stress response, and thus data obtained during the first 6 h of tracking were not used for any analyses. Mean hourly ROMs for individual sharks are given in Table 1.

The continental shelf of the SCB is often less than 10 km wide, and extends offshore to a bottom depth of approximately 110 m (Carlucci et al. 1986). Juvenile threshers occupied waters over the continental shelf almost exclusively, and rarely

ventured into off-shelf habitat (Fig. 1, T1-T7). Specifically, 87.0% of shark positional fixes were located over the continental shelf. Of the remaining points, most were due to sharks traversing deep submarine canyons that bisected the shelf close to shore (6.5% of total positional fixes over La Jolla canyon; 2.2% over Santa Monica, Redondo, and Carlsbad canyons). Only 4.3% of total shark positional fixes were located beyond the shelf and unassociated with canyons. Sharks showed no preference for any particular depth zone, utilizing the entire area above the continental shelf (Fig. 2). The course of two tracked sharks took them within 1 km of extensive giant kelp beds near La Jolla Point, and both appeared to alter their direction in order to avoid entering this habitat (Fig. 3).

The waters occupied by tracked sharks had an average SST of $18.8 \pm 1.6^\circ\text{C}$ (range: 16.7 to 21.7°C). Mean chlorophyll concentration at all shark track locations for which data were available was $5.11 \pm 1.27 \text{ mg m}^{-3}$. This was significantly higher by one order of magnitude than in adjacent off-shelf habitat ($0.54 \pm 0.05 \text{ mg m}^{-3}$) ($p < 0.001$, paired t-test).

Five of the seven sharks exhibited high site fidelity (SFI values of 0.654 to 0.915) over the course of the tracking period (Table 1). SFIs were lower, however, for sharks 2 and 3 (SFI values of 0.394 and 0.281, respectively). SFI values were not related to mean SST or mean chlorophyll levels (linear regression, $p > 0.05$).

The vertical distribution of juvenile threshers was generally limited to the upper 20 m of the water column (91.6% of shark depth readings) (Figs. 4 & 5a), and temperatures encountered by sharks during vertical excursions ranged from 11 to 19°C . Most sharks

showed diel depth distribution patterns, with daytime depths significantly deeper than nighttime depths ($p = 0.014$, general linear model) (Fig. 5b).

DISCUSSION

The concept of the nursery area as an integral component in the life history of many shark species has been in place for nearly a century (Meek 1916, Olsen 1953, Springer 1967, Clarke 1971, Bass et al. 1978). It is generally accepted that ample food resources and reduced predation risk are potential benefits derived by juvenile sharks occupying nursery areas, though the degree to which this is true likely varies by species (Bass et al. 1978, Branstetter 1990, Castro 1993, Heupel et al. 2007). Although shark nurseries are often located in bays, lagoons, and estuaries (Gruber et al. 1988, Holland et al. 1993, Heupel & Simpfendorfer 2005), open waters over the continental shelf may also function as a nursery habitat for certain shark species (Branstetter 1990). The objective of this study was to examine the movement patterns and habitat preferences of juvenile thresher sharks in the SCB, and to determine if the waters over the continental shelf in this region serve a nursery area function for this species.

Habitat preferences

The track records for juvenile threshers, obtained at several localities throughout the SCB, consistently demonstrate the preferential use of coastal waters over the continental shelf as opposed to further offshore where larger threshers are found. Tracked juvenile threshers were distributed over the entire continental shelf

zone (Figs. 1 & 2). For example, shark 2 spent the majority of its time near the outer edge of the continental shelf, while shark 7 never swam over waters deeper than 15 m.

An additional aspect of the habitat preference of juvenile threshers is revealed by the observation that two tracked sharks appeared to alter their direction to avoid entering dense kelp beds near La Jolla Point (Fig. 3). Corroborative evidence that juvenile threshers do not frequent kelp habitat comes from Hubbs Sea World Research Institute (HSWRI) gillnet survey data, which shows an extremely low CPUE of juvenile threshers in kelp beds relative to other shark species commonly found on the SCB continental shelf, such as soupfin, *Galeorhinus galeus* and leopard shark, *Triakis semifasciata* (L. Belquist, HSWRI, pers. comm.). This avoidance may be related to prey availability; an ongoing study of juvenile thresher shark stomach contents (A. Preti, NMFS, unpublished data) indicates that they feed primarily on northern anchovy *Engraulis morax*. Although the northern anchovy is occasionally observed in kelp *Macrocystis* forests, it is generally a pelagic schooling species, and more commonly found in open waters over soft bottom (Stephens et al. 2006).

Other facets of juvenile thresher shark behavior appear consistent with predation on northern anchovy. Anchovy normally school in near-surface waters during the day (PFMC 1998), and may disperse at night (Allen & DeMartini 1983). Juvenile threshers occupy the upper 20 m of the water column, but are slightly deeper during the day, which may enable detection of schools of anchovy silhouetted by downwelling light. Good agreement also exists between the SST range (16.7 to 21.7°C) where the tracked juvenile threshers occurred, the SST range (15 and 22°C)

yielding the highest catch rates of larger (mainly subadult and adult) threshers in the CA-DGN (PFMC 2003), and the SST preference of northern anchovy in the SCB (Checkley et al. 2000). This is perhaps not surprising given that adult threshers also prey largely on northern anchovy, although they apparently have a greater dietary diversity than juveniles (Preti et al. 2001, 2004).

High site fidelity indices were recorded for some but not all of the tracked sharks. Three of the four threshers tracked off La Jolla, and the one tracked at Imperial Beach (Fig. 1, T7) all showed high SFIs, implying that generally favorable habitat conditions prevailed in the areas occupied by those sharks during the tracking period. However, SFI values were not related to SST or chlorophyll levels, and were likely not related to bottom substrate due to the shark's preference for the upper water column. It is possible that SFIs may have been affected by factors that could not be quantified during the present study, such as prey abundance and local ocean currents. Although high SFI values imply habitat preference during the tracking period, it is unknown whether the sharks remained in these areas after tracking. Heupel et al. (2007) pointed out that an important focus for future shark nursery research is determining whether juvenile sharks repeatedly use specific areas for successive years, as the tendency of sharks to aggregate in these preferred habitats may make them more vulnerable to fisheries exploitation or other anthropogenic disturbances.

Are the continental shelf waters of the SCB a nursery area for threshers?

The findings for habitat preference support the hypothesis that juvenile threshers primarily utilize the continental shelf area of the SCB. Here we analyze the potential link between habitat preference and a nursery area function by considering two key features of the shark nursery area concept, access to ample food resources and reduced predation (Castro 1993, Heupel et al. 2007).

1) Ample resources: Prey resources appear to be abundant for juvenile threshers in the SCB, where continental shelf waters are more productive than offshore waters (Hardy 1993). Indeed, our determinations during the period when tracking was done show that there was a ten-fold greater chlorophyll-a concentration in shelf waters than in offshore waters. A higher productivity can support a larger biomass of planktivorous northern anchovy. During favorable conditions, the northern anchovy can be the most abundant fish species over the SCB continental shelf (Allen & DeMartini 1983). Ichthyoplankton surveys conducted by the CalCOFI program during the time of this tracking study indicate that the highest concentration of northern anchovy eggs (and, by extension, spawning biomass) was in nearshore waters of the SCB (Goericke et al. 2007, McClatchie et al. 2008).

2) Decreased predation risk relative to adult habitat: The offshore pelagic habitat of adult threshers is also inhabited by large, abundant predators such as adult blue and shortfin mako sharks. In contrast, in the continental shelf habitat occupied by juvenile threshers, co-occurrence with these pelagic predators is minimal. Nevertheless, some potential for predation exists. For example, juvenile white sharks in the SCB may utilize habitat similar to that of juvenile threshers (Dewar et al. 2004,

Weng et al. 2007); other predators with the capacity to feed on small sharks include the sevengill shark, *Notorhynchus cepedianus* (Lucifora et al. 2005, Braccini 2008), and California sea lion, *Zalophus californianus* (Lowry et al. 1990). However, none of these species has been documented to prey on *A. vulpinus*. Therefore, relative to the pelagic environment, the continental shelf habitat used by juvenile threshers in the SCB may decrease predation risk.

Life history features related to nursery area utilization

How might life history traits of the thresher shark contribute to reduced juvenile mortality? Branstetter (1990) noted that large neonatal size is an important attribute contributing to early survival of shark species such as sand tiger, *Odontaspis taurus* and dusky sharks, *Carcharhinus obscurus* whose juveniles inhabit shallow, coastal waters. The low fecundity of the thresher shark (2-4 pups per litter, 2 year cycle; PFMC 2003), may directly contribute to reduced predation by allowing for a relatively large pup size of 60-70 cm FL (Smith & Aseltine-Neilson 2001). Moreover, neonatal size is markedly accentuated by an elongate tail, resulting in a total length (TL) of 114-156 cm (Smith et al. 2008). Finally, the relatively rapid growth rate of juvenile threshers may also make them less vulnerable to predation. Estimated values of k , the growth coefficient in the von Bertalanffy curve describing the time to reach maximum length (Pauly 1983), reported for this species are relatively high compared to other sharks, ranging from 0.12 - 0.19 (Smith et al. 2008).

Life history traits may be determinants of nursery area use for other pelagic sharks in the SCB as well. In contrast to the coastal nursery habitat used by juvenile threshers, juvenile blue shark and shortfin mako in the SCB inhabit offshore, pelagic waters (Nakano 1994, Sepulveda et al. 2004), are rarely encountered over the continental shelf, and thus may not have nursery areas as defined herein. Although the young are at greater risk to large open ocean predators, higher mortality may be offset by larger litter sizes in these species. The shortfin mako has an average of 12 pups, born at approx. 60-70 cm TL (Stevens 2008), and blue sharks have an average of 30 pups, born at 35-50 cm TL (Nakano & Stevens 2008). Cailliet et al. (1983) reported growth rates of $k = 0.072$ for the shortfin mako and $k = 0.223$ for the blue shark in California waters. However, the high variability of these values throughout the literature precludes a direct comparison with growth rates of other pelagic species such as the thresher (Tanaka et al. 1990, Nakano 1994, Ribot-Carballal et al. 2005, Skomal & Natanson 2003).

Fishery management implications

Commercial fishery operations over the continental shelf pose a potential threat to juvenile threshers in the SCB. However, National Marine Fisheries Service (NMFS) data indicate that recent catch rates of juvenile threshers in CA bottom-set gillnet fisheries for white seabass *Atractoscion nobilis* and Pacific halibut *Paralichthys californicus* are relatively low (NMFS Southwest Region Fishery Observer Program, unpublished data). This is likely attributable to the Marine Resources Protection Act of

1990 (article 10B of the California constitution), which bans gillnets within 3 miles (4.83 km) of shore in the SCB. Because very little of the SCB continental shelf extends beyond this 3 mile limit, these regulations appear adequate to protect juvenile threshers from excessive mortality in commercial gillnet fisheries. The major inshore non-gillnet fishery in the SCB is the purse seine fishery targeting northern anchovy, Pacific sardine *Sardinops sagax*, chub mackerel *Scomber japonicus*, and market squid *Loligo opalescens*. Although purse seine vessels are not legally restricted to fishing outside a 3 mile limit, catch of juvenile threshers is rare; of 667 sets documented by NMFS observers, only 4 contained thresher sharks (L. Enriquez, NMFS Southwest Region Fishery Observer Program, Pers. Comm.). Recreational anglers fish for threshers in the SCB when seasonally abundant, but typically target the larger subadults and adults (D. Kacev, unpublished data).

Our study provides evidence that the SCB continental shelf serves as a nursery area for juvenile threshers; however, little is known regarding the extent of this nursery area north or south of this region. Juvenile threshers are not commonly captured in commercial fisheries north of the SCB (PFMC 2003), although Bedford (1992) speculated that during warm water years the range of juveniles might extend as far north as Monterey, CA. In contrast, preliminary studies indicate that juvenile threshers are common below the SCB along the Pacific coast of Baja California, Mexico, to as far as Guerrero Negro (28° N latitude) (Olvera 2009, D. Cartamil, unpublished data), suggesting that this region functions as a nursery for threshers as well. Threshers are a target of artisanal fisheries in the region, and gillnetting over the

continental shelf is the most common fishing method employed to capture threshers and other coastal elasmobranchs. However, the level of protection afforded to juvenile thresher sharks by gillnet fishery regulations in the U.S. portion of the SCB is not present in Mexican waters. In practical terms, these fisheries have gone unregulated for decades, and the vast majority of threshers captured are juveniles (D. Cartamil, unpublished data). Although new Mexican fishery regulations (NOM-029-PESC-2006) place effort and gear configuration limits on gillnetting in nearshore waters, these have proven difficult to enforce due to the remote locations of many fishing camps and lack of enforcement personnel. Because of the probable population connectivity of thresher sharks off the Pacific coast of North America (Trejo 2005), juvenile thresher mortality in Baja California gillnets poses a threat to the sustainability of thresher shark fisheries in U.S. and Mexican waters, and needs to be quantified in order to effectively manage this species.

Table 3.1: Sex, length, and track details for seven juvenile thresher sharks tracked in the Southern California Bight. SFI = site fidelity index, ROM = rate of movement (km h^{-1}).

Thresher Shark #	Sex	FL (cm)	Track		Total Track		Mean hourly	
			Start Date	Duration (h)	Distance (km)	SFI	ROM \pm SD	
T1	F	84	9 Sept 2005	38	58.2	0.866	1.42 \pm 0.31	
T2	M	66	22 June 2006	32	60.8	0.394	1.89 \pm 0.36	
T3	F	78	13 Sept 2006	54	114.6	0.281	2.11 \pm 0.24	
T4	M	108	20 June 2007	67	94.1	0.864	1.32 \pm 0.62	
T5	M	108	25 June 2007	58	89.2	0.858	1.50 \pm 0.45	
T6	M	73	5 Sept 2007	46	82.0	0.654	1.84 \pm 0.49	
T7	M	101	11 Sept 2007	75	73.7	0.915	1.00 \pm 0.36	

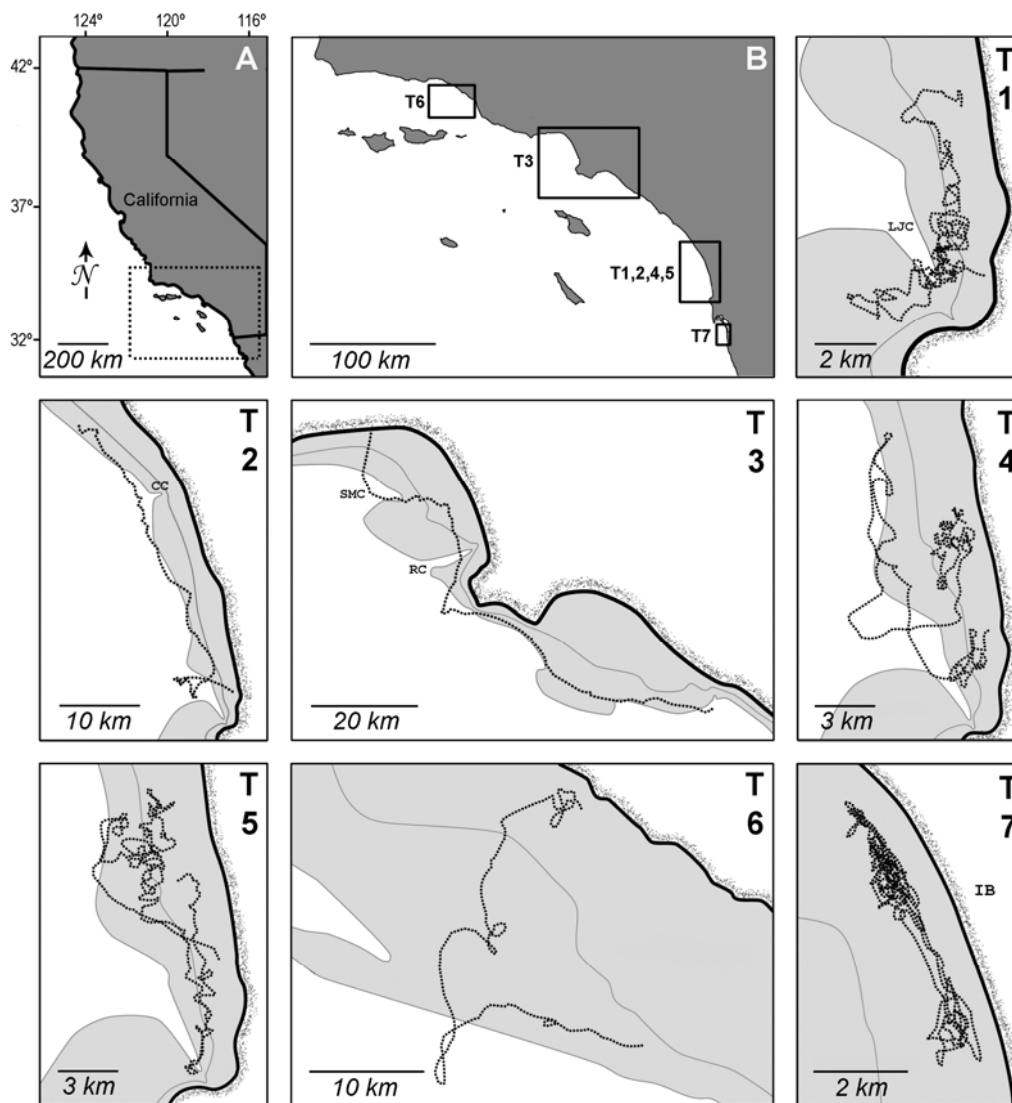


Figure 3.1: **A.** Coastline of California, U.S.A., showing the Southern California Bight (SCB, in dashed box), which extends into northern Baja California, Mexico. North latitude and West longitude values shown. **B.** The SCB, in which the black boxes show locations where juvenile thresher sharks (1-7) were tracked. **T1-T7:** Bathymetric maps and track records (dotted lines) for each shark. In each map, the continental shelf (in light grey) is shown extending offshore to a depth of approximately 100 m. Depth contour lines - Outer: 110 m, Inner: 55 m. Shark 7 was tracked in very shallow water off Imperial Beach (IB), and only the 10 m contour is shown. Within each panel, individual tracks of juvenile thresher sharks are shown as dotted lines (dotted lines do not represent 5-min data collection intervals). La Jolla Canyon (labeled LJC in panel 1) bisects the continental shelf in panels 1, 2, 4 and 5. Other major canyons are labeled: CC, Carlsbad Canyon; RC, Redondo Canyon; SMC, Santa Monica Canyon. Scale bars are shown in the bottom left of each panel.

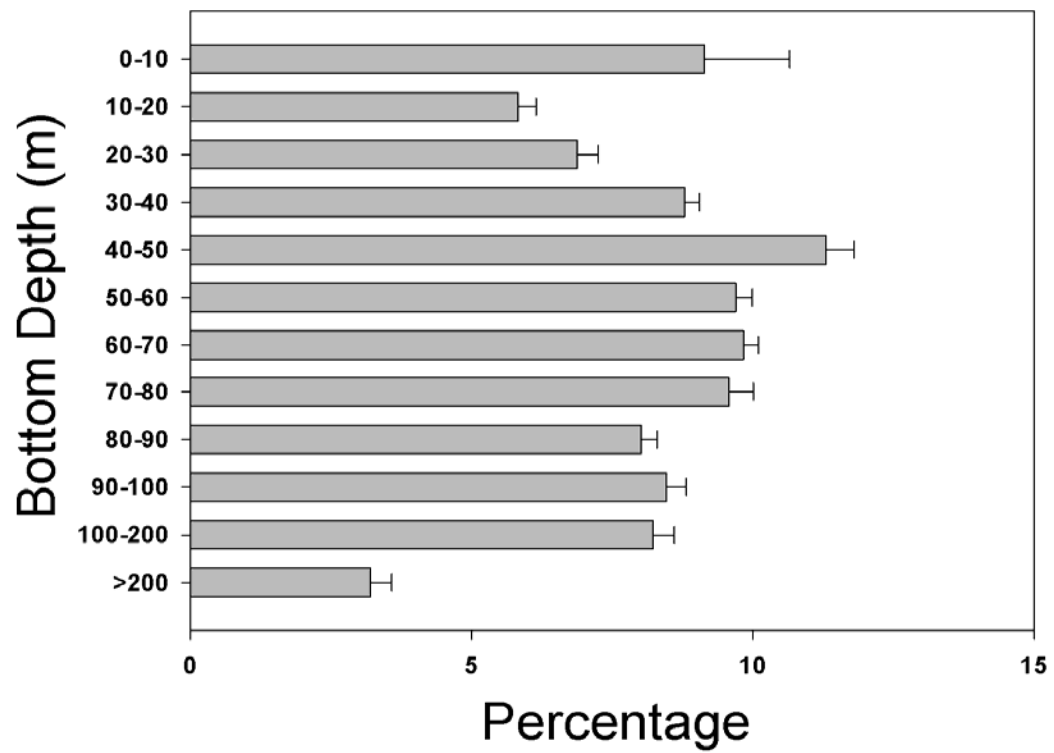


Figure 3.2: Histogram showing the mean percentage (\pm standard error) of time that seven tracked juvenile thresher sharks swam over given bottom depths (in 10 m bins).

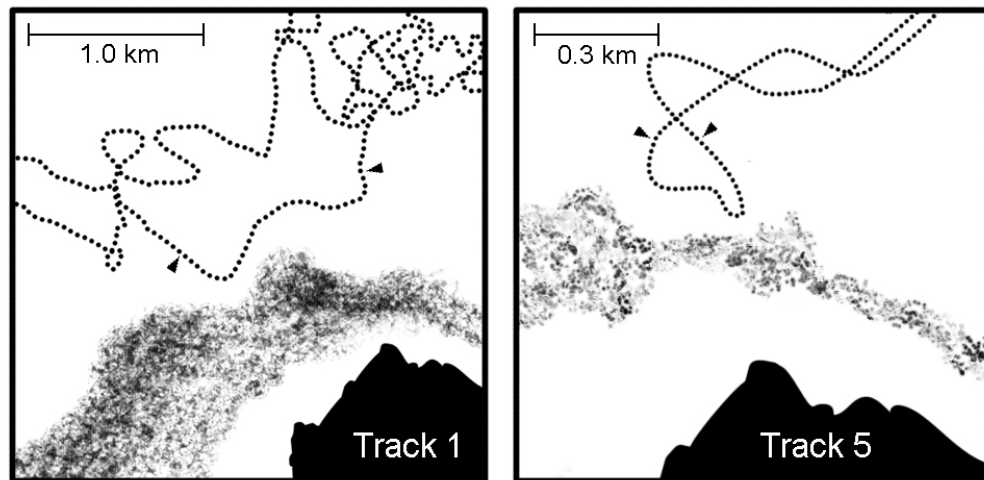


Figure 3.3: Segments of juvenile thresher tracks 1 and 5 showing the likely influence of giant kelp beds off La Jolla Point, California on course changes. Tracks are indicated by dotted lines, and the extent of the kelp bed is indicated by the stippled area. Arrowheads show course changes mirroring the kelp bed perimeter for durations of approximately 1 h for Track 1 and 0.5 h for Track 5.

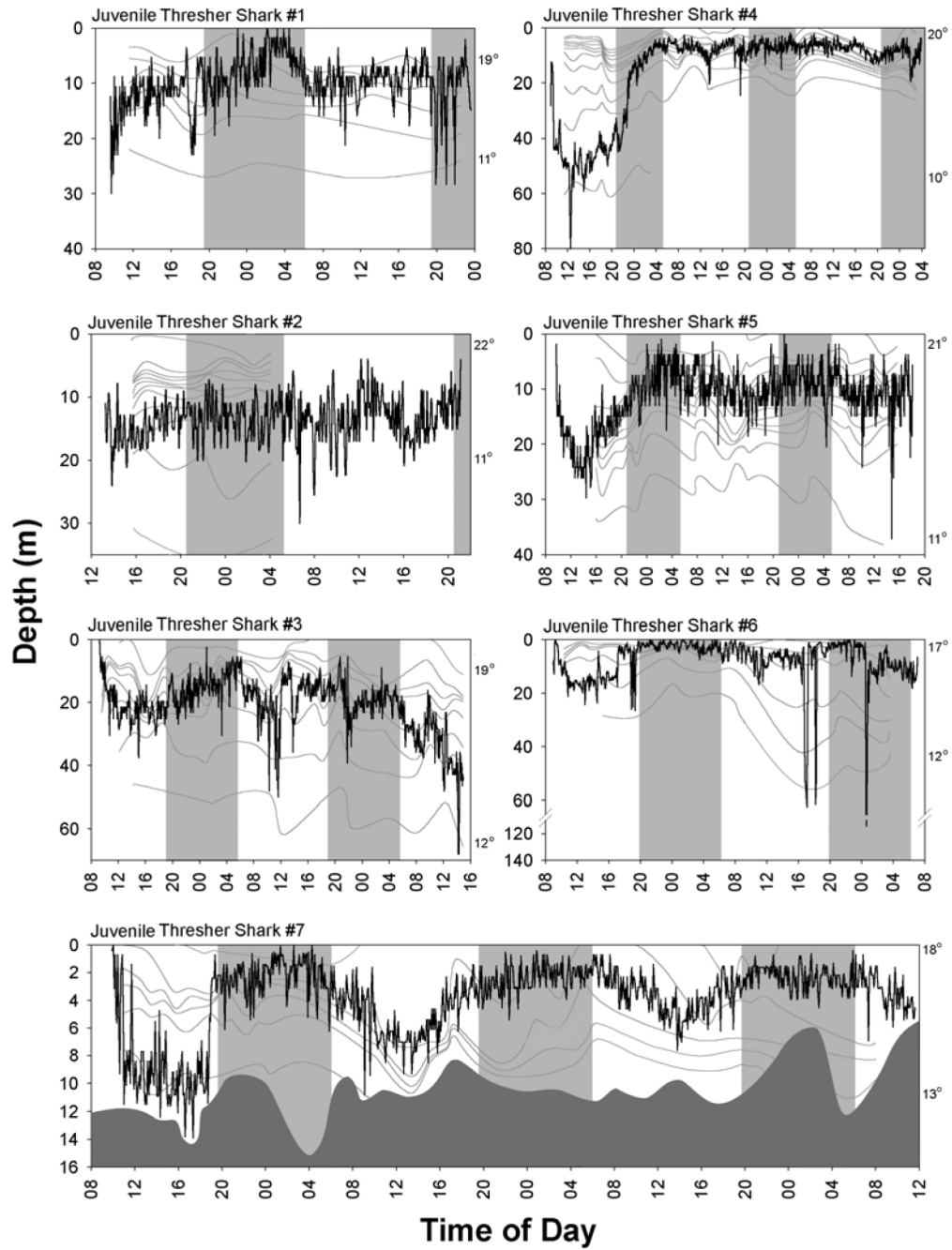


Figure 3.4: Dive profiles of juvenile thresher sharks 1 through 7. Shaded areas indicate nighttime hours. Gray lines represent 1°C isotherms; maximum and minimum isotherm temperatures are given on the right. For track 7, the bottom contour is shown in dark grey.

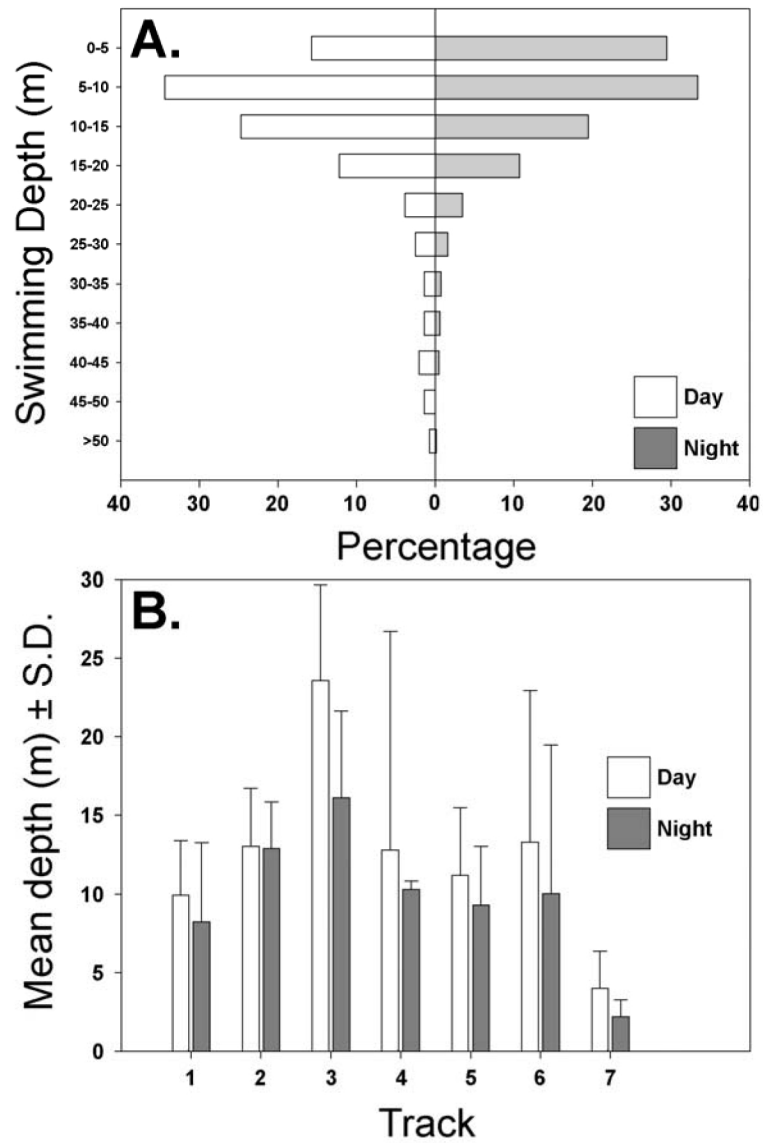


Figure 3.5: Swimming depth (5 m bins) histograms for juvenile thresher sharks during day (white) and night (grey). **B.** Mean swimming depths (\pm S.D.) of sharks 1-7 during day (white) and night (grey).

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ACKNOWLEDGEMENTS

Funding for this study was provided by CA Sea Grant, the Ocean Protection Council, the Moore Family Foundation, the William H. and Mattie Wattis Harris Foundation, the Tinker Foundation, the Save Our Seas Foundation, and U.C. Mexus-CONACYT. D. Cartamil was supported by a California Sea Grant traineeship, and the Tuna Industry Endowment Fund at Scripps Institution of Oceanography. We acknowledge the following individuals for assistance with fieldwork: E. Kisfaludy, P. Pelzer, S. Aalbers, D. Ramon, H. Dewar, S. Snyder, R. Runcie, M. Olvera, O. Santana, C. Sepulveda, M. Musto, A. Nosal, J. Schram and H. Selbie. SST and chlorophyll maps were kindly provided by Terrafin Software (www.terrafin.com).

This chapter, in full, was submitted for publication as:

Cartamil D, Wegner N, Kacev D, Ben-Aderet N, Kohin S, Graham JB. In review. Movement patterns and nursery habitat of the juvenile thresher shark (*Alopias vulpinus*) in the Southern California Bight. Marine Ecology Progress Series. The dissertation author is the primary investigator and author of this paper.

CHAPTER 4: THE ARTISANAL ELASMOBRANCH FISHERY OF THE PACIFIC COAST OF BAJA CALIFORNIA, MEXICO

ABSTRACT

Artisanal fisheries account for up to 80% of elasmobranch fishing activity in Mexican waters, yet details associated with fishing effort and species composition are generally unavailable. This chapter describes a survey of the artisanal elasmobranch fishery of the Pacific coast of Baja California, Mexico from 2006 - 2008. The objectives were to determine the geographical extent, size, and targets of the artisanal fishery, and describe the catch characteristics at Laguna Manuela, a representative artisanal camp where elasmobranchs are the primary target. Forty-four fishing sites were identified in the region, of which 29 (66%) targeted elasmobranchs at least seasonally, using primarily bottom-set gillnets and longlines. At Laguna Manuela 25 species of elasmobranchs were documented. Gillnetting accounted for 60% of fishing effort, and the most commonly captured species were *Rhinobatos productus*, *Zapteryx exasperata*, and *Myliobatis californica*. Longline fishing accounted for 31% of fishing effort, and the most commonly captured species were *Prionace glauca* and *Isurus oxyrinchus*. Catch was composed of mainly juveniles for many species, suggesting that the immediately surrounding area (Bahia Sebastian Vizcaino) may be an important elasmobranch nursery habitat. The results of this study will serve as a valuable baseline to determine future changes in the artisanal fishery, as well as changes in species demography and abundance.

INTRODUCTION

Elasmobranchs have historically been an important traditional food resource in Mexico, and exploitation of elasmobranch resources can be traced back to the Aztecs and Olmecs, two of the most important Mexican pre-Hispanic cultures (Applegate et al. 1993). Written records for Mexican elasmobranch fisheries do not exist until the 1890's when shark fins were first exported to Asia from Baja California Sur. Since that time elasmobranch fisheries have increased dramatically in their size and geographical extent. Elasmobranchs are an important constituent of the Mexican diet and up to 90% of Mexican harvest is consumed domestically (Bonfil 1997). Elasmobranch fishing moreover provides both sustenance and income for some of the poorest sectors of Mexican society (McGoodwin 1976).

For most of its history, elasmobranch fishing in Mexico has been dominated by traditional artisanal fisheries. These are relatively small-scale operations in which pangas (small outboard-powered open boats) with a crew of three or fewer undertake one to two day fishing trips. Sharks and other catch are brought back to a base camp on the beach where they are processed. In Mexico, an estimated 130,000 artisanal vessels annually harvest approximately 40% of the marine catch, and comprise up to 80% of the elasmobranch fishing effort (Arreguin-Sanchez et al. 2004).

Unfortunately, the well documented history for elasmobranch fisheries, in Mexico and in many other localities around the world, demonstrates that many are not sustainable (Walker 1998). Compared to other important commercial species such as sardines, anchovies, and tunas, elasmobranchs grow slowly, require many years to

reach sexual maturity, and have low reproductive rates. Therefore, elasmobranch populations are far less resilient and are slow to recover following over-fishing (Smith et al. 1998). Declines in Mexican elasmobranch fisheries have been documented for the Gulf of Mexico (Bonfil 1997, Castillo-Geniz et al. 1998) and along the central Pacific coast (Perez-Jimenez et al. 2005). In addition, Mexican elasmobranch landings have decreased substantially in recent decades, from 45,250 tons (t) in 1996 to an average of 35,264 t during the period 1997 to 2005, while effort has not declined (FAO 2005).

Management of a sustainable elasmobranch fishery in Mexico is hampered by a lack of basic fisheries data. Historical records of elasmobranch landings are extremely generalized and probably greatly underestimate the actual take (Castillo-Geniz et al. 1998). In many remote areas, it is unknown how many artisanal camps exist and what level of effort is directed towards elasmobranchs. In addition, baseline, species-specific information is largely unavailable for most artisanal elasmobranch fisheries, but is essential for the monitoring of exploited populations and the development of effective management plans (White et al. 2006, Henderson et al. 2007). Without some benchmark of fisheries effort and catch composition, changes in relative abundance and other potential impacts on exploited species are unlikely to be identified.

This paper describes the artisanal elasmobranch fisheries of the Pacific coast of the Mexican state of Baja California (BC). Previous studies in this region are few and limited in scope. Holts et al. (1998) gave a brief general description of the artisanal

fishery for pelagic sharks, and Gonzalez (2001) described the artisanal shark fishery near San Quintin. Andrade et al. (2005) surveyed the fishing activity and infrastructure of many artisanal camps in the region. However, no previous assessment specific to elasmobranch capture in the artisanal fishery has been conducted. The objectives of this study were to 1) survey the geographical extent, size, and targets of the artisanal fishery, and 2) examine the catch characteristics at a representative artisanal camp where elasmobranchs are the primary target, and provide biological information for the most abundant species in landings.

METHODS

Study area

The study area is the approximately 880 km of Pacific coastline of the Mexican state of Baja California (BC) (Fig. 1). BC is bordered on the north by the United States and on the south by BC Sur. Much of BC is sparsely populated, with most of the approximately 2.8 million inhabitants (INEGI 2007) concentrated in border cities such as Tijuana and Mexicali. The northern portion of the Pacific BC coastline (from the U.S. border to approximately 29° N latitude) is strongly influenced by the cold southward-flowing California Current, and is characterized by high primary productivity driven by coastal upwelling (Zaytsev et al., 2003). The marine biota and annual sea surface temperature range are similar to those of the Southern California Bight (SCB) to the north. The continental shelf is narrow, extending from five to twenty km offshore. South of 29° N latitude the coastline transitions into Bahia

Sebastian Vizcaino (BSV), a large embayment (35,678 km²) where the continental shelf extends to as far as 140 km offshore (Fig. 1, 2A). BSV is regarded as a temperate-tropical transitional zone, influenced by both the California Current and warmer waters to the south. Punta Eugenia, at the southern extreme of BSV represents the southern limit of the distribution of many fish taxa common to the San Diegan Province, and the northern limit of distribution for many fish species common to the tropical Panamic Province (Quast 1968, Horn & Allen 1978, Horn et al. 2006).

Survey of artisanal camps

A survey of all artisanal fishing camps along the Pacific coast of BC was conducted between September 2006 and December 2008. Although the locations of some camps were previously reported by Andrade et al. (2005), the entire coastline was traveled by 4-wheel-drive vehicle to ensure that all camps were located. Informal, semi-structured interviews (Lindlof & Taylor 2002) were conducted with fishers to determine the following information: a) primary species or species group targeted at each camp, b) seasonal aspects of fishing activity, c) fishing gear used and gear characteristics, d) level of fishing effort (i.e., # of fishing vessels), e) permanence or seasonality of camp, g) level of organization, and h) level of infrastructure. The location of each camp was determined by GPS and plotted on a map of the study region. For three camps where fishers were not available for interview, we used data from Andrade et al. (2005).

Laguna Manuela

Within BSV, and approximately 30 km from the BC Sur border, is the artisanal fishing camp of Laguna Manuela (LM) (Fig. 2A,B). Preliminary investigations identified LM as one of the most important artisanal elasmobranch fishing camps in the region. Accordingly, LM was selected as the site of a detailed study of elasmobranch species composition and fishery characteristics. The camp is located on the inside of a sand spit at the entrance to the extensive Laguna Manuela estuary. There are no permanent structures, boat launch ramps, or electricity at LM, and its access roads are unpaved and poorly maintained. Most fishers utilizing LM live in the nearby villages of Ejido Morelos and Villa de Jesús María (7 and 10 km inland) (Fig. 2B).

Twenty-seven field trips, ranging from 1 to 5 days in length, were conducted to survey the fishing activity at this camp; the frequency of these trips was higher in summer when fishing activity increased and lower in winter when it diminished (Table 1). During field visits, the catch of each vessel that fished that day was sampled. Fishers did not process their catch at sea, and therefore almost all specimens were identifiable to species level. In addition to recording the species and sex of all retained elasmobranchs, gear type was noted, and fishers were interviewed to determine ex-vessel price for elasmobranchs and other species.

Due to the high volume of total catch and limited time in which to collect data, measurements were recorded only for elasmobranchs. Measurements (to the nearest 0.5 cm) made were total length (TL; measured using the ‘natural’ extension of the caudal fin) (Taylor 1993) for shark species [except fork length (FL) for thresher shark,

Alopias vulpinus], and disc width (DW) for batoids [except TL for guitarfishes (Genus *Rhinobatos* and *Zapteryx*)]. Although several species of the genus *Mustelus* were observed (*M. californicus*, *M. henlei*, *M. lunulatus*, and possibly *M. hacat*), these were grouped into the category *Mustelus* spp. due to the possibility of identification errors. In some cases, unambiguous identification was possible for *M. henlei*; these data are reported separately.

Fishing effort was not standardized (i.e., a vessel could fish with variable numbers of hooks or nets), and therefore catch per unit effort (CPUE) could not be accurately quantified. Mean catch per trip (CPT) was calculated for each species within each major gear type. Histograms of sex-specific size distributions were plotted for each species, along with size-at-maturity data from Ebert (2003). In cases where $n < 10$, only summary statistics (mean size \pm SD) are given. For all species with ≥ 50 measured individuals, the difference in average size between females and males was compared using a linear mixed-effects ANOVA model (Pinheiro and Bates 2004), with a trip effect (random effect) to capture variability among trips (in a number of cases multiple sharks were measured from the same trip) and sex as a fixed effect. Histograms showing the percentage of total trips relative to CPT values were also plotted for species where $n > 50$. Additionally, the assumption of equal sex ratios (1:1) within the landings was tested using chi-square analysis with Yate's correction for continuity (Zar 1996, Bizzarro et al. 2009). For all statistical tests, a p value of < 0.05 was considered significant.

RESULTS

Survey of artisanal camps

Forty-four artisanal camps were located along the Pacific coast of Baja California (Fig. 1). Camps ranged from seasonal and very small with no permanent structures or electricity (e.g., Punta Colonet), to permanent locations featuring high year-round fishing that supported entire villages (e.g., Santa Rosalilita). Table 2 details the comparative characteristics of the camps.

Elasmobranchs were the primary target at 5 of the 44 camps and were targeted secondarily at 25 additional camps. Coastal elasmobranchs (primarily batoids and small sharks) were targeted using bottom-set gillnets deployed on the continental shelf. These nets are monofilament with lengths of 100 to 500 m, depths of up to 5.5 m, and stretched mesh sizes of 6 to 12 cm. Multiple gillnets were often used, either strung together or set in various locations, and gillnets were typically deployed for a 24 h period before retrieval. The maximum number of gillnets observed in use simultaneously by one fishing vessel was eight. Pelagic sharks were targeted with longlines that typically ranged from 3 to 4.5 km in length, with highly variable hook counts (range 200 to 500), and hooks set at depths of 5 to 10 m. 'J'-style hooks of 6-10 cm length were commonly used, whereas the use of circle hooks was rare. Fishers usually set longlines before sunrise and left them in the water for eight to twelve h, but regularly checked them to remove ensnared sharks and re-bait hooks. Lines were retrieved by late afternoon, and fishers generally returned to camp near sunset. Although most trips did not exceed one day, the maximum observed longline trip duration was 3 days.

Teleosts were the primary target at 19 of the 44 artisanal fishing camps, and targeted secondarily at 17 additional camps. Although most often fished with bottom-set gillnets (of the same configuration as those used to target elasmobranchs), trap and hook-and-line fishing were also used to target teleosts. It is important to note that elasmobranchs were an incidental, and often major, bycatch of teleost-directed gillnet fishing.

Invertebrates were also an important component of the artisanal fishery, and one or more of these groups were the primary target at 17 of the 44 camps, and secondarily targeted at 9 additional camps. Although quantification of invertebrate catch is beyond the scope of this paper, the high fishing effort and ex-vessel prices for invertebrates (urchin: 100 pesos kg^{-1} ; abalone: 300 to 500 pesos kg^{-1} ; lobster: 150 to 250 pesos kg^{-1} ; bivalves: 120 to 200 pesos kg^{-1} ; crab: 20 to 30 pesos kg^{-1} ; snail: 50 pesos kg^{-1} ; octopus: 50 pesos kg^{-1} ; sea cucumber: 30 pesos kg^{-1}) indicate their economic importance regionally. However, because most invertebrate fishing methods are highly species-specific and characterized by low bycatch, their impact on elasmobranchs is considered negligible, and they are not dealt with further in this paper.

Laguna Manuela

Between September 2006 and December 2008, a total of 67 days was spent at LM (Table 1). During this period the mean (\pm SD) number of vessels fishing day^{-1} was 7.35 ± 3.93 . A maximum of 15 vessels day^{-1} was observed working simultaneously in

summer, while inclement weather during winter months occasionally reduced effort to zero. The survey covered 387 panga trips that captured 10,595 elasmobranchs. This sampling accounts for 90.6% of all the fishing that occurred during field visits.

Three fishing methods - gillnet, longline, and trap - accounted for the entire catch observed during the study period. Gillnetting was used by 232 of the 388 pangas (60% of fishing trips) and the primary target was elasmobranchs (7,518 individuals from 24 species; Table 3). The three most abundant elasmobranchs taken by gillnet were the shovelnose guitarfish (*Rhinobatos productus*; 46.1%), banded guitarfish (*Zapteryx exasperata*; 27.9%), and California bat ray (*Myliobatis californica*; 9.4%). The CPT values for these species were 14.9, 9.0 and 3.1 individuals per fishing trip. Banded guitarfish showed the highest tendency to be captured in large numbers (Fig. 3). Of the eleven species caught in numbers greater than 50, there were significant, sex-specific differences in size distribution for two. *Cephaloscyllium ventriosum* females (mean size: 81.8 ± 6.9 cm TL) were significantly larger than males (77.6 ± 4.5 cm TL), and *Zapteryx exasperata* females (83.4 ± 10.0 cm TL) were significantly larger than males (79.9 ± 6.9 cm TL). Two of these eleven species had a significantly larger proportion of females: *G. galeus* (females: 165, males: 86) and *Squatina californica* (females: 64, males: 37). Fig. 4 summarizes the sex and size-frequency data for gillnet caught elasmobranchs. All specimens of *A. vulpinus*, *Carcharhinus brachyurus*, *Carcharodon carcharius*, and *Sphyrna zygaena* were juveniles; specimens of other species were primarily mature, or a mix of juveniles and adults (Fig. 4).

The ex-vessel value of elasmobranchs captured with gillnets at LM ranged from six to sixteen pesos kg^{-1} . Five elasmobranch species had no commercial value but were occasionally retained as bait for trap fishing; these accounted for only 1.2% of the catch. The fins of seven elasmobranch species had ex-vessel values ranging from 800 to 1000 pesos kg^{-1} dry weight (Table 3).

Gillnet fishing was opportunistic, and commercially valuable teleosts were occasionally targeted when abundant. The most important of these targets were Pacific halibut (*Paralichthys californicus*; ex-vessel price: 20-40 pesos kg^{-1}), white seabass (*Atractoscion nobilis*; 40 - 60 pesos kg^{-1}), yellowtail jack (*Seriola lalandi*; 10 to 15 pesos kg^{-1}), black seabass (*Stereolepis gigas*; 30 to 40 pesos kg^{-1}), and fantail sole (*Xystreurus liolepis*; 15 to 25 pesos kg^{-1}). These species also constituted the majority of bycatch when elasmobranchs were targeted. Other minor bycatch species included barred sandbass (*Paralabrax nebulifer*), Pacific bonito (*Sarda chiliensis*), Pacific chub mackerel (*Scomber japonicus*), California scorpionfish (*Scorpaena guttata*), and Pacific barracuda (*Sphyrna argentea*).

Longline fishing was done by 121 of the 388 pangas sampled (31% of fishing trips), and the primary target was elasmobranchs (3,111 individuals from 8 species; Table 3). The most commonly caught species was the blue shark (*Prionace glauca*; 68.2%), followed by the mako shark (*Isurus oxyrinchus*; 28.3%). Corresponding CPT for these two species was 17.4 and 7.2 individuals per fishing trip. Blue sharks were most often caught in groups of 11 to 50 individuals (Fig. 3). Female blue sharks (150.5 ± 29.1 cm TL) were significantly larger than males (132.7 ± 22.2 cm TL), and were

also present in significantly larger proportion ($n = 679$) than males ($n = 348$). There was no significant sex-specific difference in size distribution or significant difference in proportion of females versus males for other longline-caught species where $n > 50$. CPT of blue shark and mako showed opposite seasonal abundance patterns, with blue shark dominating longline catch from December through July, and mako shark dominating catch from July through December (Fig. 5). The catch of blue and mako shark consisted almost entirely of juveniles, while specimens of *G. galeus* were a mix of juveniles and adults, and all *Pteroplatytrygon violacea* were mature (Fig. 6).

Elasmobranch species captured on longline had carcass values of 12 to 16 pesos kg^{-1} and fin values of 800 to 1000 pesos kg^{-1} (with the exception of *P. violacea*, with a carcass value of 7 pesos kg^{-1} and no fin value). Bycatch consisted of large numbers of Humboldt squid (*Dosidicus gigas*), and one infrequently captured teleost, the mahi-mahi (*Coryphaena hippurus*). These bycatch species had no ex-vessel value, and were retained only for personal consumption.

A minority (9 %) of the sampled vessels fished with traps. During the summer, trap fishing targeted the barred sandbass (*Paralabrax nebulifer*), which spawns in the area during summer months (Allen & Hovey 2001). Traps were usually deployed for 2 day periods and catch rates were as high as 100 to 800 kg per vessel, with an ex-vessel price of 6 to 10 pesos kg^{-1} . Bycatch was low (< 5% by number), consisting primarily of small numbers of ocean whitefish (*Caulolatilus princeps*) and California sheephead (*Semicossyphus pulcher*). Elasmobranch bycatch was not observed.

During lobster season (September 15 to February 15), trap fishing targeted spiny lobster (*Panulirus interruptus*). Trap fishing for lobster was the dominant activity at LM during December and January. This is an important supplemental income fishery at LM, as ex-vessel value for lobster is as high as 150 to 250 pesos kg⁻¹. The unloading of lobster traps was not observed, as this was done at sea, but interviews with fishers indicate that elasmobranch bycatch in this fishery is negligible.

DISCUSSION

This paper provides the first description of the geographical extent, size, gear characteristics, and target species of the artisanal fisheries along the Pacific coast of BC, with an emphasis on profiling artisanal fishery impacts on elasmobranchs. In addition, this work details a 26 month study of elasmobranch catch composition at Laguna Manuela fishing camp and greatly improves the current status of knowledge regarding the relative abundance and size distribution of elasmobranchs exploited by artisanal fisheries in the BSV region.

Survey of artisanal camps

The investigation located 44 artisanal fishing camps along the Pacific coast of BC. These camps vary considerably in size, effort level, target species, and fishing methods. The number and size of artisanal camps in the study region is similar to other areas along the Pacific coasts of BC Sur and mainland Mexico (Bellido-Millan & Villavicencio-Garayzar 2002, Perez-Jimenez et al. 2005, Bizarro et al. 2007a,

Bizzarro et al. 2009). However, the Pacific coast of BC has a larger number of artisanal fishing camps than the Gulf of California (GOC) coast of BC (Bizzarro et al. 2007a), which has received far more attention as regards declines in elasmobranchs and other large predators (Saenz-Arroyo et al. 2005, Lercari & Chavez 2007, Montes et al. 2008). Although elasmobranchs are not the primary target in all camps, they were targeted on some level in 68% of the camps, indicating that artisanal fisheries likely have a substantial impact on elasmobranch populations.

This study provides a ‘snapshot’ of the artisanal fishery during a specific period (September 2006 through December 2008). Although the lack of historical data precludes comparisons with the past status of the fishery, these data will serve as a valuable base-line for future comparisons. In this regard, the information contained in Table 2 will be useful to determine the magnitude of changes in the number and size of artisanal fishery camps, their effort levels (as gauged by the number of pangas), and species targeted.

Laguna Manuela

Laguna Manuela proved to be an ideal site for a detailed study of catch composition due to the high volume of elasmobranchs captured, constancy of fishing activity, and the high level of cooperation received from fishers. In the same way that the general characteristics of the artisanal fishery can be used as a base-line for fishing effort, the size and CPT of elasmobranch species documented in the LM fishery can be used as a base-line to determine future changes in species demography and abundance.

The primary fishing methods utilized at LM were longline, gillnet, and trap. Longlines exclusively targeted elasmobranchs, gillnets targeted elasmobranchs and teleosts, and trap fishing exclusively targeted teleosts or lobster. Although alternative target species were taken, elasmobranchs dominated the total catch at this camp. Gillnet-captured teleosts commanded a higher ex-vessel price than most elasmobranchs, but were not as abundant or reliably caught. Trap fishing for barred sand bass required a relatively low fuel expenditure and minimal at-sea work, however the low market value for this species, in combination with the long processing time for the small carcasses made it a less attractive activity for many fishers. Conversely, ex-vessel value for trap-caught lobster was substantially higher than for any elasmobranch (Table 3). However, because of the limited season of this fishery, it served only to supplement income from elasmobranch fishing at LM.

Biological considerations

Twenty-five species of elasmobranchs were registered at LM, which is lower than what has been reported for other areas along the Pacific coast of Mexico. Castillo-Géniz et al. (1998) registered 34 species of elasmobranchs in the GOC, while Bizzarro et al. (2009) registered 41 species off the GOC coast of Sonora. This comparison reflects lower elasmobranch species diversity on the Pacific coast of BC relative to the GOC, although our sample sizes were also generally lower due to differences in size of catch at GOC camps.

The number of species encountered in the survey did not increase after the first year, and thus likely represents the actual species composition of the region. Nevertheless,

additional species would likely be encountered during unusual oceanographic conditions such as El Niño/La Niña events (Lea & Rosenblatt 2000, Rojo-Vazquez et al. 2008). In addition, smaller size classes (including neonates) of many species may be absent or under-represented due to selectivity for larger animals by fishing gear (Marquez-Farias 2005). Species with little or no market value (e.g., *Urobatis halleri*, *Raja inornata*, *Platyrhinoidis triseriata*) were often discarded at sea, and thus are also under-represented by catch data.

Skewed sex ratios, in which females were approximately twice as abundant as males, were noted for three species: *P. glauca*, *G. galeus*, and *S. californica*. This may indicate sexual segregation, which is a relatively common phenomenon in elasmobranchs (Sims et al. 2005) such as the blue shark, *P. glauca* (Nakano & Seki 2003, Mucientes et al. 2009). Skewed sex ratios have previously been reported for *G. galeus* in California (Ebert 2003) and *S. californica* off Sonora, Mexico (Bizzarro et al. 2009). For some elasmobranchs inhabiting the continental shelf, skewed sex ratios may indicate the migration of gravid females into nearshore waters for pupping (Marquez-Farias 2005). While this remains a possibility, a large percentage of the captured females of these two species were immature. We also detected significant sex-specific differences in size for *C. ventriosum* and *Z. exasperata*. However, these differences were small and probably lack biological significance. Fig. 3 shows that CPT values were often high for both blue shark and banded guitarfish, which may indicate that these species are particularly susceptible to fishing activity due to aggregating behavior. The tendency of blue sharks to dominate catch during cooler

water months and mako sharks during warmer months is similar to the seasonal pattern observed in California waters (Ebert 2003).

The capture of large numbers of juveniles at LM indicates that the surrounding area [i.e., continental shelf waters of Bahia Sebastian Vizcaino (BSV)] may serve as nursery habitat for many elasmobranch species. Many shark species that are pelagic as adults [e.g., *S. zygaena*, *A. vulpinus*, and *C. carcharodon* (Buencuerpo et al. 1998, Weng et al. 2007, Cartamil et al. in review)] were represented only by juveniles captured over the shelf. In addition, the capture of substantial numbers of juvenile *A. vulpinus* extends the known nursery area of this species southward from the SCB (PFMC 2003). Although some gillnet-caught elasmobranchs, such as *R. productus* and *Z. exasperata* were represented primarily by adults, the morphology of these species is such that juveniles often escape entanglement in gillnets (Marquez-Farias 2005). Additionally, there are extensive estuarine and lagoonal systems connected to BSV that are difficult or illegal for fishers to access, and these may serve as nurseries for various species. Elasmobranch nursery areas are critical to the sustainability of adult populations, and an important future research direction will be to delineate nurseries within the BSV complex, with the goal of establishing protected areas to effectively conserve and manage these species.

According to interviews with fishers at LM, this camp has existed at the same location for over 35 years, and has apparently sustained consistently high elasmobranch catch rates. However, fishers in other areas of western BC have described declines in elasmobranch abundance over the same period. Several factors likely contribute to this

phenomenon. The extremely wide continental shelf in BSV provides a correspondingly large habitat (35,678 km²) that can support a higher biomass of elasmobranchs than the narrower shelf areas found offshore of the northern portion of western BC. The amount of fishing pressure per area is further reduced because the surrounding coastline is sparsely populated with few artisanal camps. BSV also has a higher productivity than adjacent coastal areas throughout the year (Lluch-Belda 2000, Morales-Zarate et al. 2000).

Elasmobranch species composition at LM is probably similar to that of the other artisanal camps located within BSV, but not necessarily representative of the entire western coast of BC. Species composition at camps in the northern half of the region will likely be more similar to the temperate fauna found in the SCB, and therefore, a more detailed investigation of elasmobranch fisheries in this sector of BC is warranted. There are also many differences in species composition between the present study and that reported for the Pacific coast of BC Sur by Villavicencio-Garayzar & Abitia-Cardenas (1994). These authors summarized elasmobranch capture data for artisanal fisheries in Laguna San Ignacio and Bahia Magdalena and documented many species that did not occur at LM, including *Heterodontus mexicanus*, *Galeocerdo cuvier*, *Sphyrna moccara*, and *Myliobatis longirostris*. Similarly, Bizzarro et al. (2007b) reported on a fishery for *Rhinoptera steindachneri* near Bahia Magdalena, another species not documented at LM. These observations support the assertion that BSV (or more precisely, Punta Eugenia) delineates the limits

of latitudinal distribution for many fish species (Quast 1968, Horn & Allen 1978, Horn et al. 2006).

Management Implications

Although no base-line data comparable to the present study exist, interviews with older fishermen suggest that both the abundance and average size of elasmobranchs have declined significantly in recent decades off the western coast of BC (with the possible exception of LM). Many of these declines have been exacerbated by a historic lack of governmental regulation. However, several steps have recently been taken to manage elasmobranch fisheries in Mexican waters. For example, the Mexican National Institute of Fisheries imposed a moratorium on the issuance of new elasmobranch-fishing permits in the early 1990s (Castillo-Geniz et al. 1998). This was followed in 2007 by NOM-029-PESCA-2006 (www.ordenjuridico.gob.mx), a major piece of legislation that includes rules specific to artisanal fisheries.

Some general predictions as to how NOM-029 will affect artisanal Pacific BC fishers can be made based upon the present study. Artisanal longline fishers in BC typically deploy up to 500 hooks, while elasmobranch gillnet fishers use multiple gillnets per vessel with mesh sizes of 6 to 12 cm. NOM-029 guidelines limit longline fishers to a maximum of 350 hooks, and limit gillnet fishers to the use of one gillnet per vessel with a minimum mesh size of 15 cm. Most longline fishers will not have to dramatically modify fishing practices to conform to NOM-029. Indeed, NOM-029

may be beneficial to artisanal longliners in that it restricts large commercial longline vessels to waters 50 nautical miles or more from shore, thus reducing competition with artisanal vessels. However, gillnet fishers will not only have to greatly reduce the number of gillnets deployed, but the larger mesh size required will result in reduced catch rates of smaller fish. Although NOM-029 will likely have a negative economic impact on artisanal gillnetters, it represents an important step towards the conservation of elasmobranchs in Mexico. However, very few fishers interviewed in the survey fully understood the NOM-029 guidelines, and less were in compliance with them.

The declines in elasmobranch abundance noted in many regions of Mexico (Bonfil 1997, Castillo-Geniz et al. 1998, Perez-Jimenez et al. 2005) perhaps justify a decrease in elasmobranch-directed fishing effort by artisanal fisheries. Vieira and Tull (2008) determined that the cessation of elasmobranch fishing by artisanal fishers in Indonesia did not result in substantial economic hardship, as fishing could be directed towards alternative species. Given the higher ex-vessel prices for most teleost and invertebrate species harvested by western BC artisanal fishers, a shift in effort to these more sustainable resources may be warranted. For example, the Humboldt squid is a major longline bycatch that was actually viewed as a plague by fishers because it would become hooked before sharks, but had no ex-vessel value. This species could potentially represent a major alternative target for artisanal fishers if a market was developed (Ehrhardt et al. 1983).

The status of elasmobranch fisheries in Mexico is also of concern to U.S. fisheries management, as elasmobranchs are a shared resource economically important

to both countries. Many commercially valuable pelagic shark species, such as the blue, the thresher, and the mako, have geographical ranges that expose them to fisheries in both the U.S. and Mexico (Hanan et al. 1993, Obrien & Sunada 1994, Gonzalez 2008, Olvera 2009). Though less understood, the movement patterns of many coastal sharks and batoids likely span the international border as well (Ebert 2003).

Ultimately, binational management strategies will be required that take into account mortality introduced through the activities of fisheries in both countries to calculate acceptable harvest levels, and this study represents an important first step forward towards that goal.

Table 4.1: Sampling dates and number of pangas sampled per trip at Laguna Manuela artisanal fishing camp.

Year	Date(s)	Days	Pangas
2006	September 25	1	2
2007	March 12-16	5	14
	April 18-19	2	2
	May 22-24	3	19
	June 13-14	2	5
	June 21-22	2	4
	June 27-28	2	4
	July 23-26	4	17
	September 3-5	3	11
	September 21	1	8
	November 6-7	2	7
	November 21	1	2
	December 18-20	3	6
	2008	February 10	1
March 11-13		3	8
April 6-8		3	5
April 29-30		2	22
May 13-15		3	24
June 11-13		3	22
June 17-19		3	33
July 2-4		3	27
July 22-24		3	32
August 11-13		3	34
August 27-29		3	34
October 6		1	10
October 14-16		3	17
December 4-5		2	15
Total		67	387

Table 4.2: Characteristics of surveyed artisanal camps.

Map	Camp Name	Pangas	Target	Perm	Structures	N Lat	W Long
1	Popotla	6/30	T, I(L, C, U), CE(G)	P	V	32.282	117.034
2	Puerto Nuevo	6	I(L, C), T, CE(G)	P	V	32.243	116.936
3	El Sauzal	6/20	I(L, U, S), T, CE(G), PE(L)	P	V	31.894	116.706
4	Ensenada	4/7	PE(L), T	P	V	31.859	116.632
5	Rincon de Ballenas	7	T, CE(G)	P	S(4)	31.718	116.671
6	Arbolitos ^A	12	I(U, B, H)	T	S(1)	31.702	116.685
7	Puerto Santo Tomas	10/15	I(U, G), T	P	P(20), S(10)	31.554	116.681
8	Punta San Jose	2/12	T, CE(G)	P	P(1), S(1)	31.467	116.600
9	Campo de Enmedio	2/6	T, CE(G)	T	S(6)	31.450	116.533
10	San Juan de las Pulgas	2	T, CE(G)	T	S(2)	31.408	116.500
11	Erendira	8/10	T, I(B), CE(G), K	P	V	31.285	116.400
12	Punta Colonet	3	T	T	S(1)	30.970	116.280
13	Camalu	14	T, IE(G)	P	S(2)	30.935	116.237
14	Punta Azufre (San Quintin)	4/6	T, PE(L), I(B)	P	S(2)	30.389	115.986
15	El Chute (San Quintin)	6/8	T, PE(L), I(B)	P	P(3), S(6)	30.436	115.987
16	El Pabellon	4/6	T	P	none	30.373	115.852
17	El Socorro	2/8	T, PE(L)	P	none	30.310	115.820
18	El Tranquilo	4/6	T, CE(G)	T	none	30.281	115.803
19	Punta Baja	15/25	I(U,C,B, H, G), T, PE(L)	P	P(28), S(3)	29.950	115.811
20	Campo Nuevo	2/4	I(L,U,A), T	P	S(1)	29.698	115.602
21	Punta San Carlos	15	T, CE(G), I(L,C)	P	P(11), S(11)	29.627	115.478
22	Puerto Catarina	6/20	I(C), T, CE(G)	P	S(15)	29.525	115.270
23	Puerto Canoas	6	T, I(L), CE(G)	P	P(2), S(10)	29.420	115.120
24	Faro de San Jose	5/8	CE(G), T, I(A,L,C,G)	P	P(3), S(6)	29.286	114.877
25	El Cuchillo	4	CE(G), T, PE(L), I(C)	T	S(3)	29.242	114.834
26	Bahia Blanca ^A	NA	I(L,C,B), T	P	S(4)	29.113	114.678
27	Punta Cono South	3	T, CE(G), PE(L)	P	S(4)	28.975	114.580
28	Punta Cono North	3/6	I(L)	T	S(6)	28.973	114.591
29	Bahia Maria	6	T, CE(G), PE(L), I(L)	P	S(6)	28.934	114.510
30	El Cardon	1	T	T	none	28.911	114.452
31	El Marron	4	I(L,O), T, CE(G), PE(L)	P	P(5)	28.814	114.375
32	Puerto San Andres	NA	NA	NA	NA	28.707	114.287
33	Santa Rosalilita	6/20	T, CE(G), I(L), PE(L)	P	V	28.667	114.217
34	Punta Rosarito ^A	NA	CE(G), T, PE(L),	T	S(1)	28.570	114.160
35	Campo Esmeraldas	1/10	T, PE(L)	T	P(1), S(1)	28.515	114.068
36	El Tomatal	3/6	I(L), T	T	P(1)	28.486	114.067
37	Laguna Manuela	10/25	CE(G), PE(L), T, I(L)	P	S(1)	28.247	114.084
38	Puerto Carranza (La Isla)	8/16	I(B), T, CE(G)	P	S(1)	28.037	114.119
39	Puerto Viejo	6/8	I(B)	P	P(4)	28.016	114.118
40	Las Casitas	15/80	I(B, C, G), T, CE(G), PE(L)	P	P(6)	27.851	114.158
41	El Datil	NA	NA	T	none	27.796	114.176
42	El Queen	4/6	I (A, L, B, H, O)	P	P(3)	27.801	114.720
43	Malarrimo	9	I (A, L, B, H, G, O), T, CE(G)	P	P(15), S(10)	27.801	114.720
44	El Chevo / Campito	6/8	I(L,O), T, CE(G)	P	P(17), S(4)	27.823	114.852

Table 4.3: Elasmobranch species taken by gillnet and longline at Laguna Manuela between September 2006 and December 2008, with number (n) of individuals documented, and percentage (%) of catch comprised of that species. CPUE = mean catch per unit effort. S.E. = standard error. Carcass and Fins refers to ex-vessel price paid to fishers (in Mexican pesos kg^{-1}). (Note: during the time frame of this study, the peso was equivalent to approx. 0.09\$ in U.S. currency.)

Method	Species	n	%	CPT	S.E.	Carcass	Fins
Gillnet	<i>Alopias vulpinus</i>	64	0.85	0.28	0.10	16	≤ 800
	<i>Carcharhinus brachyurus</i>	19	0.25	0.08	0.03	12	≤ 1000
	<i>Carcharodon carcharius</i>	12	0.16	0.05	0.02	12	≤ 1000
	<i>Cephalloscyllium ventriosum</i>	75	1.00	0.32	0.13	none	none
	<i>Dasyatis brevis</i>	5	0.07	0.02	0.01	8 to 12	none
	<i>Galeorhinus galeus</i>	274	3.64	1.18	0.24	12 to 16	≤ 800
	<i>Gymnura marmorata</i>	53	0.70	0.23	0.06	6 to 10	none
	<i>Heterodontus francisci</i>	14	0.19	0.06	0.02	6 to 10	none
	<i>Isurus oxyrinchus</i>	12	0.16	0.05	0.02	14 to 16	≤ 1000
	<i>Mustelus henlei</i>	54	0.72	0.23	0.06	12 to 14	none
	<i>Mustelus</i> spp.	191	2.54	0.82	0.32	12 to 14	none
	<i>Myliobatis californica</i>	710	9.44	3.06	0.66	8 to 12	none
	<i>Narcine entemedor</i>	2	0.03	0.01	0.01	none	none
	<i>Notorhynchus cepedianus</i>	2	0.03	0.01	0.01	8 to 12	none
	<i>Platyrrhinoidis triseriata</i>	6	0.08	0.03	0.01	none	none
	<i>Prionace glauca</i>	1	0.01	0.00	0.00	6 to 10	≤ 800
	<i>Raja inornata</i>	8	0.11	0.03	0.02	none	none
	<i>Rhinobatos productus</i>	3464	46.08	14.93	3.42	10 to 12	none
	<i>Sphyrna zygaena</i>	306	4.07	1.32	0.37	12 to 16	≤ 1000
	<i>Squalus acanthias</i>	3	0.04	0.01	0.01	12 to 14	none
	<i>Squatina californica</i>	140	1.86	0.60	0.11	12 to 14	none
	<i>Triakis semifasciata</i>	5	0.07	0.02	0.01	12 to 14	none
	<i>Urobatis halleri</i>	1	0.01	0.00	0.00	none	none
	<i>Zapteryx exasperata</i>	2097	27.89	9.04	1.08	6-10	none
	Subtotal	7518	100				
Longline	<i>Alopias vulpinus</i>	5	0.16	0.04	0.03	14 to 16	≤ 800
	<i>Carcharhinus brachyurus</i>	1	0.03	0.01	0.01	12	≤ 1000
	<i>Carcharodon carcharius</i>	3	0.10	0.02	0.02	12	≤ 1000
	<i>Galeorhinus galeus</i>	74	2.38	0.61	0.33	12 to 16	≤ 800
	<i>Isurus oxyrinchus</i>	881	28.32	7.22	1.58	14 to 16	≤ 1000
	<i>Prionace glauca</i>	2120	68.15	17.38	1.92	6 to 10	≤ 800
	<i>Pteroplatytrygon violacea</i>	17	0.55	0.14	0.04	7	none
	<i>Sphyrna zygaena</i>	10	0.32	0.08	0.03	12 to 16	≤ 1000
		Subtotal	3111	100			

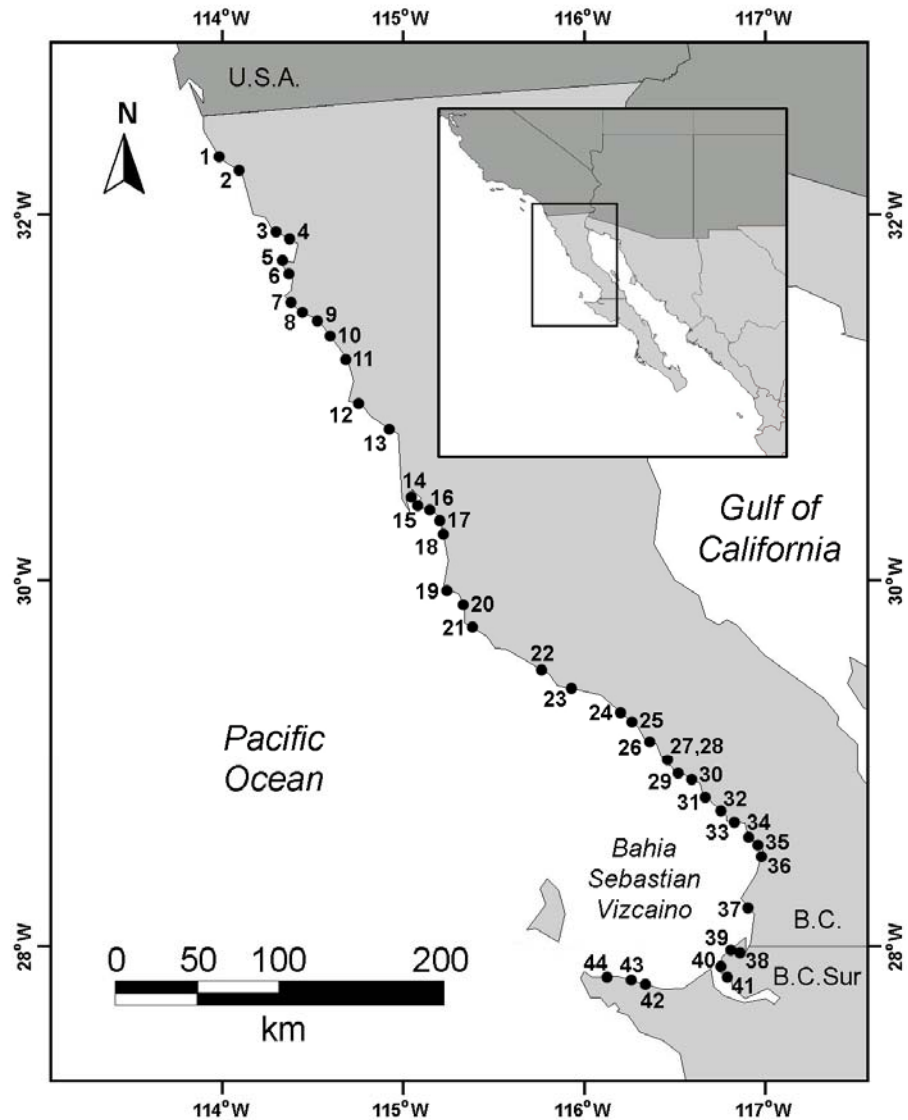


Figure 4.1: Location of artisanal camps along the Pacific coast of the state of Baja California, Mexico. Numbers refer to map codes in Table 1. Inset shows the location of the study area relative to the United States and mainland Mexico.

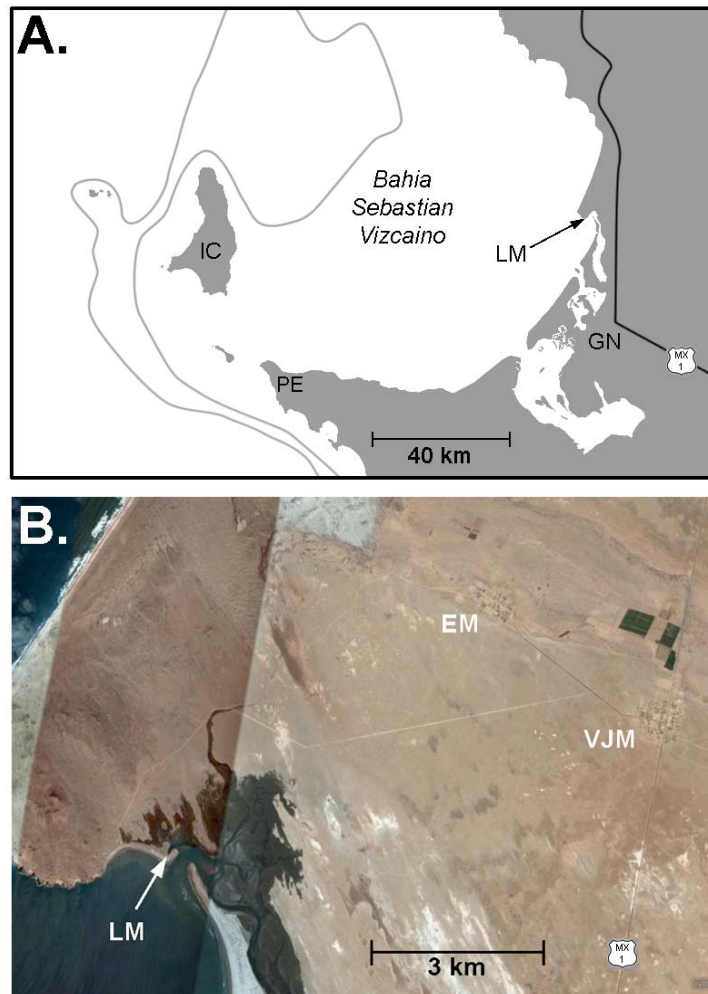


Figure 4.2: **A.** Bahia Sebastian Vizcaino. The extent of the continental shelf is indicated by the 100 m (inner) and 200 m (outer) bathymetry lines, in grey. Black line indicates the paved Transpeninsular Highway (MX 1). LM = Laguna Manuela; GN = Guerrero Negro; IC = Isla Cedros, PE = Punta Eugenia. **B.** Detailed satellite image (Google Earth) of LM fishing camp and immediate surroundings. EM = Ejido Morales, VJM = Villa Jesus Maria.

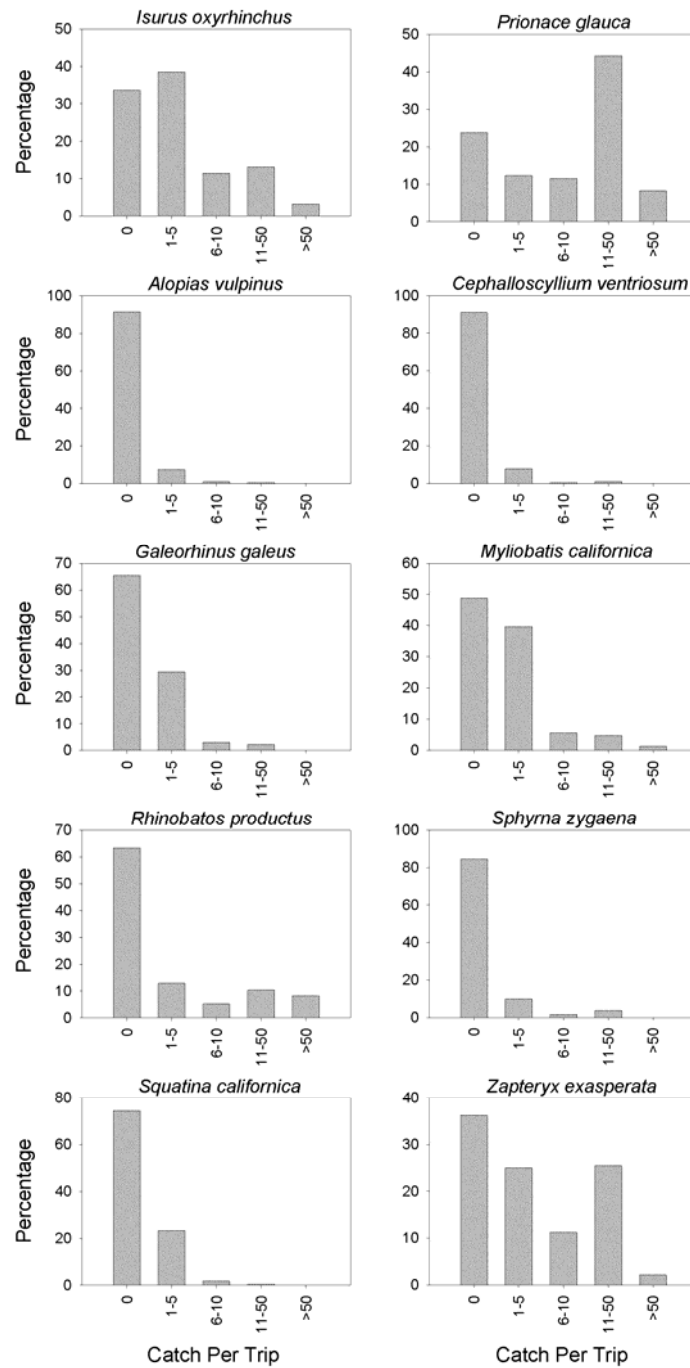


Figure 4.3: Histograms showing the percentage of total trips with varying CPT values for species where $n > 50$.

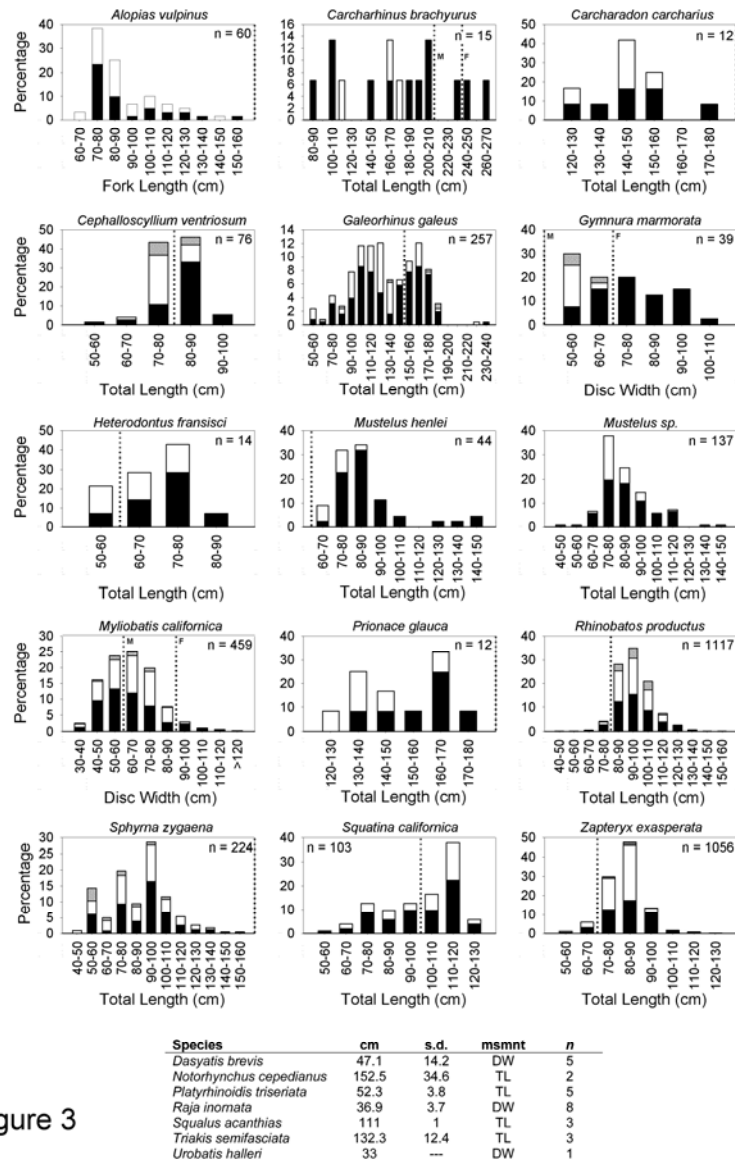


Figure 3

Figure 4.4: Sex-specific size frequency distributions of elasmobranchs sampled from the gillnet fishery at Laguna Manuela. *n* refers to the number of measured individuals upon which size histograms are based (not necessarily the total number captured). Females are depicted in black, males in white, sex unknown in grey. Dotted lines indicate approximate size at maturity (Ebert 2003). In cases where a substantial difference in size at maturity exists between sexes, lines are labeled M (male) or F (female). Dotted lines on the left or right x axis indicate that size at maturity is either less than or greater than the scale shown. Tabular data at the bottom provides summary statistics for species where *n* < 10. cm is mean size ± s.d. (standard deviation) for the specified measurement (msmnt) taken for that species.

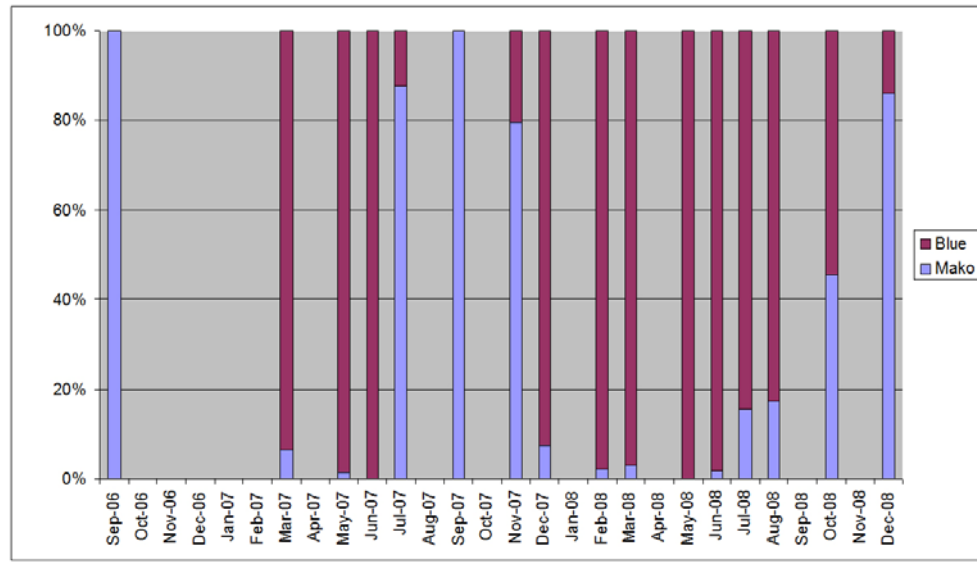


Figure 4.5: Relative catch of mako and blue sharks at Laguna Manuela as monthly proportion of total catch.

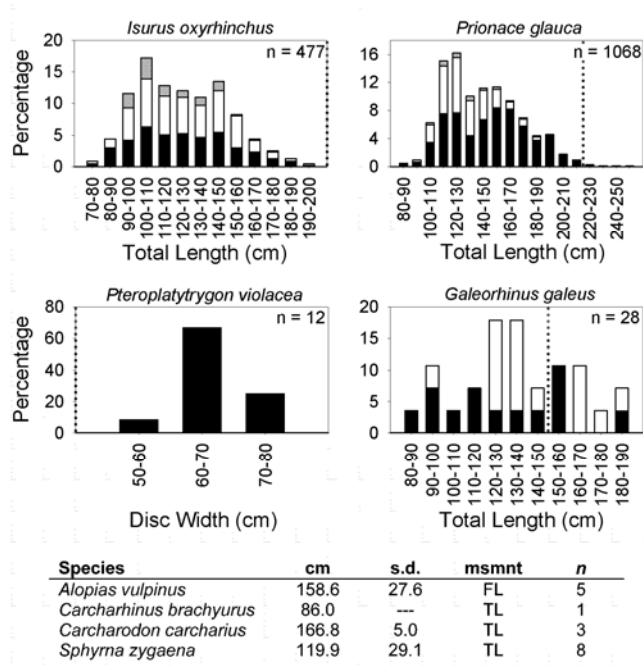


Figure 4.6: Sex-specific size frequency distributions of elasmobranchs sampled from the longline fishery at Laguna Manuela. n refers to the number of measured individuals upon which size histograms are based (not necessarily the total number captured). Females are depicted in black, males in white, sex unknown in grey. Dotted lines indicate approximate size at maturity, from Ebert 2003. In cases where a substantial difference in size at maturity exists between sexes, lines are labeled M (male) or F (female). Dotted lines on the left or right x axis indicate that size at maturity is either less than or greater than the scale shown. Tabular data at the bottom provides summary statistics for species where $n < 10$. cm is mean size \pm s.d. (standard deviation) for the specified measurement (msmnt) taken for that species.

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ACKNOWLEDGEMENTS

This work was supported by CA Sea Grant, UC Mexus-CONACYT, the Moore Family Foundation, the Tinker Foundation, the Save Our Seas Foundation, and the Scripps Institution of Oceanography Tuna Industry Endowment Fund. Jonathan Rubén Sandoval Castillo, Erick Cristóbal Oñate González, Alfoncina Romo Curiel, and Luis Malpica Cruz assisted with field data collection. Thanks to C. McKay and L.

Williams for their help with data entry. I am especially grateful to the artisanal fishers of Laguna Manuela for their cooperation and assistance.

**CHAPTER 5: MOVEMENT PATTERNS, HABITAT PREFERENCES,
DISTRIBUTION, AND FISHERIES BIOLOGY OF THE THRESHER SHARK
(*ALOPIAS VULPINUS*) IN THE SCB AND BEYOND: CURRENT STATUS OF
KNOWLEDGE AND FUTURE DIRECTIONS**

ABSTRACT

Using acoustic telemetry, archival tagging, and artisanal fishery surveys, this dissertation provides the first fisheries-independent data on thresher shark movement patterns and habitat preference. This concluding chapter combines results of the dissertation with those of previous and ongoing studies to provide a synoptic view of thresher shark biology in the Southern California Bight (SCB) and Mexican waters. Juvenile threshers use the SCB continental shelf as a nursery area. Subadults and adults (i.e., sharks of > 120 cm fork length) preferentially utilize off-shelf waters, and may undertake extensive vertical excursions to feed on deeper prey. The primary nursery area of the thresher appears to range from Pt. Conception, CA to Punta Eugenia, Baja California, Mexico, while the distribution of larger threshers appears to extend beyond these landmarks. Trans-border movements and fisheries for threshers in both the U.S. and Mexico indicate the need for bi-national management strategies.

INTRODUCTION

The history of over-fishing of the common thresher shark (*Alopias vulpinus*) suggests that precautionary management strategies are needed to ensure sustainability. The eastern Pacific thresher population underwent the archetypical ‘boom and bust’ cycle characterizing the initial stages of many shark fisheries (Walker 1998). Five

years after the inception of the California drift gillnet fishery (CA-DGN), thresher catch rates peaked in 1982 at over 1000 metric tons (mt), but decreased rapidly to less than 300 mt by 1986 (Hanan et al. 1993). Regulatory measures enacted after this crash resulted in both greatly reduced fleet size and thresher catch rates (Holts 1988, Hanan et al. 1993, Smith and Aseltine-Nielson 2001). Current harvest levels are less than 100 metric tons (well below the annual guideline of 340 mt), and the thresher population appears to have stabilized but may be only about half of pre-exploitation levels (Smith et al. 2008).

Thresher fishery management requires basic biological information about movement patterns and the environmental factors influencing habitat preference. This information contributes to an understanding of potential interactions of the thresher shark with the spatio-temporal aspects of fishery effort. The acoustic telemetry and archival tagging studies reported in Chapters 1-3 of this dissertation provide the first fisheries-independent data on movement patterns and habitat preferences of the thresher shark in the Southern California Bight (SCB). These studies established that large-scale movements to and from Mexican waters are likely. In view of the large data void for threshers in Mexican waters, the survey of artisanal elasmobranch fisheries reported in Chapter 4 was undertaken. New studies germinating from this dissertation, including an expansion of the Mexican artisanal fishery survey, pop-up satellite tag (PSAT) deployments, and genetic analyses contribute to the present level of understanding of thresher shark essential habitat.

This concluding chapter combines the findings reported in the dissertation with the results of previous and ongoing studies to provide a synoptic view of thresher shark movement patterns and habitat preference in the SCB and adjacent waters. It also describes ongoing research in Mexico designed to gain a more complete understanding of thresher biology and management issues pertaining to this and other species having a binational occurrence.

Juvenile thresher sharks in the SCB

The young of many shark species spend the first few years of life in nursery areas that are separate from the areas occupied by adult sharks. These nursery areas appear beneficial in providing ample food resources and reduced predation risk at a vulnerable life stage, and are thus seen as critical to the survival of young sharks (Clarke 1971, Castro 1993, Gruber et al. 2001, Heupel and Simpfendorfer 2002). Chapter 3 reports acoustic telemetry tracking studies documenting the occurrence of juvenile threshers in coastal waters of the SCB. Juveniles occupy the upper 10-20 m of the water column, and preferentially inhabit waters over the continental shelf. These shallow inshore waters provide abundant prey (e.g., northern anchovy, *Engraulis mordax*) and presumably provide protection from potential predators that occur offshore, such as the blue shark (*Prionace glauca*) and the mako shark (*Isurus oxyrinchus*). The preference of juveniles for continental shelf waters confirms the importance of the Marine Resources Protection Act of 1990 (article 10B of the California constitution), which bans gillnets within 3 miles (4.83 km) of shore in the

SCB. Because very little of the SCB continental shelf extends beyond this 3 mile limit, this act appears to protect juvenile threshers from excessive mortality in commercial gillnet fisheries.

Heupel et al. (2007) emphasized the importance of knowing whether juvenile sharks repeatedly occur in specific areas over successive years, as the predictability of sharks aggregating in preferred habitats may subject them to fisheries exploitation or other anthropogenic disturbances. To determine areas of abundance of juvenile thresher shark in the SCB, the National Marine Fisheries Service (NMFS) has operated an annual longline survey since 2003 (Smith 2005). This study shows highest concentrations of juveniles between Point Conception and Santa Monica Bay (Fig. 1). However, this survey is conducted only once annually in September or October when SCB water temperatures are highest. Therefore, this localized abundance likely represents the northern extent of the juvenile thresher shark's primary range, although juveniles are occasionally encountered north of Pt. Conception (Dubsky 1974, Hanan et al. 1993). Areas of abundance throughout the remainder of the year are not known, and there may be a southward migration into Mexican waters.

Subadult and adult thresher shark in the SCB

Larger thresher sharks appear to have a more off-shore distribution, and the thresher is commonly reported to be a coastal pelagic species (Compagno 2001). A survey by Strasburg (1958) in the eastern Pacific found highest densities of common thresher within 80 km of shore. In the SCB, threshers are targeted by the CA-DGN

from 10 to 100 km from shore, and most (approximately 85%) captured individuals range from 120 to 200 cm FL (Council 2003). Prior to this dissertation, little was known about the fine-scale utilization of this offshore habitat, or how the movement patterns of larger threshers relate to interactions with the CA-DGN.

The acoustic telemetry tracking study of subadult and adult threshers (Chapter 1) shows that threshers of this size class preferentially utilize waters offshore of the SCB continental shelf. By day, they often make extensive vertical excursions to depths of over 200 m that may be related to foraging. However, at night threshers occupy depths of 5 to 15 m, and their vertical movements are restricted by the depth of the thermocline. Nocturnal depth distribution is important in determining thresher shark susceptibility to CA-DGN gear, which is deployed at night at a legally mandated minimum set depth of 11.0 m. This study found that 50.5 % of nocturnal depth readings were below 11 m, and thus threshers were within CA-DGN ‘capture range’ a substantial portion of the time.

With archival tags, vertical movement patterns could be examined for time periods longer than possible using acoustic telemetry (Chapter 2). Archival tags that recorded depth and temperature for up to 45 d were placed on subadult and adult thresher shark in the SCB. Results show that the daytime vertical distribution of threshers consisted of two distinct modes; a ‘shallow’ mode (wherein sharks occupied only the upper 20 m of the water column), and a ‘deep’ mode (characterized by vertical excursions to depths of up to 320 m). This modal switch is interpreted as relating to regional differences in abundance of surface oriented prey [e.g., northern

anchovy and Pacific sardine (*Sardinops sagax*)] and prey in deeper water [e.g., Pacific hake (*Merluccius productus*)]. In contrast to the acoustic tracking results, only 23% of nocturnal depth readings were below 11 m for archivally tagged thresher. Because archival records represent a substantially longer data acquisition period, it may be that these results are more accurate. However, thermocline depth varies seasonally and between years, and its strong influence on thresher nocturnal depth distribution justifies inclusion of this parameter into habitat-based fisheries models (Link 2002, Brill et al. 2005).

In summary, tracking studies presented in Chapters 1,2 and 3 demonstrate an ontogenetic shift from juvenile habitat (continental shelf waters) to subadult and adult habitat (off-shelf waters). By utilizing SCB shelf waters as a nursery area juveniles may encounter a reduced predation risk relative to the pelagic environment. At a size of approximately 120 cm FL (age 2-3 y), they may effectively be beyond the risk of predation, allowing them to expand their habitat to off-shelf waters, concurrently increasing dietary scope to include deeper prey. Sharks between the approximate size range of 120 to 160 cm FL are sexually immature yet share the same habitat as adults, thus the designation of ‘subadult’ for this size class. The thresher attains sexual maturity at approximately 160 cm FL (Cailliet and Bedford 1983, Smith et al. 2008).

The Mexican Connection

To this point, discussion of thresher shark movement patterns has been limited to waters within the U.S. portion of the SCB, where CA-DGN effort is concentrated.

However, a general migratory pattern that has been hypothesized for the common thresher in the eastern Pacific (Bedford 1992, Hanan et al. 1993) includes Mexican waters (Fig. 2). According to this hypothesis, the thresher migrates north into the SCB from Mexican waters during early spring and summer, when pupping may occur. Subadults and smaller adults remain in the SCB throughout the summer, while larger adult sharks may move farther north along the west coast of the U.S. A southward movement would then occur in late fall and early winter, with sharks over-wintering in Mexican waters. It must be noted that this migratory hypothesis is based upon fisheries data of limited duration, and large-scale movements outside of the CA-DGN season (Aug 15 to Jan 15) remain unknown.

Few fisheries-independent data are available to support or refute the hypothesized migratory pattern. A NMFS pop-up satellite archival tag (PSAT) study (Baquero 2006) of primarily subadult and adult threshers showed that most tagged sharks were indeed resident in the SCB during summer months. However, no consistent pattern indicative of migratory behavior beyond this period was observed. Movements from U.S. to Mexican waters were demonstrated for the first time (as far south as 110° N latitude and 870 km offshore; Fig. 1). However these movements occurred in summer, which does not agree with the hypothesized migration timing. Chapter 2 of this dissertation provides limited evidence for northward spring migration; two sharks archivally tagged in spring and recaptured later in the year showed a northward displacement within the SCB. By contrast, subadult and adult threshers acoustically tracked in the SCB (Chapter 1) showed no consistent

directionality. However, acoustic telemetry studies are inappropriate for inferring migratory behavior due to the limited duration of the tracking periods.

If the thresher overwinters in Mexican waters as hypothesized, this would be important information from a fishery management perspective. Although there are various reports of captures of common thresher in the Gulf of California (Bellido-Millan and Villavicencio-Garayzar 2002, Bizzarro et al. 2009, Smith et al. 2009) and as far south as 21° N latitude along the central Mexican Pacific coast (Perez-Jimenez et al. 2005), these records represent sporadic captures of few individuals. Interestingly, there have been no published reports of *A. vulpinus* along the Pacific coast of the Baja California (BC) peninsula. Villavicencio-Garayzar and Abitia-Cardenas (1994) reported landings of *Alopias* sp. on the Pacific coast of BC Sur, but these could be *A. pelagicus*, which has a more tropical distribution than *A. vulpinus* and is often found in BC Sur waters (Compagno 2001). In addition, it had been suggested that the nursery area of the thresher is contained primarily within the SCB (PFMC 2003), as the occurrence of juveniles in Mexican waters below this region had not been verified.

In order to fill this data void, a survey of the artisanal fishing camps along the Pacific coast of BC, Mexico, was conducted and is reported in Chapter 4. The purpose of this survey was to describe the extent, target species, and effort levels of the artisanal fisheries. Additionally, catch composition was evaluated at a major elasmobranch fishing camp, Laguna Manuela (LM) (Fig. 1). Common thresher was captured by LM fishers using gillnets set over the continental shelf, and 88% were juveniles (i.e., < 120 cm FL). These findings extend the known nursery area of the

thresher considerably southward to at least 28° N latitude. However, the major contribution of this dissertation chapter to thresher shark biology may be the studies that it generated, and that were conducted in collaboration with Mexican researchers. These studies and their significance towards providing a synoptic view of thresher shark movement patterns and habitat preferences are described below. Grant support will enable D. Cartamil to continue these collaborations as a post-doctoral researcher.

In tandem with Chapter 4, Santana (2008) assessed catch composition at LM using the novel method of identifying elasmobranch carcasses discarded in the desert adjacent to the fishing camp but preserved due to the extreme aridity of the environment. He identified 31,861 carcasses to species, of which 137 were *A. vulpinus*, providing further evidence of the occurrence of the common thresher at this southerly locale. This work formed part of Santana's MS degree at Centro de Investigación Científica y de Educación Superior de Ensenada (CICESE), under the direction of his advisor Dr. O. Sosa-Nishizaki.

Various surveys of artisanal elasmobranch fishing camps are now being conducted along the entire coast of the BC peninsula, and these have the potential to provide important additional data regarding thresher shark distribution. For example, a survey of the artisanal fishing camps along the northern extreme of the BC Pacific coast (from the U.S. – Mexico border to Erendira, BC) (Fig. 1) is being conducted by Santana (now a biological technician at CICESE). Preliminary results indicate a higher catch rate of threshers in this region than that reported at LM in Chapter 4, and the

majority are juveniles (Fig. 3), indicating that the entire Pacific coastline of BC is used as nursery habitat by juvenile threshers.

A survey of the artisanal camps located along the Pacific coast of BC Sur is also underway. This survey includes two detailed studies of elasmobranch species composition at selected fishing camps, similar to the study conducted at LM (Chapter 4). The first is being conducted at Bahia Tortugas (27.7° N Latitude) by Universidad Autónoma de Baja California Sur (UABCS; La Paz, MX) graduate student S. Amaro. This work will form part of Amaro's MS degree, under the direction of his advisor Dr. Gerardo Barba-Gonzalez. The second is being conducted at Bahia Magdalena (25° N Latitude) by Centro Interdisciplinario de Ciencias Marinas (CICIMAR; La Paz, MX) graduate student E. Bareño. This work will form part of Bareño's MS degree, under the direction of his advisor Dr. Felipe Galvan-Magaña. The locations of these two camps are shown in Fig. 1. Preliminary results indicate that catches of *A. vulpinus* juveniles are rare at Bahia Tortugas, and thus far there are none at Bahia Magdalena. These results suggest that the southern limit of thresher shark nursery habitat lies between LM and Bahia Tortugas. Specifically, it is hypothesized that the geographic feature that demarcates this southern limit is Punta Eugenia (Fig. 1), which represents the southern limit of the distribution of many fish taxa common to the temperate San Diegan Province, and the northern limit of distribution for many fish species common to the tropical Panamic Province (Quast 1968, Horn and Allen 1978, Horn et al. 2006). Additional data are needed to verify this hypothesis.

A migratory pattern has not been suggested for juvenile threshers, yet it is likely that juveniles migrate between Mexican waters and the SCB. Cartamil and colleagues (in progress) are examining the large-scale movement patterns of juvenile threshers through the use of pop-off satellite tag (PSATs). Three PSATs were deployed offshore of San Diego, CA in September 2008, and all three tags reported six months later over the BC continental shelf (Fig. 1). One of the tagged sharks had traveled as far south as 28° N Latitude (just south of LM). These are the first data that demonstrate trans-border movements of juveniles, and an additional 17 PSATs will be deployed in September 2009 in collaboration with the NMFS juvenile thresher shark abundance survey.

The use of Mexican waters by subadult and adult threshers is also being investigated. Olvera (2009) analyzed the records of the Ensenada, BC drift gillnet fishery (Ens-DGN) and organized a limited observer program to monitor this fishery and describe its catch characteristics. This work formed part of Olvera's MS degree at CICESE, under the direction of his advisor Dr. O. Sosa-Nishizaki. He found that subadult and adult threshers are targeted with drift gillnets offshore of the continental shelf, and captured as far south as 26° N Latitude (Fig. 1), supporting a geographic range of subadult and adult threshers that, unlike that of juveniles, extends south of Punta Eugenia and into BC Sur waters. Ongoing data analyses are expected to quantify thresher shark mortality in the Ens-DGN over the past decade.

Genetic studies may be useful to reveal population structure in thresher sharks by quantifying the degree of relatedness among geographically distinct populations.

The extent to which there is genetic overlap between U.S. and Mexican populations is not known, but could benefit management of the species by showing whether exploited groups of individuals need to be managed as a single stock or multiple, overlapping stocks. A microsatellite analysis study has been initiated to compare thresher shark tissue samples collected in Mexican waters with samples collected in U.S. waters. This work is being conducted by D. Kacev as part of his doctoral degree at UC Davis, under the direction of his advisor Dr. R. Lewison.

Clearly, much remains to be learned regarding the movement patterns of the thresher shark in Mexican waters. In addition, the trans-border movements documented in this dissertation indicate that bi-national research and management strategies are essential for sustainable exploitation of the thresher in both U.S. and Mexican waters. For this reason D. Cartamil and advisor Dr. J. Graham have initiated an international collaboration of scientists, fishery managers, and outreach agencies formally known as the Southern California Bight Elasmobranch Consortium (SCBEC). The Consortium's mission is to study and effectively manage elasmobranchs both within the SCB and adjacent waters, and to make the conservation status of elasmobranchs in the region known to the public. At present, the essential working members of the SCBEC are SIO, NMFS, and the Birch Aquarium at Scripps (U.S.), and CICESE, UABCS, CICIMAR, and Centro Regional de Investigación Pesquera, Ensenada (Mexico). Due to the close working relationship of these groups, bi-national research projects are conducted more efficiently, and results are disseminated directly to the appropriate management agencies.

Concluding statement:

This dissertation describes the movement patterns, habitat preferences, and fisheries biology of the common thresher shark in the SCB and Mexican waters. Integrating a variety of research tools such as acoustic telemetry, archival tagging, and artisanal surveys, it provides fisheries independent data that have greatly expanded the current state of knowledge of thresher shark biology. These data will aid in the formulation of management strategies for sustainable thresher shark fisheries. This final chapter illustrates that the work described herein has raised new research questions that require bi-national collaborations among scientists and management agencies from both the U.S. and Mexico. As a post-doctoral researcher at SIO, D. Cartamil will continue to foster these collaborations needed to address critical issues in the fields of shark biology, management, and conservation.

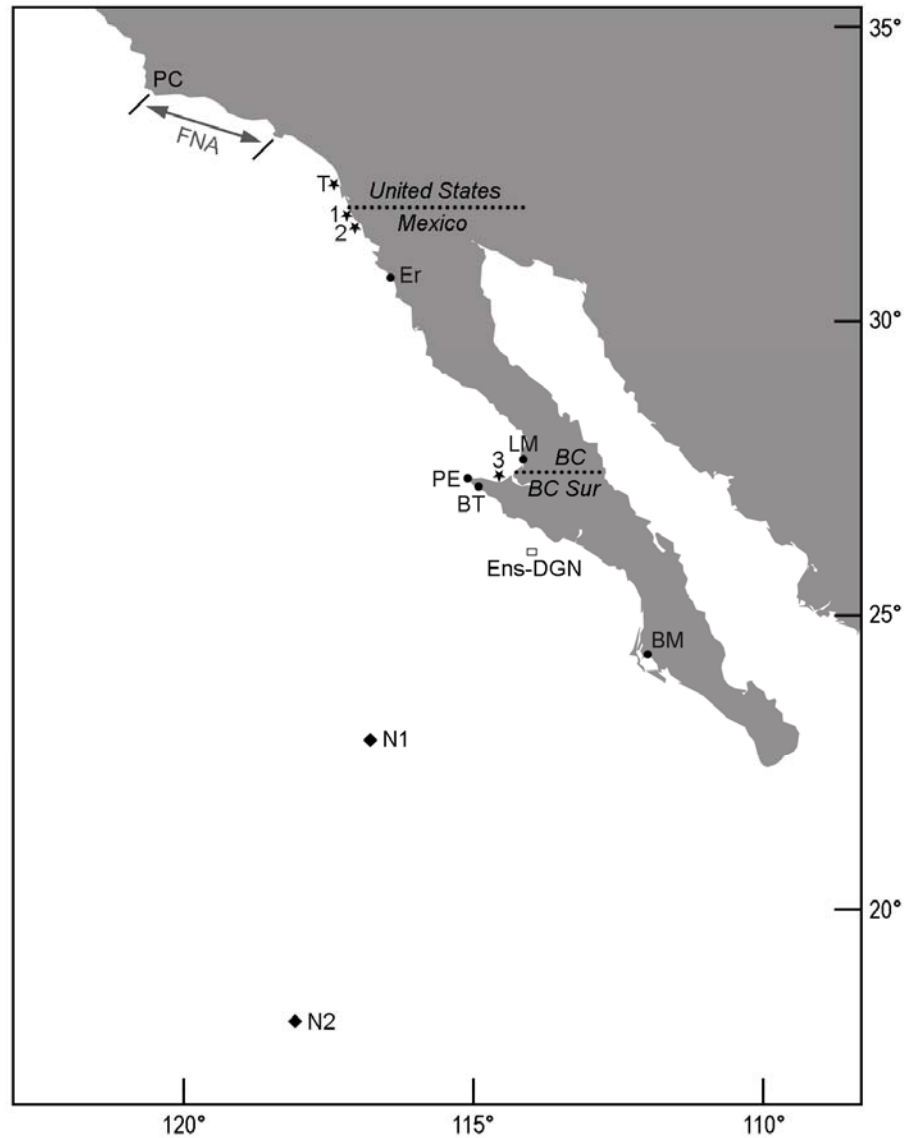


Figure 5.1: Map of the SCB and the Pacific coast of the Baja California peninsula, showing various locales described in text. FNA = Fall nursery area (S. Kohin, NMFS, unpublished data). Diamonds (N1 and N2) are the two southernmost PSAT pop-up locations for adult thresher tagged by NMFS (Baquero 2006). Stars are locations of SIO juvenile thresher shark PSAT tagging (T) and pop-up locations (1,2, and 3). Open square labeled Ens-DGN shows the southernmost documented capture location of an adult thresher in the Ensenada-based drift gillnet fishery (Olvera 2009). PC = Point Conception, Er = Erendira, LM = Laguna Manuela, PE = Punta Eugenia, BT = Bahia Tortugas, BM = Bahia Magdalena, BC = Baja California.

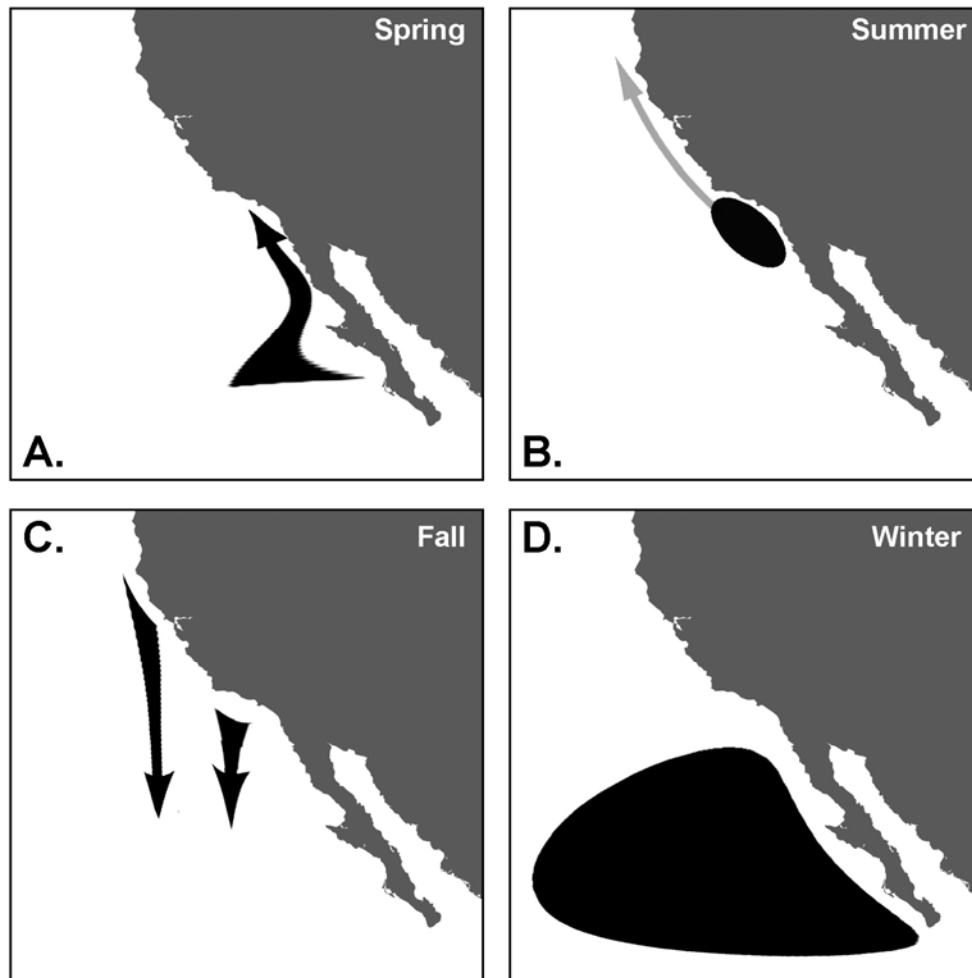


Figure 5.2: Putative migratory route of subadult and adult thresher sharks in the eastern Pacific. A. Northerly Spring migration along the coast of BC and southern California. B. Summer habitat in the SCB; larger adults may move farther north. C. Late Fall migration via offshore route to overwintering grounds in Mexican waters (D.).

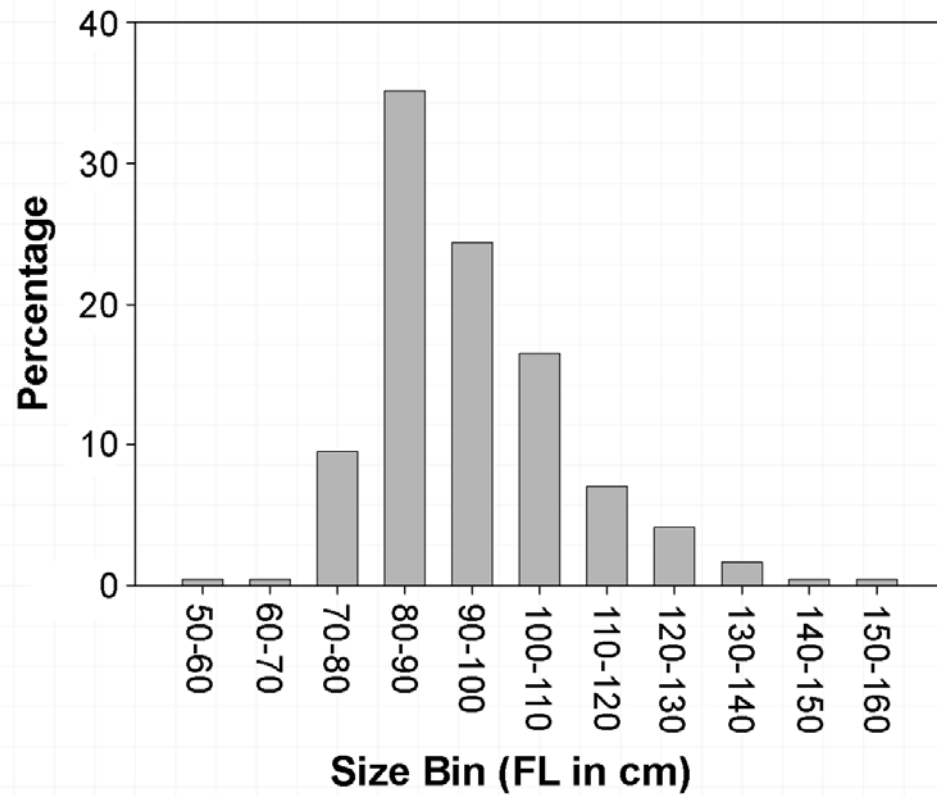


Figure 5.3: Size frequency distribution of common thresher shark captured in the artisanal elasmobranch fishery between the U.S. – Mexico border and Erendira, Baja California, Mexico. FL = fork length.

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