Multiaxial Shark Conservation: How vertical distribution can inform marine management

By

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List of Abbreviations

PSAT: Pop-off satellite archival transmitting [tag]

ICCAT: International Commission for the Conservation of Atlantic Tuna

SDM: Species distribution model

NAFO: Northeastern Atlantic Fisheries Organization

EEZ: Exclusive economic zone

FAO: Food and Agriculture Organization of the United Nations

COSEWIC: Committee on the Status of Endangered Wildlife in Canada

SARA: Species at Risk Act

CITES: Convention on International Trade in Endangered Species of Wild Fauna and Flora

MSC: Marine Stewardship Council

SFF: Sustainable Fisheries Framework

DFO: Fisheries and Oceans Canada

TAD: Time at depth

TAT: Time at temperature

HMM: Hidden Markov model

IUCN: International Union for the Conservation of Nature

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Abstract

Understanding how sharks are spatially and temporally distributed is critical to formulating effective conservation and management strategies. Many shark species are threatened around the world, and knowledge on diving behaviours and vertical habitat use remains limited, hindering the development of contemporary, multiaxial management strategies. The recent advent of satellite technology facilitates the investigation of vertical habitat use by pelagic sharks through the analysis of diving behaviours. Comparing temperature profiles and track analyses between shortfin mako (*Isurus oxyrinchus*), white (*Carcharodon carcharias*), and porbeagle (*Lamna nasus*) sharks tagged with pop-off satellite archival tags (PSATs) in Atlantic Canada indicates potential seasonal and species-specific characteristics of the local shark community. The explicit comparison of interspecific shark species distribution to understand the extent of their overlap on the vertical plane is novel, and vertical habitat characteristics such as preferred temperature and depth are rarely incorporated into vertical distribution and range using species distribution models (SDMs). Through developing an understanding of species-specific vertical habitat characteristics, depth-specific fisheries gear and bycatch mitigation regulations can be formulated to reduce the incidental capture of individual species instead of targeting sharks more broadly. In addition, periodically updating the Policy on Managing Bycatch to reflect contemporary data availability and establishing a centralized document outlining bycatch management for sharks beyond the implementation of recommendations by ICCAT are recommended paths to progress in the context shark conservation, bycatch mitigation, and species at risk recovery objectives in Canada.

Keywords: *sharks, conservation, vertical distribution, bycatch, management*

Acknowledgements

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Finally, I would like to thank my dad for sharing my fascination with sharks and always supporting my passion for pursuing research related to their conservation and management. My gratitude extends to my family and loved ones for their continued support throughout the duration of my academic and professional endeavours—I love you all.

With that, I offer my most sincere congratulations to the Master of Marine Management Cohort of 2022-23, as well as my best wishes as we conclude this chapter together.

Chapter 1: Introduction

1.1: Sharks & their Ecological Roles

Sharks are arguably among the world's most feared predators, and some of the most fascinating, indispensable, and threatened animals on Earth. Their presence in marine ecosystems—spanning over 400 million years—is not just a testament to their evolutionary success, but also to their ecological significance. Comprised of over 500 distinct species, these cartilaginous fishes play vital roles in maintaining the balance and overall health of ocean ecosystems through their predatory activities.

Large pelagic sharks exert top-down control on marine food webs (Heupal et al. 2014). They regulate prey populations and prevent the overconsumption of lower trophic levels, and events that affect shark populations can lead to cascading impacts on prey populations (ibid). At a global scale, their presence helps maintain biodiversity and encourages prey species to adapt and develop diverse defensive strategies; ultimately enhancing the overall diversity of marine life (Ganesh & Geetha 2017). In addition, recent studies suggest that sharks play critical roles in the cycling of marine nutrients by selectively preying on weaker individuals—a process that has broader implications for ecosystem productivity, trophic interactions, and nutrient availability on the whole (Williams et al. 2018).

Beyond their ecological roles, sharks also hold considerable economic importance (Shamir et al. 2019). Emerging research continues to highlight the growing significance of shark-based ecotourism, contributing to local economies and livelihoods (ibid). Moreover, the Mi'kmaq People of Mi'kma'ki have been documented throughout history to value sharks—or *siklati*—and their teeth specifically for cultural and ceremonial purposes (Mi'kmaw Kina'matnewey 2007). However, bycatch, overfishing, and the international shark fin trade continue to threaten their populations, which—due to low reproductive rates—exhibit low resilience to fishing mortality (Kyne et al. 2015).

Sharks are more than just apex predators; they are ecological linchpins in ocean ecosystems around the world with prominent roles in social, cultural, and economic proceedings. They have, however, remained among the most severely threatened marine animals for a number of years as high exploitation rates and low resilience to harvest have resulted in precipitous global declines (Dulvy et al. 2021).

In tandem with these high exploitation rates, sharks may be facing mounting pressures from climate change, which can result in a diverse array of modifications to their behaviour—forcing changes to normative mannerisms that have previously categorized species. These alterations might be expected to influence shark growth and reproduction rates, movement and feeding habits, and habitat distribution; potentially even resulting in local extinctions if differences in environmental conditions are dramatic (O'Brien et al. 2013). As multifaceted threats to global shark populations continue to increase, so too does concern among scientists, environmental conservation advocates, and the general public (Shiffman & Hammerschlag 2016). Despite differences in management and policy by nation regarding shark conservation and protection, there is a growing impetus to implement more effective strategies and mitigate the risk posed by anthropogenic activity to these animals.

1.2.1: Current Shark Management in Canada

Canada in particular has been deemed a leader in shark conservation due to the government's employment of numerous legislative tools adapted for this purpose (Sybersma 2015). These tools include international treaty obligations under the

Northeastern Atlantic Fisheries Organization (NAFO), the International Commission for the Conservation of Atlantic Tuna (ICCAT), and both federal and provincial mandates that include the Fisheries Act, both Pacific and Atlantic Fisheries Regulations, and the Coastal Fisheries Protection Act (ibid). Despite the prohibition of shark finning, implementing occasional season closures and gear restrictions, landing bans, and supporting international policy focused on conserving these animals, the status of several shark species found in Atlantic Canadian waters remains poor (COSEWIC 2021; Table 1)—indicating that the region has work to do yet to succeed in effective shark protection and management.

Table 1: Shark species listed in the Species at Risk Public Registry by the Government of Canada current as of the COSEWIC 2021 report (Atlantic species shown in bold).

Scientific Name	Legal Common Name	COSEWIC Status	SARA Schedule	Schedule Status	Species Range
Cetorhinus maximus	**Basking shark**	**Special Concern**	**No schedule**	**No Status**	**Atlantic Ocean**
Cetorhinus maximus	Basking shark	Endangered	Schedule 1	Endangered	BC, Pacific Ocean
Prionace glauca	**Blue shark**	**Not at Risk**	**No schedule**	**No Status**	**PEI, QC, NFLD, NB, NS, Atlantic Ocean**
Prionace glauca	Blue shark	Not at Risk	No schedule	No Statas	BC, Pacific Ocean
Hexanchus griseus	Bluntnose sixgill shark	Special Concern	Schedule 1	Special Concern	Pacific Ocean
Apristurus brunneus	Brown cat shark	Data Deficient	No schedule	No Status	Pacific Ocean
Lamna nasus	**Porbeagle**	**Endangered**	**No schedule**	**No Status**	**Atlantic Ocean**
Galeorhinus galeus	Tope	Special Concern	Schedule 1	Special Concern	BC, Pacific Ocean
Carcharodon carcharias	**White shark**	**Endangered**	**Schedule 1**	**Endangered**	**PEI, QC, NFLD, NB, NS, Atlantic Ocean**
Carcharodon carcharias	White shark	Data Deficient	No schedule	No Status	Pacific Ocean
Squalus suckleyi	North Pacific spiny dogfish	Special Concern	No schedule	No Status	Pacific Ocean
Squalus acanthias	**Spiny dogfish**	**Special Concern**	**No schedule**	**No Status**	**Atlantic Ocean**

Several national and international organizations collaborate to make recommendations on the conservation of shark populations within Canada's exclusive economic zone (EEZ) and management jurisdiction. Canada also subscribes to the Food and Agriculture Organization of the United Nation's (FAO) International Plan of Action on Sharks and Rays. Additionally, the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) reviews the status of potentially endangered wildlife and categorizes each species or population in terms of its relative abundance or health (Powles 2011). The Government of Canada then receives recommendations for possible action under the Species at Risk Act (SARA). If species or populations become listed under SARA, stringent measures must be taken to aid in their conservation. However, the government may elect *not* to list a species or population under SARA even if it has been assessed by COSEWIC. In such a case, existing legislation in the Fisheries Act, rather than the Species at Risk Act, is invoked so as to promote species or population conservation and recovery (Powles 2011).

Canada is a signatory to the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), a multilateral treaty to protect plants and animals from the threats of international trade (Cardeñosa et al. 2023). Permits are required for the import and export of specimens protected by CITES, whether they are dead or alive. Appendices I-III of the Convention are lists of species that have been designated various levels of protection from over-exploitation. Appendix II lists species that are not necessarily currently threatened with extinction but may be if their trade does not become closely and immediately controlled, and Appendix III lists species that are already protected by management regimes in individual countries, but that require international cooperation to control global trade and substantially influence conservation (Cardeñosa et al. 2023). In 2005, white shark was moved to CITES Appendix II from Appendix III, where it was listed in 2000 (Pacoureau et al. 2023). In 2014, porbeagle shark were also moved to Appendix II after their listing on Appendix III, also in 2000 (ibid). In addition to several other shark species, shortfin mako are also listed on Appendix II as of 2019 (Pacoureau et al. 2023).

Finally, the Atlantic Fishery Regulations (CRC 1985) detail landing restrictions and retention allowances for shark species in Canada. Currently, there are no licenses distributed for shark, and no shark species are currently targeted by Canadian commercial fishing fleets (ibid). Retaining shark bycatch captured through angling, handline, or longline effort is, in some cases, permitted, though there is a complete closure throughout the month of December (CRC 1985). The retainment of blue shark captured by rod and reel is permitted in the bluefin tuna fishery and there is no shark retention whatsoever permitted in the longline groundfish fleet (ibid). The groundfish otter trawl fishery was never permitted to retain shark, and in the pelagic longline fishery, only blue shark and dead porbeagle may be retained (CRC 1985).

1.2.2: Bycatch

Fishing methods and gears select imperfectly for fish and invertebrates, meaning that even if a fishery does not specifically target sharks, they can still be captured or killed as an unintended consequence (Molina & Cooke 2012). In some cases, this incidental catch—called bycatch—may be retained by the fishery, but often, it is returned to the sea where survival rates vary (ibid).

Regulatory bodies are aiming to address bycatch at an increasing rate, often in response to legal mandates to rebuild endangered, threatened, and protected species populations (Jubinville et al. 2022). Many commercial fisheries are also incentivized to reduce bycatch and other environmental impacts by eco-certification organizations such as the Marine Stewardship Council (MSC; ibid). Sharks are often highlighted as key species of international concern in terms of mitigating fisheries bycatch due to their limited population resilience, which is largely caused by their late maturity and low productivity (Jubinville et al. 2022).

In response to ongoing bycatch management challenges, the Government of Canada introduced the Policy for Managing Bycatch in 2013 under the Sustainable Fisheries Framework (SFF) to address the collateral impacts of commercial fishing (Jubinville et al. 2022). Though this policy tool was developed with the intention to guide Fisheries and Oceans Canada (DFO) in formulating ecosystem-based fisheries management plans with bycatch mitigation as a primary objective, bycatch continues to remain poorly understood and regulated (ibid). To date, there are no regional standards that govern fisheries observer coverage or discard monitoring on the east coast of Canada (Jubinville et al. 2022). Further, Canadian policy focuses predominantly on preventing landings in an attempt to reduce fishing mortality but does not specifically limit bycatch. For this reason, activities that reduce gear-shark interception rates and the incidental capture of sharks in non-target fisheries become paramount.

1.2.3: Horizontal Distribution

Movement ecology aims to understand both why animals move and what constrains their movement—ultimately shaping their life history and population dynamics (Hayes et al. 2016). Studying the movement ecology and ecophysiology of marine megafauna like sharks is critical to developing an understanding of how environmental stressors overlap with species distribution; ultimately affecting species behaviour (Favilla 2023).

Horizontal distribution data is an asset to ecological studies for a variety of reasons, especially in marine environments. Evaluating species commonness and abundance, investigating interspecific interactions and environmental response, and identifying suitable habitat are just some of the practical implications that can be extrapolated from where aquatic animals move—both horizontally across the surface of the earth and vertically into the depths of the sea (Murphy & Smith 2021). The vast majority of comparative studies by shark species, however, focus specifically on horizontal movements (Andrzejaczek et al. 2022). Despite habitat selection in accordance with species-specific thermal optima, feeding behaviors, and competitive interactions in sharks occurring across both horizontal *and* vertical planes, knowledge on diving behaviours and vertical habitat use remains limited (ibid; Mead et al. 2023).

Environmental conditions are considered predominant factors that shape pelagic shark distributions (Bangley et al. 2018). Water temperature and related characteristics of the water column, in particular are often used to describe suitable habitat and predict spatial use by marine animals (ibid). The distribution and range of a species relative to suitable habitat results from individual animal movement. This is to say that sharks choose where they remain, when they leave, and how far to travel relative to the environmental conditions they encounter at the individual level, moderated by previous experience and species-specific physiological requirements (Kubisch et al. 2014). The movement ecology of sharks, then, is a behavioural process that is closely associated with habitat selection (Matthysen 2012).

Previous studies have shown that the horizontal distribution of ectothermic marine predators is correlated with temperature preference and metabolism (Favilla 2023). However, the vertical dimension—where temperature, specifically, will influence metabolism, behaviour, and predation success—has yet to be fully integrated into the understanding of marine megafauna distributions and their ecological consequences (ibid). Sea surface temperature has traditionally been input into Species Distribution Models (SDMs) because this data was easily measured and accessible. Recent advancements, however, have facilitated the implementation of oceanographic reanalysis data products, which predict temperatures throughout the water column. These temperatures can now be compared with shark movements, and further elucidate associations between temperature and shark habitat (Russo et al. 2022).

1.3: Vertical Distribution

Temperature profiles, time at depth (TAD) and time at temperature (TAT) analyses, and consideration of the diving behaviour of sharks in Atlantic Canada are currently available in the literature. The explicit comparison of interspecific shark species distribution to understand the extent of their overlap on the vertical plane is, however, novel. Currently, there is only one study detailing global investigations of the species-specific vertical distribution of sharks (Andrzejaczek et al. 2022), and the description of vertical habitat characteristics such as preferred temperature and depth are very rarely incorporated into vertical distribution and range using SDMs.

Existing literature regarding the species distribution of sharks around the world predominantly focuses on the horizontal axis—or where and how shark species are moving on a global and regional geographic scale. Sharks, like birds, occupy a threedimensional environment, yet the vertical component of a shark's position in the water column is poorly understood. In order to understand the extent of their exposure to anthropogenic activities, knowledge not only of their horizontal distribution but their species-specific vertical distributions are vital (Andrzejaczek et al. 2022). Additionally, vertical movement data can help marine scientists and managers identify species-specific aggregations and expected overlap in the water column across space and time, which can then offer insight into potential similarities and differences between these species in terms of their respective behaviours, interactions, and realized overlap (ibid).

Depth distribution data can also help inform species' susceptibility to capture due to overlap between shark habitat and fishing gear, and when combined with research on gear characteristics and selectivity, vertical distribution can inform potential mitigation measures to reduce the bycatch of threatened species while maintaining and even promoting more efficient capture of target species (Cortés et al. 2020). As such, knowledge of species-specific vertical movement is vital to spatial management efforts such as the designation of special fisheries areas, marine protected areas, and marine parks and sanctuaries, as well as short term fisheries closures, for example, at established spawning grounds (Andrzejaczek et al. 2022).

Though the only existing global study of vertical shark distribution data did not focus on the Scotian Shelf and was instead situated predominantly across the North Pacific, Tropical Western Atlantic, Tropical Indo-Pacific, and Coastal Indian Ocean (Andrzejaczek et al. 2022), it is reasonable to expect the findings of this investigation to be relevant to Atlantic Canada as well. To this end, conclusions drawn from this global study regarding the typical species-specific behaviours of sharks as a result of their preferred depth distribution may have practical applications to the current management of sharks by the Government of Canada. The global study found that substantial vertical overlap occurred between many shark species inhabiting the open ocean from the surface to a depth of 200m and that vertical habitat usage by a series of globally threatened species was consistent across the study area—indicating similar vulnerabilities to fisheries and bycatch pressures (Andrzejaczek et al. 2022).

A better understanding of vertical habitat use may yield tractable alternatives to current policy that can further reduce mortality by changing the likelihood of capture in the first place. Diving behaviour gives sharks greater flexibility in habitat use compared to either bottom or surface-dwelling species. If components of the water column don't match an individual's physiological requirements, they can simply use less of the water column rather than having to move away from that location entirely. This may also be prompted by interspecies interactions—meaning that one species may prefer a certain depth due to the absence of other species at that depth. Conditions throughout the water column vary seasonally at the same location, and present different useable habitat seasonally through time—further arguing for the development of vertical distribution understanding among sharks so as to inform multiaxial management strategies.

1.4: Management Problem

Canada's Policy on Managing Bycatch within the SFF is only current to 2011 (Jubinville et al. 2022). Recent advancements in satellite tagging technologies have since provided scientists growing opportunities to resolve previously unknown elements of spatial ecology in marine predators like sharks, such as diving behaviours and vertical distribution (Hussey et al. 2015). This advancement facilitates access to new data that should be included in conservation and management of shark species—horizontal distribution data continues to dominate the conservation and management space.

Additionally, the effective management of bycatch species continues to be an issue in Canada. The nation's original tool for shark conservation and management—the National Plan of Action for the Conservation and Management of Sharks—was established in 2007 and became inapplicable when shark landings were prohibited. Other fisheries have Integrated Fisheries Management Plans that outline total allowable catch, quotas, and other management metrics, and some include shark-specific provisions, but these are often piecemeal and difficult to find. Moreover, there is no centralized document outlining bycatch management for sharks in Canada beyond the implementation of recommendations by ICCAT, and Government of Canada webpages outlining current shark conservation and management are largely defunct, yet still presented to the public as current.

To improve existing species at risk recovery and bycatch mitigation objectives with a particular application to COSEWIC-listed shark species in the Atlantic, the Government of Canada may consider periodically updating the Policy on Managing Bycatch to reflect contemporary data availability and act as a centralized source of information. Furthermore, the consideration of diving behaviours and water column usage may inform tractable management options that can reduce the likelihood of shark capture. By identifying seasonal or species-specific characteristics, overlap between sharks and fishing gear may be reduced—decreasing the probability that they will be captured as bycatch.

Chapter 2: Methodology

2.1: Satellite Tags & Data Collection

Recent advances in tracking technologies have allowed scientists to gain unprecedented insights into shark behaviour and movement patterns, providing invaluable data for conservation and management efforts (Hammerschlag et al. 2010). Pop-off satellite archival tags (PSATs) are programmed to release from tagged animals at a predetermined date and float to the surface of the ocean (Jepsen et al. 2015). They then transmit stored summary data to a satellite, and if they are physically recovered, their complete raw data record can be offloaded directly onto a computer. These tags record light, depth, and temperature information, and position data can be estimated from recorded light observations. Because of their size, PSATs are mainly used to study largescale movements of large pelagic fishes like sharks, and they are very useful for studying their temperature and depth preferences (Jepsen et al. 2015). These tags provide unbiased temperature and depth preferences, as surface conditions may not correlate with the temperature preferences of an animal who lives primarily at depth. To maximize data capture relative to anticipated behaviour, researchers can specify how depth and temperature information will be summarized for transmission to satellite.

In this study, shortfin mako (*Isurus oxyrinchus*), white (*Carcharodon carcharias*), and porbeagle (*Lamna* nasus) sharks were outfitted with external PSATs (Mk10-PAT, MiniPat; Wildlife Computers), anchored in the musculature below their dorsal fins. Tags were deployed on numerous research trips between 2012-2020, by the Canadian Atlantic Shark Research Laboratory of Fisheries and Oceans Canada. In total, 37 mako, 19 white, and 63 porbeagle sharks were tagged, of both female and male sexes. Tagged mako sharks range in size from 80-229 centimetres (fork length), white sharks from 270-459 centimetres (total length), and porbeagle sharks from 76-249 centimetres (fork length).

Aggregated data were downloaded from the Argos network and position estimates were generated using GPE3. The RchivalTag R package (Bauer 2023) was used to produce depth and temperature histograms and to interpolate the thermal conditions of the water column that were experiences by tagged animals.

Residency and behaviour estimates can be generated from movement data collected with PSATs (Pederson et al. 2011). A hidden Markov model (HMM) on a spatial grid in continuous time facilitates the estimation of location based entirely on environmental data, such as temperature and light—which are collected by deployed tags (ibid). The HMM computes the probability distribution of location and behaviour at individual points in time, and the behaviours of tagged animals can be associated with spatial zones, which can then indicate movement behaviours (Pederson et al. 2011).

2.2 Data Processing & Analysis

Comparative analyses were conducted in R (R Core Team 2022) from the PSAT data for shortfin mako, white shark, and porbeagle sharks. For all analyses, individual outputs from each tag were combined using the rowbind function in base R. Differences in date formats were standardized by converting datetime data from character to POSIXct format, which is a datatype designed to store date and time information as the number of seconds since January 1, 1970, at midnight UTC. POSIXct format can include fractional seconds to represent time with sub-second precision, and is, as such, commonly used for handling date and time information in a consistent and precise manner. The RchivalTag package was used to generate temperature profiles in addition to time-at-depth and time-at-temperature histograms for each species. Satellite tracks were plotted using the sf and raster R packages (Pebesma 2018; Hijmans 2023).

Table 2: Number of tagged sharks from which data was used for each analysis, by species.

	Shortfin Mako	**White**	**Porbeagle**
Temperature Profiles	21	14	36
Track Plots	15	14	39
TAD	20	12	17
TAT	20	7	17

2.2.1: Temperature Profiles

To facilitate a seasonal comparison of the conditions in the water column experienced by each species, the year in all date and timestamps in the PDT files was arbitrarily set to 2023 using the lubridate package in R (Grolemund & Wickham 2011). The average temperature at depth profile was interpolated and then visualized for all individuals of each species in aggregate. The interpolate function was then used on that output to return an average temperature at depth profile for all of the tagged sharks.

2.2.2: Track Analyses

Using a pipeline, facilitated by the dplyr package (Wickham et al. 2023), columns of interest for this analysis were selected from each individual data file (Tag ID, date, most likely latitude, most likely longitude). Data were categorized by month and a filter was applied to remove “NA” values., and the satellite tracks were then plotted on top of a bathymetry element, the North American land mass, and the Canadian EEZ.

First, the Canadian EEZ filter was downloaded from GitHub through Natural Resources Canada and unzipped. A shapefile of North America was also downloaded from Statistics Canada (2022) and loaded into R. The Coordinate Reference System for each object was transformed to identical values (EPSG code 2960). A polygon was then created to clip all layers to the same projections (X = -90, -90, -55, -55, Y = 23, 49. 49. 23).

Bathymetry data (resolution of 7510 metres in the x-direction and 9250 metres in the y-direction) from Bio Oracle was then read into R in the form of a raster layer (Tyberghein et al. 2011). A bounding box was created using the sf package to identify the geographical area of interest over which to lay the bathymetry element using the same coordinate reference system as the other objects. Finally, the bathymetry data was clipped to the same projection as the track data. The bathymetry data was then visualized in the form of a 200m contour line, which is used as a visual reference for coastal versus offshore areas when interpreting spatial distribution patterns. All data layers were plotted using the ggplot2 package (Wickham 2016).

2.2.3: Time at Depth & Time at Temperature Analyses

For white sharks, time at depth (TAD) and time at temperature (TAT) analyses were conducted using time-series data. A data filter was applied to remove rows with missing data. Using RchivalTag, TAD and TAT histograms were generated that demonstrate the percentage of the tag deployment that each shark spent within specific depth and temperature bins. For shortfin mako and porbeagle, the same process was completed histogram files instead of time-series data.

Chapter 3: Results

3.1: Temperature Profiles

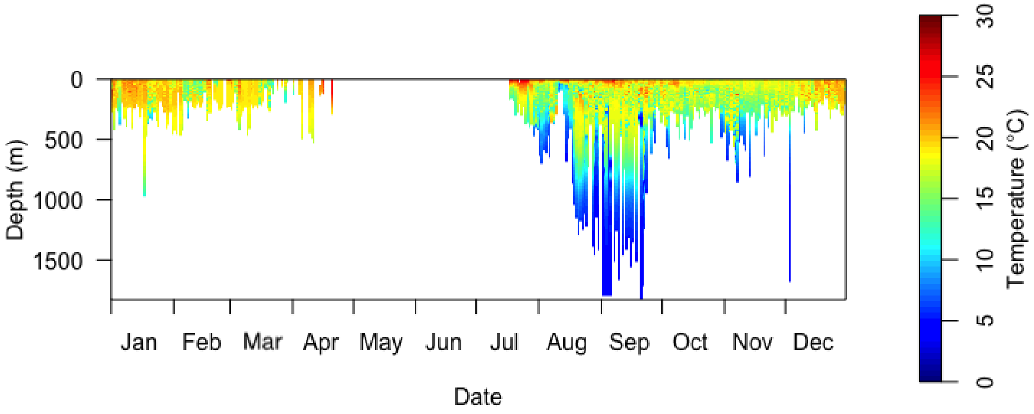

Figure 1: Temperature Profile for Shortfin Mako Shark (*Isurus oxyrinchus*).

Cooler temperatures were experienced when sharks dove to deeper depths in the summer months, rather than when they remained at the surface. Tagged shortfin mako in this study spent December-April/into May closer to the surface (<1000m) where temperatures seemed to consistently stay within a range of approximately 15-25°C (Figure 1). However, between August-October, shortfin mako exhibited deeper diving behaviour, descending to depths in excess of 1000m and surpassing even 1500m. At such depths, temperatures decreased to below 10°C. Gaps such as that pictured in this plot (i.e., no data between May-July) suggest that these particular tags did not collect or transmit data on dates within this range.

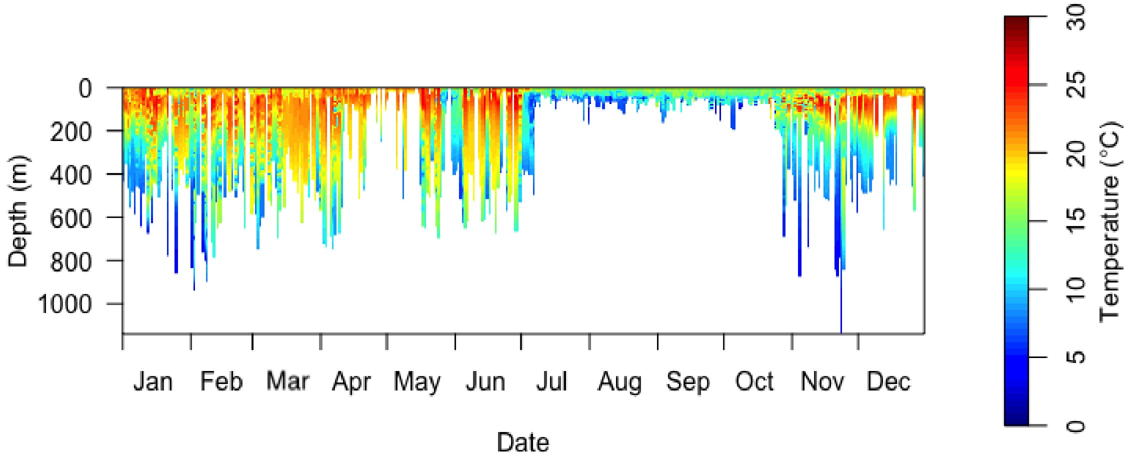

Figure 2: Temperature Profile for White Shark (*Carcharodon carcharias*).

It appears to be rare for tagged white sharks to descend beyond 1000m deep, preferring instead to remain in shallower habitat than shortfin mako (Figure 2). They seem to spend the majority of their time in water 800m deep or less, and at temperatures above 10°C. Between July and November, specifically, this species seems to linger nearer to the surface of the ocean, with the majority of their deeper dives occurring between December and June. White shark tended to remain in shallow habitats throughout the summer and dive deeper into the winter months (Figure 2), while shortfin mako exhibited the opposite behaviour—diving into deeper, cooler waters in the summer and remaining closer to the surface throughout the winter months (Figure 1).

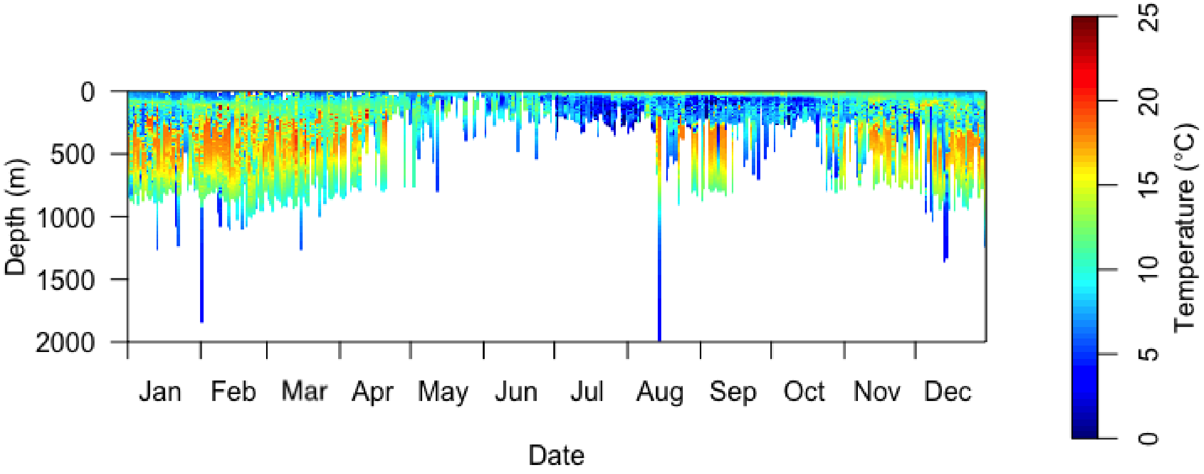

Figure 3: Temperature Profile for Porbeagle Shark (*Lamna nasus*).

Tagged porbeagles seem to have spent most of the time that they were tagged in water approximately 1000m deep, or less—consistently diving deeper and using cooler habitats than white sharks (Figure 3). The temperature range of the water in which they seem to have spent most of this time is approximately 10-20°C. The data does appear to show one individual diving to a depth of approximately 2000m, however, this is likely due to this individual sinking to this depth following its death, which its tag recorded. Between May and August, tagged porbeagle seemed to linger closer to the surface of the ocean in water less than 500m deep.

3.2: Track Analyses

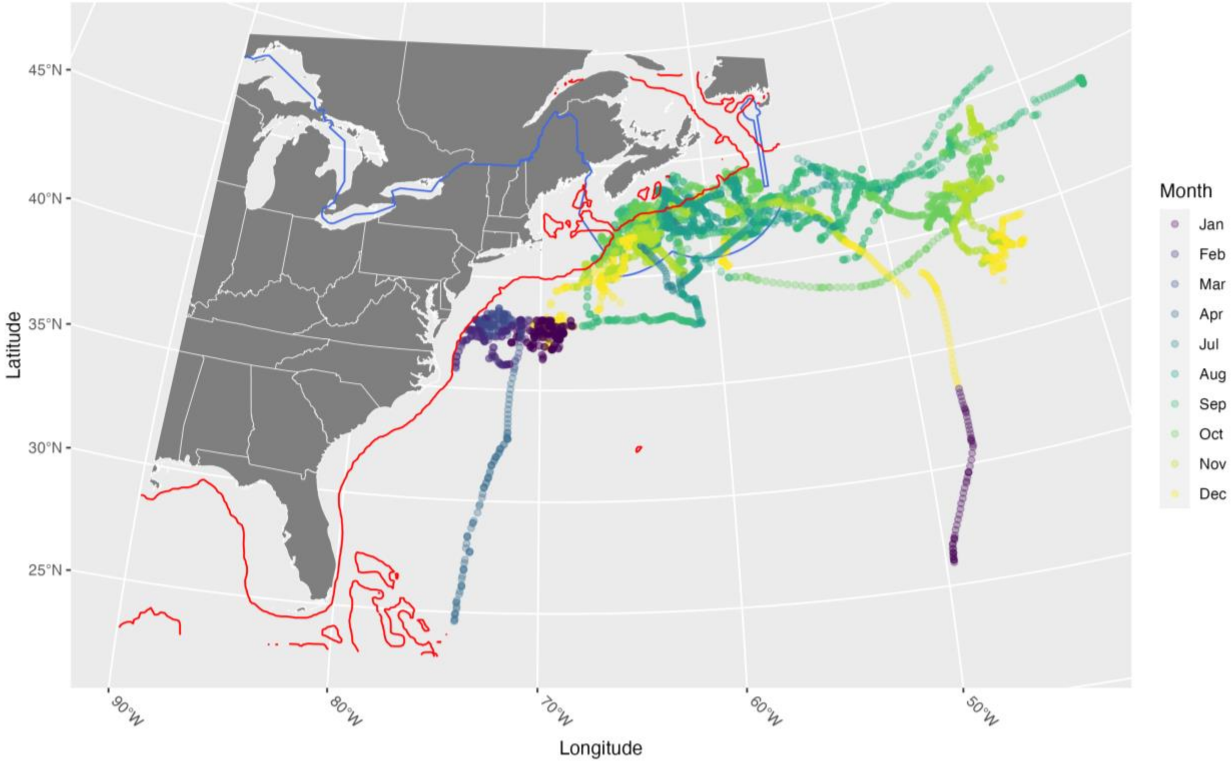

Figure 4: Track Plot for Shortfin Mako Shark *(Isurus oxyrinchus*). The Canadian EEZ is shown in blue and the 200-metre bathymetric contour in red. Data point colours show differentiation by month.

The majority of time spent by shortfin mako within the jurisdiction of the Canadian EEZ and in Atlantic Canada both occur during the months of July-December (Figure 4). These individuals seem to have spent the most time inshore between August and October, with an easternly shift to open ocean in December and January. Additionally occurring from January to March seems to be a southwest movement along the Eastern Seaboard to offshore waters near New Jersey and Delaware. One individual shows a trajectory toward The Bahamas in April, and more generally, there seems to be a north-easterly movement through the fall and winter.

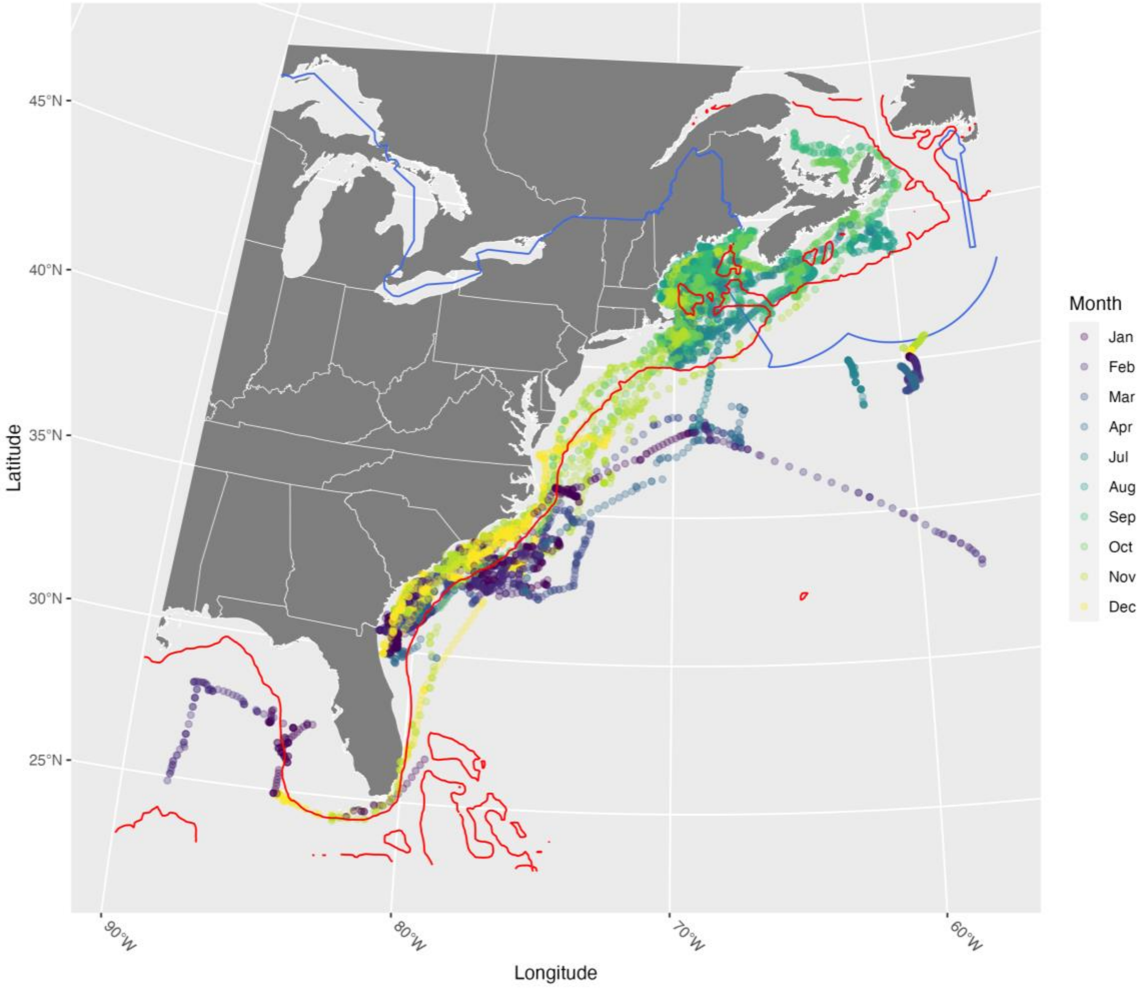

Figure 5: Track Plot for White Shark (*Carcharodon carcharias*). The Canadian EEZ is shown in blue and the 200-metre bathymetric contour in red. Data point colours show differentiation by month.

The white sharks in this study spent more of the time during which their tags were transmitting inshore than did shortfin mako (Figure 5). In fact, the majority of the time that the tags deployed on white sharks were observing data appears to have occurred in inshore waters as opposed to offshore. Moreover, these individuals seem to have travelled around Newfoundland and Labrador and northeast of Prince Edward Island. They appear to have spent the most time in Atlantic Canada during the months of July to October, quite far inshore. Then, from November to April, they seem to move down the southwest down the Eastern Seaboard relatively close to shore, with some individuals wrapping around Florida into the Gulf of Mexico. In one instance during February, a white shark travelled southeast into the open Atlantic Ocean. Generally, shortfin mako and white shark appear to spend more time inshore than porbeagle.

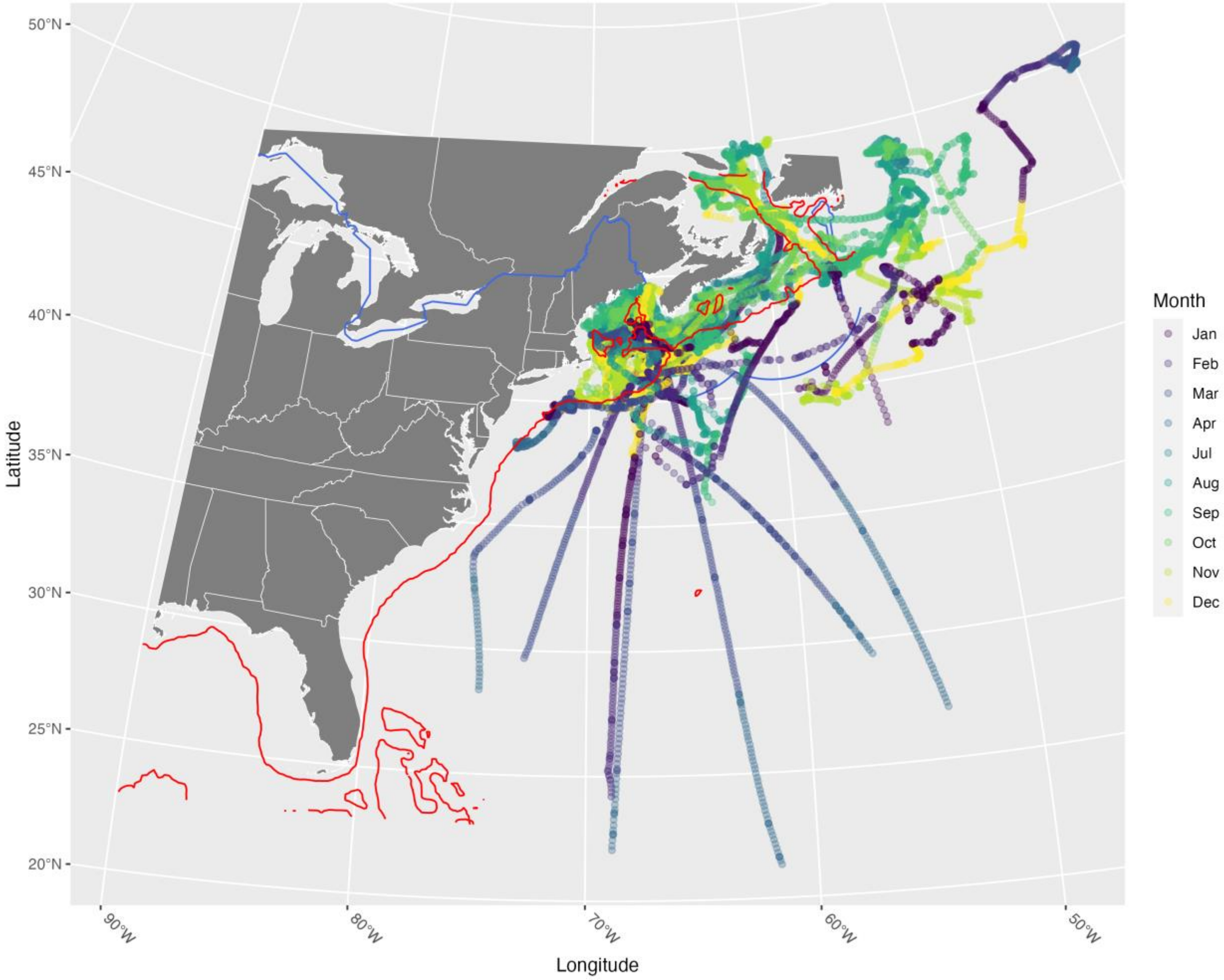

Figure 6: Track Plot for Porbeagle Shark *(Lamna nasus*). The Canadian EEZ is shown in blue and the 200-metre bathymetric contour in red. Data point colours show differentiation by month.

The range of the porbeagle sharks tagged in this study extends farther northeast than that of the shortfin mako and the white shark (Figure 6). Their travels appear to extend more northwesterly of Nova Scotia and the Canadian Maritime Provinces up into Baffin Bay off the coasts of Nunavut and Greenland. Moreover, the porbeagle seems to have a more year-round distribution across Atlantic Canada with individuals from all seasons making appearances in this region. The months with the greatest concentration of porbeagle tag transmissions within Atlantic Canada and the Canadian EEZ, however, seem to be July to November and into December. Finally, the tagged porbeagle seem to travel farther southeast into the open Atlantic Ocean during January to April rather than hugging the Eastern Seaboard like their two counterparts.

3.3: Time at Depth & Time at Temperature Analyses

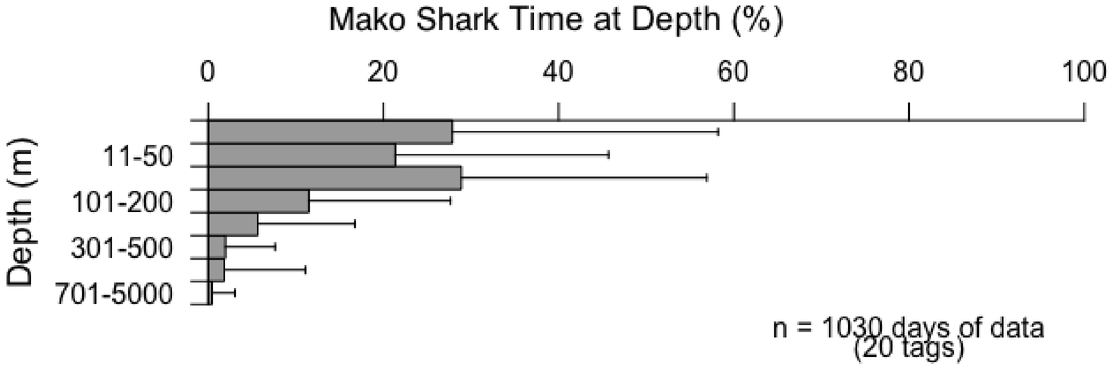

Figure 7: Time at Depth Histogram for Shortfin Mako Shark (*Isurus oxyrinchus*) showing the percent duration of tag deployments that tagged animals spent in specific depth bins.

Nearly 30% of the 20 tag deployments visualized with this data over 1030 days were spent at 0-11m and 50-100m depths, with just over 20% of the deployment time being spent at depths between 11-50m (Figure 7). <20% of total time was spent at depths >101m throughout tag deployment. This plot indicates that the shortfin mako sharks from which this data was collected seem to spend the majority of their time relatively close to the surface (<101m), though they do exhibit diving behaviour to depths >700m.

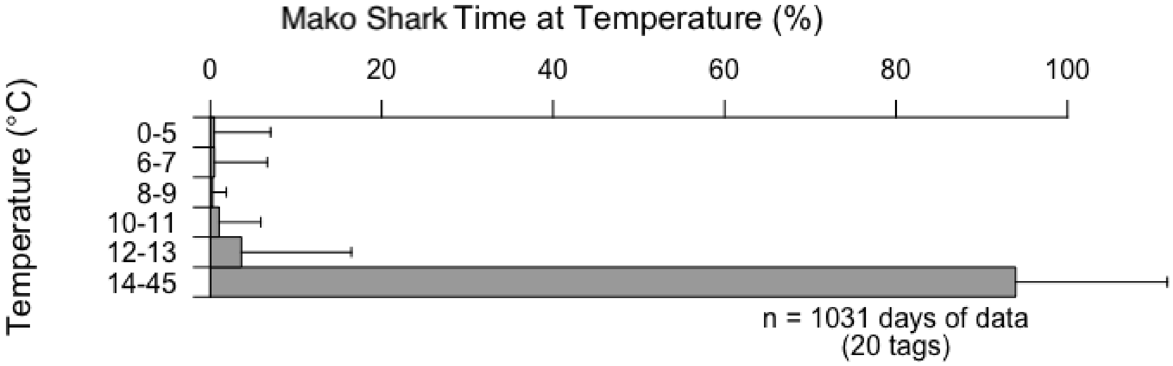

Figure 8: Time at Temperature Histogram for Shortfin Mako Shark (*Isurus oxyrinchus*) showing the percent duration of tag deployments that tagged animals spent in specific temperature bins.

Nearly 95% of the 20 tag deployments visualized with this data over 1031 days were spent at temperatures >14°C, with <5% of time spent at 12-13°C (Figure 8). Less than 5% of overall tag deployment duration was spent at temperatures <10°C. This plot indicates that the shortfin mako sharks from which this data was collected seem to spend the majority of their time >14°C, however, the range of the final temperature bin in this particular analysis is very broad and limits the accuracy of this thermal preference analysis in this species.

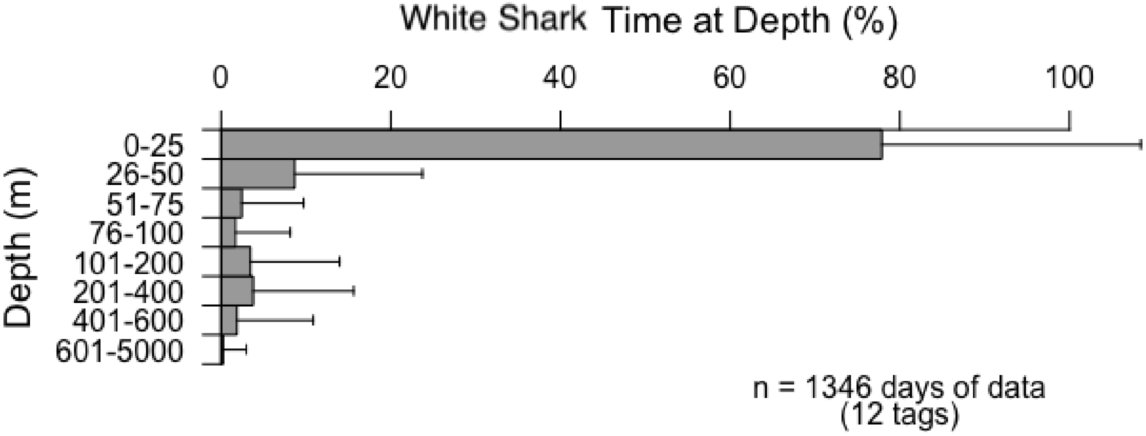

Figure 9: Time at Depth Histogram for White Shark (*Carcharodon carcharias*) showing the percent duration of tag deployments that tagged animals spent in specific depth bins.

Nearly 80% of the 12 tag deployments visualized with this data over 1346 days were spent at 0-25m depth, with <10% of the deployment time being spent at depths between 26-50m and <5% at depths that exceed 50m (Figure 9). This plot indicates that the white sharks from which this data was collected seem to spend the majority of their time relatively close to the surface, though they do exhibit diving behaviour to depths >600m. White sharks seem to spend the greatest amount of time at the shallowest depth between these three species.

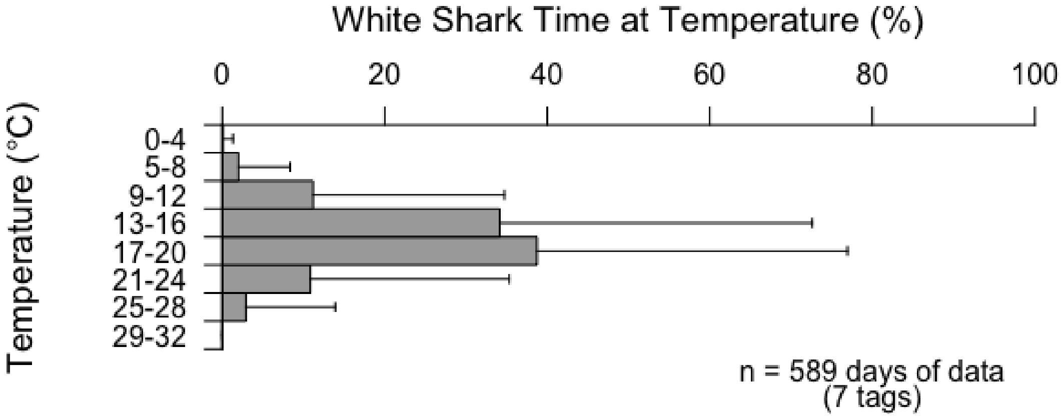

Figure 10: Time at Temperature Histogram for White Shark (*Carcharodon carcharias*) showing the percent duration of tag deployments that tagged animals spent in specific temperature bins.

Nearly 40% of the 7 tag deployments visualized with this data over 589 days were spent at temperatures between 17-20°C, with slightly less time being spent at 13-16°C (Figure 10). Approximately 10% of tag deployment was spent at 9-12°C and 21-24°C respectively, and <5% at 5-8° and 25-28°C. This plot indicates that the white sharks from which this data was collected seem to spend the majority of their time between 13-20°C, though they do exhibit a broad thermal range and tolerate temperatures from 5-28°C.

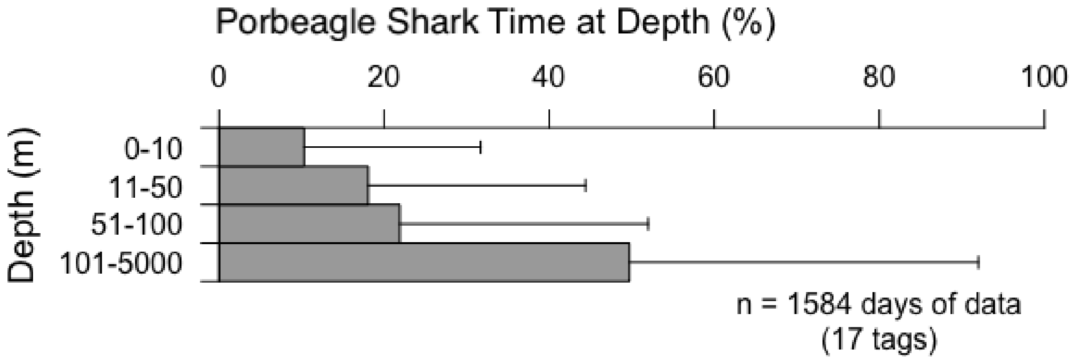

Figure 11: Time at Depth Histogram for Porbeagle Shark *(Lamna nasus*) showing the percent duration of tag deployments that tagged animals spent in specific depth bins.

Nearly 50% of the 17 tag deployments visualized with this data over 1584 days were spent at a depth of greater than 100m, with just over 20% of the deployment time being spent at depths between 51-100m and <20% at depths less than 50m (Figure 11). This plot indicates that the porbeagle sharks from which this data was collected seem to spend the majority of their time >100m, though they do travel as close to <10m from the surface. Porbeagle appear to have spent the greatest amount of time at the greatest depths between these three species.

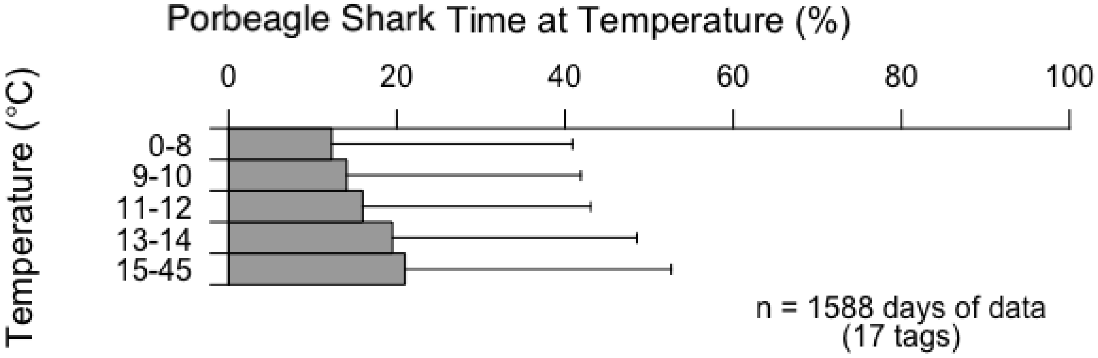

Figure 12: Time at Temperature Histogram for Porbeagle Shark *(Lamna nasus*) showing the percent duration of tag deployments that tagged animals spent in specific temperature bins.

Approximately 20% of the 17 tag deployments visualized with this data over 1588 days were spent at temperatures of 15°C or greater, with slightly less time being spent at 13-14°C (Figure 12). Approximately 10% of tag deployment was spent at 0-8°C and 15%, at 11-12°C respectively, with the remaining time being spent between 9-10°. This plot indicates that the porbeagle sharks from which this data was collected seem to spend the majority of their time at temperatures >15°C, though they do tolerate temperatures as low as <8°.

Chapter 4: Discussion & Management Approach

4.1: Discussion

General community structure and environmental factors like water temperature and food availability influence where sharks move and how long they remain at specific locations (Matthysen 2012). Given that shortfin mako remained much farther offshore during the months when white sharks travel to Canadian waters, the satellite data suggest seasonal habitat separation among these two species on both the horizontal and vertical axes. This is corroborated by their diving behaviours, which appear to show white shark and mako inhabiting deeper, cooler waters and warmer, shallower depths respectively during opposite seasons to one another. Furthermore, the satellite data suggest that porbeagle consistently use deeper, cooler habitat than white shark—indicating habitat separation between these species as well.

By incorporating water column use and diving behaviours into existing SDMs and migration patterns, tractable management options to further reduce shark mortality may be developed. The depth of gear deployment varies with target species (Gilman et al. 2023) and could be regulated differently in coastal as opposed to offshore areas to reduce the risk of overlap with sharks. By identifying the interspecific vertical habitat characteristics of various shark species in Atlantic Canada, which also differs by season, fisheries gear and bycatch mitigation regulations can be made specific to depth. This is likely to better reduce overlap between fishing gear and individual shark species compared to the current, more generalized approach wherein bycatch mitigation objectives are to reduce the incidental capture of “sharks” collectively (Cortés et al. 2020).

Conservation efforts in the North Atlantic have largely moved away from the measures outlined in the National Plan of Action on the Conservation and Management of Sharks (current to 2007) following the prohibition of pelagic shark landings and cessation of commercial shark licenses in Canada (Mucientes et al. 2023). However, several species are still listed by the IUCN, SARA, and COSEWIC. The need persists to maintain current conservation measures, develop contemporary strategies that consider contemporary data, and to monitor and reduce bycatch captures (ibid). One of the ways that decision-makers and managers may minimize the amount of incidental shark catch is to reduce the spatial overlap of sharks and fishing activities. Though spatial overlap alone does not imply threat, gear type, catch susceptibility, and handling measures may. It is for this reason that management requires a delicate balance of maximizing target efficiency with minimizing mortality rates for non-target species.

Increased collaboration between organizations involved in the management of highly migratory shark species has also been recommended by other researchers so as to develop data collection opportunities, data inclusivity, assessment robustness, and clarity for managers and scientists, alike (Haugen et al. 2022). Moreover, previous studies, in addition to this one, demonstrate the need for an interdisciplinary approach to shark management and conservation as no isolated, singular approach is typically effective (ibid). The differences in space use by the species in this study are a testament to the fact that no one approach is unilaterally effective to conserve “sharks”; instead, species-specific strategies like depth-oriented regulations must be implemented to effectively reduce capture probability. Additionally, there is value in using multiple tag types (sometimes, PSAT and acoustic both on one shark, for example) to track long-term movements (Franks et al. 2021).

While this study provides valuable insights, it is essential to recognize its limitations. A limited sample size of tagged individuals was examined throughout the included analyses, and future research should endeavour to further expand the dataset. Furthermore, more information may be garnered from the TAD/TAT analyses with the re-binning of the data so as to show more specific depth and temperature ranges. Specifically in the TAT analysis for shortfin mako, a large proportion of the data is contained within the same bin, which demonstrates a large and relatively unspecific temperature range.

4.2: Management Options

4.2.1: Bycatch Management

Canada's federal policy on managing bycatch aims to reduce the capture of non-target species in fisheries as well as mitigate waste and discards within the industry, with no centralized information regarding current efforts to reduce the incidental capture of sharks.

New Zealand has adopted their own National Plan of Action for the Conservation and Management of Sharks per the International Plan of Action developed by the FAO (Fisheries New Zealand 2022). In their NPoA, New Zealand identifies specific management objectives that include the development of regional governance capacity, initiating a research programme that identifies, monitors, and mitigates an array of adverse anthropogenic impacts that affect sharks, and mandates a continued effort to improve data collection and information sharing of commercial catches and incidental bycatch (Fisheries New Zealand 2022). Included as "adverse anthropogenic effects other than fishing on shark populations" are chronic disturbances from vessel operation, habitat loss due to human activity, litter and marine debris, mining, and global climate change (ibid).

Compared to Canada, New Zealand adopts a much more holistic approach in their management objectives. Canada tends to separate target catch, bycatch, international management, and national species at risk. The model implemented by New Zealand may offer an interesting template for Canada to harmonize ongoing shark management efforts under SARA with objectives under the bycatch policy—while consolidating this information in one, accessible location.

Chapter 5: Conclusion & Management Plan

The impetus for improved shark conservation and management strategies around the world continues to intensify with mounting ecological pressures that result from overexploitation, international fisheries and bycatch, climate change, and marine habitat degradation (Dulvy et al. 2021). Nearly one third of global shark species are threatened with extinction, and coastal communities around the world rely on the ocean for carbon sequestration, oxygen production, livelihoods, food security, and economic stimulus (Andrzejaczek et al. 2022; Delgado-Ramírez 2022). The importance of effective marine management in this eleventh hour is, then, paramount.

While national policy has led to the prohibition of shark finning and the import and export of shark fins as well as numerous restrictions on pelagic shark landings, the SARA and COSEWIC statuses of sharks found in Atlantic Canada continue to remain bleak—for some, even after 19+ years (i.e., porbeagle listed in 2004). Canada's current management strategies align with international agreements due to federal commitments, such as signatory status to the ICCAT Regulations, however, the national policy on managing bycatch—specifically in the context of sharks—must be improved to avert additional shark population declines.

The policy for managing bycatch—nested within the national SFF—was established nearly a decade ago when vertical distribution data was not readily available. This information does not incorporate mitigation measures derived from contemporary understandings of animal movement on the vertical plane, which can contribute to improved habitat characterization in SDMs. Additionally, current shark management and bycatch mitigation provisions included in integrated fisheries management plans for various Canadian commercial fisheries are piecemeal and inaccessible. To improve the efficacy of species at risk recovery initiatives and bycatch mitigation measures in the context of Canadian shark management, it is recommended that the federal government a) adopt species-specific bycatch mitigation provisions informed by interspecific vertical habitat characterization to effectively reduce capture probability and b) consolidate management efforts in a centralized and accessible document, which should undergo periodic updates. It should be noted that the development of bycatch mitigation provisions in cooperation with fisheries may promote compliance with associated management changes and regulations.

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