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Evaluating the Effectiveness of Large-Scale Marine Reserves on Wide-Ranging Sharks: A Case Study of the Cook Islands Shark Sanctuary

PhD thesis submitted by
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For Dr. Budalar S. Thyagarajan (1929-2020): beloved professor, mentor, and friend.

"There is no comparison between that which is lost by not succeeding and that which is lost by not trying."

-Sir Francis Bacon

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Publications related to thesis

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Abstract

Oceanic shark populations have declined 77% over the past 50 years as a result of overexploitation in fisheries. While protective measures for sharks have increased in the past 20 years, the persistent downward trajectory of many species means that current protection levels are inadequate and sustainable shark management is limited to a few developed nations that have the capacity to implement sophisticated fisheries management. Developing nations are limited by a lack of funding, data, and capacity, which has resulted in the widespread use of spatial management to address shark conservation due to relative ease of implementation. These spatial approaches include marine protected areas (MPAs) and bans on commercial retention of sharks across exclusive economic zones (EEZs), defined as shark sanctuaries. Globally, shark sanctuaries cover 19 million km^2 of ocean, or about 5% of the world's oceans, with 88% of the global sanctuary area in the waters of Pacific Island nations. Although shark sanctuaries ban the retention of sharks by fishing vessels, they do not ban fishing; rather they change the fate of hooked sharks by requiring their release. Some sanctuary nations have provisions that exempt coastal fishers, meaning that the de facto focus of sanctuaries is on protection of sharks interacting with industrial vessels. Those sharks are typically wide ranging, capable of migrating long distances, meaning they might move beyond sanctuary boundaries. Despite the widespread coverage of sanctuaries, no study has used a multidisciplinary approach to evaluate the effectiveness of sanctuaries for the wide-ranging species they are meant to protect.

This thesis investigated the effectiveness of shark sanctuaries on wide-ranging sharks, using a case study in the Cook Islands, which declared its EEZ a shark sanctuary, covering 1.997 million km^2, in 2012. Evaluating conservation and management policy effectiveness for migratory species requires a multidisciplinary approach. Therefore, each chapter in the thesis focused on a different aspect of sanctuary effectiveness, including analysis of global and regional policies that affect sharks in the Cook Islands. The thesis had four main objectives: (1) to identify gaps and inconsistencies in global shark policies that can preclude mortality reduction in wide-ranging species; (2) to identify habitat linkages between pelagic (wide-ranging) and reef-associated sharks, and identify the predictors of shark abundance in areas that are fished by local vessels; (3) to understand whether implementation of the Cook Islands Sanctuary led to changes in

industrial fishing behavior, and (4) to examine movement ecology of wide-ranging sharks associated with industrial fisheries to determine benefits derived from the Cook Islands Shark Sanctuary.

Policy interventions for sharks and their relatives have expanded significantly over the past twenty years. Thesis Chapter 2 examined current international and regional conservation and management policies for sharks and their relatives and highlighted gaps and inconsistencies in the underlying definitions and protective measures upon which policies rely for success. Policy analyses found that critical definitions were vague or missing from global and regional policies intended to protect sharks from fishing and trade, leaving room for political interference. While a lack of implementation has been highlighted by others, this new analysis found missing definitions contributed to the lack of clarity and prescription in policies, which made them more difficult to implement, and therefore less likely to produce the intended conservation results for elasmobranchs.

In Chapter 3, which addressed the second aim, the presence of a shark sanctuary was found to be a significant factor in predicting higher abundance of reef sharks in Pacific Island nations, including the Cook Islands. Reef elasmobranchs (sharks and rays) are often managed at national and local scales because of restricted movements, but the scarcity of baseline data hinders effective conservation and management. To establish locally relevant baselines, reef elasmobranch abundance was examined using Baited Remote Underwater Video Station (BRUVS) deployments across 18 nations across the western and central Pacific Ocean. A total of 7,065 individual elasmobranchs were recorded, comprising 42 species. No elasmobranchs were observed on 24% of deployments. Surveys revealed the three most abundant shark species, Grey Reef Sharks (*Carcharhinus amblyrhynchos*)*,* Blacktip Reef Sharks (*Carcharhinus melanopterus*)*,* Whitetip Reef Sharks (*Triaenodon obesus*), and showed that their relative abundance related to minimum monthly sea surface temperature with highest abundances in warmer waters. The presence of a shark sanctuary was a positive influence on abundance for all species except *T. obesus*.

Chapter 4 addressed the third aim by exploring fishery catch records from longline and purse seine vessels before and after the Sanctuary implementation. No reductions were apparent in the number of sharks captured by vessels in the years following sanctuary implementation, however a peak in retention coincided with sanctuary announcement in 2012. Shark retention decreased in logbook and observer records of the longline dataset, indicating a change in fisher behavior following implementation of the shark sanctuary regulations that likely reduced shark mortality in Cook Islands waters. This behavior change likely resulted in a substantial mortality reduction for animals released in good condition. However, scarcity of data in the purse seine records did not support a strong conclusion of decreased shark retention, therefore, better reporting is required to assess the extent of impacts of the Sanctuary implementation on fisher behavior in all fisheries.

Despite the potential benefits of decreased fishery retention, the wide-ranging movements of pelagic species means they might move quickly beyond the sanctuary border into unprotected waters. The dispersal ability of species raises questions about whether sanctuaries can be effective in affording protection to wide-ranging, oceanic sharks. The fourth and final aim of this thesis examined this issue through tracking the movements of three pelagic species. Results indicated the Sanctuary offered benefits to two of the three species, Oceanic Whitetip Sharks (*Carcharhinus longimanus*) and Silky Sharks (*Carcharhinus falciformis*), but likely provided minimal benefits to Blue Sharks (*Prionace glauca*). The activity spaces of Blue Sharks were primarily outside Cook Islands waters. While the time and activity spaces of Oceanic Whitetip and Silky Sharks were primarily inside the Cook Islands EEZ, all species overlapped with unprotected waters, including the high seas. These combined results suggest sanctuaries likely provide benefit to wide-ranging species whose movements are primarily restricted to sanctuary waters. Neighboring sanctuaries provide an opportunity for greater protections, but implementing uniformity in sanctuary regulations between countries would increase benefits to sharks. However, because movements of wide-ranging sharks span high seas and non-sanctuary countries, additional conservation and management tools need to be employed to protect these sharks.

The combination of results across the multiple dimensions explored in this thesis provides a unique and comprehensive perspective on the efficacy of the Cook Islands Shark Sanctuary. Overall, an adapted systematic conservation planning approach (SCP) is necessary to close loopholes and gaps found in shark conservation policy, including measures that will specifically reduce interactions with fishing vessels and increase survival of sharks following capture. Particularly, because of the extensive shark movements between neighboring EEZs and the high seas, regulations in these areas are necessary for effective conservation of wide-ranging species. Specifically, uniformity in sanctuary regulations between the Cook Islands and neighboring sanctuaries could strengthen protections and promote implementation because fishing standards regarding sharks would be uniform across jurisdictions. Additional research is necessary to elucidate measures that reduce shark capture and increase post-capture survival, such as operational-level fishing methods or gear modifications, funding, and habitats of importance. The political will of sanctuary nations like the Cook Islands could be leveraged to strengthen data collection, trial methods or techniques that would result in policy changes to promote stronger conservation outcomes for wide-ranging sharks.

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List of Acronyms

AIC	Akaike Information Criterion
AIS	Automatic identification system
ANOVA	Analysis of variance
BRUVS	Baited Remote Underwater Video Station
BSH	Blue Shark
CBD	Convention on Biological Diversity
CCAMLR	Commission for the Conservation of Antarctic Marine Living Resources
CCBSP	Convention on the Conservation and Management of Pollock Resources in the Central Bering Sea
CITES	Convention for the International Trade in Endangered Species of Wild Flora and Fauna
CMS	Convention for the Conservation of Migratory Species of Wild Animals
CR	Critically endangered
DD	Data deficient
EEZ	Exclusive economic zone
EN	Endangered
FAD	Fish aggregating device
FAO	Food and Agriculture Organization of the United Nations
FEI	Fishing exposure index
GFCM	General Fisheries Commission for the Mediterranean
GFW	Global Fishing Watch
IATTC	Inter-American Tropical Tuna Commission
ICCAT	International Convention for the Conservation of Atlantic Tunas
IPHC	International Pacific Halibut Commission
IUCN	International Union for the Conservation of Nature
KUD	Kernel Utilization Distribution
LC	Least concern
MMR	Ministry of Marine Resources, Cook Islands Government
MPA	Marine Protected Area
NAFO	Northwest Atlantic Fisheries Organization

NASCO	North Atlantic Salmon Conservation Organization
NEAFC	North East Atlantic Fisheries Commission
NGO	Non-government organization
NOAA	National Oceanic and Atmospheric Administration
NT	Near threatened
OCS	Oceanic Whitetip Shark
PSC	Pacific Salmon Commission
RFMO	Regional Fisheries Management Organization
SCP	Systematic conservation planning
SEAFO	South East Atlantic Fisheries Organization
SIL	Silky Shark
SIOFA	South Indian Ocean Fisheries Agreement
SPC	Secretariat of the Pacific Community
SPRFMO	South Pacific Regional Fisheries Management Organization
SST	Sea surface temperature
UN	United Nations
UNCLOS	United Nations Convention on the Law of the Sea
VIF	Variance inflation factor
VU	Vulnerable
WCPFC	Western and Central Pacific Fisheries Commission

Chapter 1:

General Introduction

1.1. Global issues for sharks:

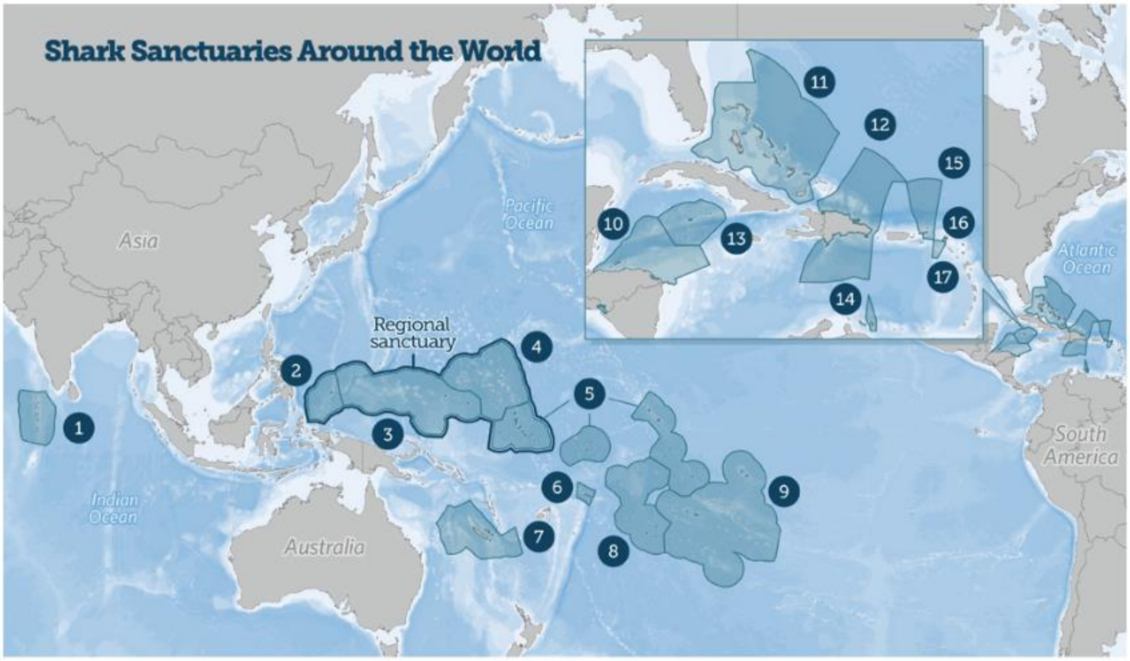
The global demand for elasmobranch (sharks and rays) parts, including fins, meat, liver oil, and gill plates, is driving the overexploitation of these fishes (Bräutigam et al. 2015; Dent & Clarke 2015). Relative to other marine taxa, elasmobranchs are long-lived, slow growing, and produce few offspring, life-history traits that make them vulnerable to overexploitation (Cortés 2000). Fisheries are the primary driver of excessive mortality in elasmobranchs as a result of both targeted capture and bycatch, or incidental capture (Stevens et al. 2000; Ferretti et al. 2010; Worm et al. 2013; Clarke et al. 2014). As a result, over 33% of all elasmobranch species are threatened with extinction (Dulvy et al. 2014; IUCN 2019), including a 77% decline in wide-ranging oceanic sharks in the past 50 years (Pacoureau et al. 2021).

To address the high levels of extinction risk in elasmobranchs, effort is required to reduce overexploitation in fisheries. Current interventions to reduce overexploitation occur primarily through fisheries-specific policy enacted at multiple scales. Global, regional and national level policy interventions, when implemented, often result in conservation and management approaches seeking to reduce fishing mortality by changing fisher behavior. These approaches incorporate a wide range of actions including: formal calls for cooperation, creation of multilateral conservation agreements, gear restrictions, size limits, catch limits, safe release guidelines for elasmobranchs, and banning retention of individual species or products (e.g. shark fins) (Shiffman & Hammerschlag 2015; Booth et al. 2019, 2020). As a result of the international trade in elasmobranch parts, trade-specific interventions (e.g. Convention for the International Trade in Endangered Species of Wild Flora and Fauna, CITES), including species-specific trade bans, are applied in conjunction with fisheries interventions. Policies work to conserve populations of threatened species, but also to provide a basis for sustainable shark fishing for certain species, so elasmobranchs can continue to meet food security and livelihood needs, particularly in developing countries (Jaiteh et al. 2016; Simpfendorfer & Dulvy 2017). Additionally, policies and resultant management measures might seek to limit fishing or trade through spatial management. Policies include time-area closures that restrict vessel access across a region, or national-level spatial protections that range from limited or no fishing areas, to no-take marine reserves, and shark sanctuaries, which are classified as bans on the targeting and retention of sharks throughout a nation's exclusive economic zone (EEZ) (Ward-Paige 2017).

1.2. Shark sanctuaries:

Shark sanctuaries gained popularity following the 2009 announcement of Palau's shark sanctuary, growing to 17 sanctuaries covering over 19.4 million km^2 by 2018 (The Pew Charitable Trusts 2018) (Figure 1.1). The majority of sanctuary countries are in the western and central Pacific Ocean, where EEZs are large and industrial and subsistence shark fishing and consumption was historically low. Despite the low levels of shark take, nations that enacted sanctuaries aimed to stop the overexploitation of sharks, including the Cook Islands, who also enacted a sanctuary as a salute to the pre-colonial importance of sharks in Polynesia (Revkin 2013; Torrente et al. 2018; Puniwai 2020). Protection levels within shark sanctuaries vary, and can include protections for rays, possession and transshipment bans, and exemptions for local fishers, among other rules (Ward-Paige 2017; Cramp et al. 2018). While national-level species retention bans exist in a number of nations and states (Humane Society International 2015), they are generally not recognized as shark sanctuaries unless they protect all sharks.

Evaluations of sanctuary effectiveness are limited to examinations in policy differences between sanctuaries (Ward-Paige 2017; Cramp et al. 2018), examinations of commercial catch records for targeting practices and estimations of mortality rates in Palau's shark sanctuary (Gilman et al. 2016a), and space of use reef-associated sharks inside of the Bahamas' shark sanctuary (Gallagher et al. 2021). However, shark sanctuaries do not stop fishing effort inside of EEZs, but change the fate of sharks once hooked by requiring release. Consequently, evaluating effectiveness of an individual sanctuary requires combining individual studies into a multi-dimensional approach that includes whether the sanctuary changes catch or alters fisher behavior, understanding how animals move across sanctuary boundaries, and calculating the risk of capture by fishing inside of sanctuaries.



1.	Maldives	916,189 sq. km. (353,742 sq. mi.)	Established 2010
2.	Palau	604,289 sq. km. (233,317 sq. mi.)	Established 2009
3.	Federated States of Micronesia	2,992,597 sq. km. (1,155,448 sq. mi.)	Established 2015
4.	Marshall Islands	1,992,232 sq. km. (769,205 sq. mi.)	Established 2011
5.	Kiribati	3,437,132 sq. km. (1,327,084 sq. mi.)	Established 2015
6.	Samoa	128,000 sq.km. (49,421 sq.mi.)	Established 2018
7.	New Caledonia	1,245,000 sq. km. (480,697 sq. mi.)	Established 2013
8.	Cook Islands	1,960,135 sq. km. (756,812 sq. mi.)	Established 2012
9.	French Polynesia	4,767,242 sq. km. (1,840,642 sq. mi.)	Established 2012
10.	Honduras	240,240 sq. km. (92,757 sq. mi.)	Established 2011
11.	The Bahamas	629,293 sq. km. (242,971 sq. mi.)	Established 2011
12.	Dominican Republic	269,489 sq. km. (104,050 sq. mi.)	Established 2017
13.	Cayman Islands	119,134 sq. km. (45,998 sq. mi.)	Established 2015
14.	Bonaire	9,706 sq. km. (3,747 sq. mi.)	Established 2015
15.	British Virgin Islands	80,117 sq. km. (30,933 sq. mi.)	Established 2014
16.	St. Maarten	499 sq. km. (193 sq. mi.)	Established 2016
17.	Saba	8,033 sq. km. (3,102 sq. mi.)	Established 2015

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Figure 1.1: Map of shark sanctuaries established between 2009-2018, including year of establishment and sizes of individual EEZs. Map courtesy of the Pew Charitable Trusts.

1.3. Cook Islands Shark Sanctuary:

The Cook Islands are a self-governing nation in free association with New Zealand, made up of 15 islands spread across 1.997 million km^2 of the South Pacific Ocean (Cook Islands Government 2001)(Figure 1.2). Approximately 17,000 people inhabit 13 of the islands where tourism accounts for >70% of the gross domestic product (GDP) and fisheries <3% (Ministry of Finance and Economic Management Cook Islands Government 2019). Fisheries in the Cook Islands include industrial longline and purse seine fishing for tuna and billfish, local commercial fishing and artisanal or subsistence fishing (Gillett 2016; MMR 2019). More than 70% of households are involved in fishing on all islands excluding the main island of Rarotonga, where >30% of households fish (Gillett 2016; Cook Islands Statistics Office 2018). Despite the high levels of household reliance on fishing nationally, elasmobranchs are not a target species for Cook Islands fishers in part because of cultural customs, and there is no commercial market for elasmobranch parts (unpublished data). Low levels of shark take occur by local fishers through bycatch, and are used for local consumption, creation of personal effects including traditional drums, fishing lures and tools (Cramp, unpublished data). Shark mortality also occurs as a result of human wildlife conflict by fishers frustrated by lost gear or competing with sharks for fish (pers. obs. 2011-2020). There are at least 23 species of sharks and rays in Cook Islands waters, with the majority of species inhabiting reef or pelagic waters, although several deepwater elasmobranchs also occur there (McCormack 2007; unpublished data).

Anecdotal reports of intermittent trading of shark parts between local fishers and foreign fishing vessels on outer islands exist, but have not been formally documented (unpublished data). Elasmobranchs were not targeted in the industrial fishing sectors operating in the Cook Islands prior to designation of the Sanctuary, but they were incidentally captured on longline and purse seine vessels that were subject to regional management measures of the Western and Central Pacific Fisheries Commission (WCPFC), the tuna Regional Fisheries Management Organization (RFMO) in the region (MMR 2012a). The management measures in place prior to sanctuary implementation were minimal, but as a member of the WCPFC, the Cook Islands were required to implement an FAO-mandated National Plan of Action for Sharks, a 5% by weight of fin to carcass ratio, and in 2013, bans on the targeting and retention of *Carcharhinus longimanus* (Oceanic Whitetip Shark) and *Rhincodon typus* (Whale Shark) (WCPFC 2012a, 2012b, 2016a). The 2013 WCPFC measure banning retention of *Carcharhinus falciformis* (Silky Shark) did not take effect until 2014 (WCPFC 2013).

On December 12, 2012, the Cook Islands Government announced the Cook Islands Shark Sanctuary (Cook Islands News 2012). The Sanctuary was implemented by regulation under the Marine Resources Act (2012) and banned the import, export, sale, trade, possession and transshipment of all elasmobranchs, as well as the targeting of elasmobranchs and the use of trace wire and shark line. Fines were written into the regulations as a minimum of $100,000 NZD per part of shark onboard (e.g. per fin, tooth or shark carcass). Exemptions for local fishers were written into the regulations, meaning that the sanctuary targeted industrial vessels that primarily interacted with wide-ranging elasmobranchs. In 2012, national spatial fishing restrictions prohibited commercial longline and purse seine vessels from fishing within 24 nm of Rarotonga and 12nm from all other islands (MMR 2012a), meaning that the shark sanctuary applied to commercial vessels. Fishing vessels with active annual fishing licenses in 2012 were allowed to implement the Sanctuary regulations at the end of their term, meaning that the Sanctuary was not fully implemented on all vessels until 2013. Because of nearshore commercial fishing vessel prohibitions and the exemption of local fishers, the sanctuary regulations had a de facto focus on wide-ranging elasmobranchs. Further national spatial management measures were implemented in 2017 as part of the Marae Moana (Cook Islands Marine Park); fishing vessels were prohibited from fishing within 50 nm of every island in the EEZ (Marae Moana Act 2017) (Figure 1.2).

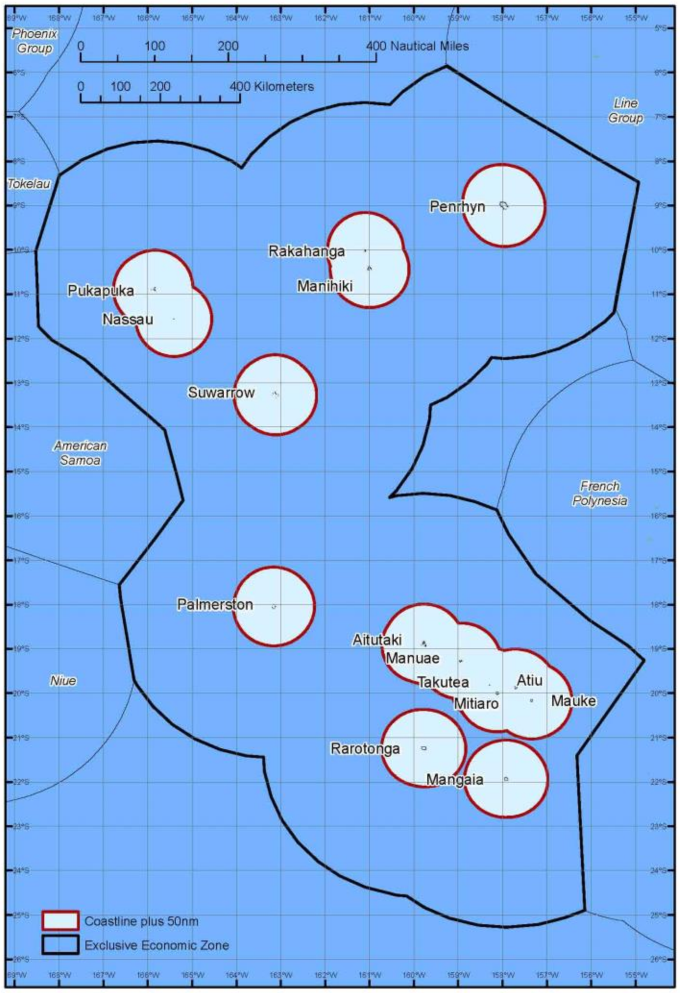


Figure 1.2: Map of the Cook Islands Exclusive Economic Zone (EEZ) and the 50 nm boundaries around each island. Thick black line delineates EEZ boundary. Red lines delineate the 50 nm commercial fisheries exclusion zones implemented by Marae Moana Act (2017). Map courtesy of Marae Moana Office.

1.4. Thesis goal and objectives:

The overarching goal of this thesis was to use the Cook Islands Shark Sanctuary as a case study to better understand whether a sanctuary can be effective at protecting the multiple types of sharks in the Cook Islands, and whether the global and regional policies, of which the Cook Islands are a party and are meant to work in conjunction with the Sanctuary, are sufficient to support broader shark protections for species and individuals that might travel inside and outside of the Cook Islands. Additionally, because the Sanctuary exists within a broader suite of policy interventions, evaluation of its effectiveness within this broader context was necessary. Therefore, RFMO policies, neighboring fishing nations, and other measures targeting elasmobranchs needed to be considered and evaluated for complementarity to fully understand implications of these protective measures. This broader analysis is the focus of my thesis.

I set out to achieve my thesis goal of understanding sanctuary effectiveness for the survival of sharks by answering three main questions: (1) are conservation and management policies for sharks that move between national jurisdictions (wide-ranging sharks) clear and inclusive? (2) does the Sanctuary influence the abundance of sharks that are resident in the EEZ (reef-associated species)? and; (3) can sanctuaries work for shark species interacting with commercial fisheries? For the first question, I explored whether the policies were clear and inclusive so that national governments could effectively implement them. This allowed me to understand the landscape of global and regional shark conservation policies within which the Cook Islands Shark Sanctuary sits. It also allowed me to understand whether these policies were complementary or contradictory to one another and to the goals of sanctuaries. The second and third questions required me to look at the two groups of sharks that will be affected differently by the Sanctuary: reef-associated species and wide-ranging species. Reef-associated species are unlikely to leave the sanctuary and so might benefit from it throughout their life, whereas wide-ranging species might spend only part of their lives in the sanctuary.

These questions were addressed by exploring four main objectives:

1. Identify gaps and inconsistencies in global elasmobranch policies that could preclude mortality reduction for wide-ranging sharks and their relatives.

2. Explore relative abundance of sharks between nations, locations, and reefs in the Western and Central Pacific Ocean to: (a) understand occurrence of elasmobranchs and habitat linkages between pelagic and reef environments; (b) identify factors related to abundance in reef environments and effect of shark sanctuaries in the Pacific region.

3. Understand whether Sanctuary implementation has resulted in a change in fishing practices in the Cook Islands.

4. Understand movement patterns and fishing exposure of wide-ranging sharks relative to Sanctuary boundaries in the Cook Islands.

1.5. Thesis structure:

The four objectives of my thesis were explored through four data chapters, including a policy analysis, deployment and analyses of baited camera units in reef environments, exploration of commercial fisheries records, and satellite telemetry on three species of wide-ranging sharks: *Prionace glauca* (Blue Shark)*, Carcharhinus longimanus* (Oceanic Whitetip Shark)*,* and *Carcharhinus falciformis* (Silky Shark). The chapters were prepared as a series of manuscripts intended for publication in peer-reviewed journals, which I adapted for this thesis.

Chapter 1 is this introduction, which gives context and overview of my research aims.

Chapter 2, the first data chapter, addressed the first objective by examining the policies mandated for implementation by the Cook Islands' participation in regional and global forums. This chapter sets the Cook Islands Shark Sanctuary in the context of broader policies applicable to wide-ranging sharks that occur in Cook Islands waters.

Chapter 3 addressed the second objective by exploring regional factors related to abundance of elasmobranchs present in reef environments across the Western and Central Pacific Ocean, and whether sanctuaries present in this region and neighboring EEZs impacted reef-associated species. For this chapter, I deployed Baited Remote Underwater Video Stations (BRUVS) in the Cook Islands and Niue as part of the Global FinPrint project (https://globalfinprint.org). I then analyzed all data from 18 countries in the study for the Western and Central Pacific region. I looked for presence of wide-ranging sharks in reef environments and factors related to abundance, including whether shark sanctuaries had an effect. I then contextualized the Cook Islands in the region for species unlikely to travel outside EEZs.

Chapter 4 considers data specific to the Cook Islands to address the third objective of my thesis, to understand whether the sanctuary had an effect on commercial fisher behavior. Industrial fishing records from the Cook Islands longline and purse seine fisheries were used to evaluate whether elasmobranch catch and retention changed following sanctuary implementation.

Chapter 5, the final data chapter, utilized satellite telemetry to address the fourth objective; to determine the activity spaces of three commonly caught species in industrial longline and purse seine fisheries. In this chapter, I examined how much time sharks tagged inside the Cook Islands Shark Sanctuary spent inside and outside of the Sanctuary and calculated the risk of overlap and capture with industrial fisheries to determine how well the Sanctuary could protect species. Using the movement data, I determined whether a combination of spatial and fisheries management policy interventions would better protect wide-ranging sharks than either spatial or fisheries management policies alone.

Chapter 6 forms the general discussion where I synthesize the results of my four data chapters to determine how well the Cook Islands Shark Sanctuary is protecting sharks, and how, based on results of policy and environmental drivers from chapters 3 and 4, policies can be improved for greater protection of sharks.

Chapter 2:

How policy gaps and inconsistencies hinder effective management of sharks and their relatives

ABSTRACT:

Policy interventions for sharks and their relatives have expanded significantly over the past twenty years. However, many species are still in decline, indicating that mortality levels remain too high. Inadequacies of current policies aimed at protecting sharks and their relatives include a lack of data, funding, and political will, and problems with implementation, enforcement, and compliance. This chapter examined current international and regional conservation and management policies for sharks and their relatives and highlighted gaps and inconsistencies in the underlying definitions and protective measures upon which policies rely for success. Results showed vague, inconsistent, or non-existent definitions and lack of policy detail that contribute to shortcomings in policy protections by allowing for inconsistent interpretation and political interference. To increase conservation and management effectiveness of current policies for sharks and their relatives, a revised species-specific systematic planning process should be created with a multi-stage definition of "protected", along with regular, planned communication to all stakeholders about species progression along the conservation process.

2.1. INTRODUCTION

Exploitation rates of chondrichthyan fishes (sharks, rays and chimaeras; hereafter "chondrichthyans") increased dramatically in the second half of the 20th century to meet growing demand for their parts (Worm et al. 2013; Davidson et al. 2016; Simpfendorfer & Dulvy 2017). Fisheries are the primary threat to chondrichthyans, although habitat loss, climate change, and pollution also contribute to some species declines (Musick et al. 2000; Simpfendorfer et al. 2002; Camhi et al. 2009; McClenachan et al. 2012; Dulvy et al. 2014). Chondrichthyans are either targeted in various fisheries or captured incidentally in fisheries targeting other species, where they are generally termed 'bycatch' or 'incidentally captured' species (Stevens et al. 2000; Gilman et al. 2008; Camhi et al. 2009; Clarke et al. 2014). Scientists, conservationists, and fisheries managers have often attributed increased catch of chondrichthyans to the increasing demand and expanding markets for shark fins in Asia (Clarke et al. 2006; Lack & Sant 2011; Fields et al. 2018). Trade statistics, however, have also shown that global markets for meat, liver oil, skin, jaws, chondroitin, gill plates, and other parts of chondrichthyans are also driving retention and targeting in fisheries (Dent & Clarke 2015; Cardeñosa et al. 2018). Rising prices and demand for these parts have further increased pressure on chondrichthyan populations, fueling an industry worth nearly one billion dollars annually (Bräutigam et al. 2015; Dent & Clarke 2015).

Population declines of chondrichthyans have been recorded in nearly all ecosystems where they occur, including freshwater, estuarine, coastal, open-ocean, and the deep sea (Stevens et al. 2000; Baum et al. 2003; Simpfendorfer et al. 2010; Dulvy et al. 2014). Importantly, estimated numbers of sharks based on fin markets indicated catches were likely three to four times higher than those reported to FAO (Clarke et al. 2006). The International Union for the Conservation of Nature (IUCN) Red List of Threatened Species includes 18.3% of chondrichthyans designated as threatened, a term covering the categories Critically Endangered, Endangered, and Vulnerable (IUCN 2019). Almost half of all chondrichthyans (40%) are Data Deficient (DD), meaning not enough information is available to assess their population status (IUCN 2019). However, estimates combining known geographic distribution and body size of DD species suggest over one quarter (24%) of all chondrichthyans are threatened, with migratory species disproportionately represented (46%) (Dulvy et al. 2014; IUCN 2019).

A change in public perception in the late 1990s and early 2000s, recognizing the need for sharks to be protected from humans based on population declines, propagated policy and fisheries management interventions (Simpfendorfer et al. 2011). Public perception in this light, however, is concentrated in the developed world, and attributed partly to non-government organizations (NGOs) operating from developed countries (pers. obs. 2011-2021). Binding and non-binding protection measures have expanded significantly over the last twenty years (Camhi et al. 2009; Heupel & Simpfendorfer 2010; Simpfendorfer et al. 2011; Techera & Klein 2011; Vincent et al. 2014). Interventions for threatened chondrichthyans include species-specific listings on international conventions for conservation and management and species-specific fishery management tools, including retention bans, catch limits, and spatial closures (Figure 2.1). Many species, though, continue to decline, indicating that fishing mortality remains too high (Worm et al. 2013; Davidson et al. 2016). Therefore, a shift in focus is required from measures that place species on lists to measures leading explicitly to reduced fishing mortality, avoiding further loss and promoting recovery of vulnerable populations (Ferraro & Pressey 2015; Pressey et al. 2015).

Many pelagic chondrichthyans, whether targeted or incidentally captured, are taken in fisheries operating in the open ocean (Dulvy et al. 2008), both in national waters and on the high seas beyond national jurisdiction, where no single nation has management authority. The majority of open-ocean fishing is regulated by Regional Fisheries Management Organizations (RFMOs), which are the intergovernmental bodies designated by the United Nations to manage and conserve shared fish stocks (Maguire et al. 2006; FAO 2019a). RFMOs are comprised of nations whose waters fall within the regional jurisdiction as well as nations whose fleets operate within the organizations' areas of jurisdiction. Historically, RFMOs have paid little attention to the status of chondrichthyans in fisheries for which they are responsible. Notable reasons for the lack of attention to chondrichthyans have been limited data and limited economic and management capacity of member nations, noting that RFMOs were initially established to manage tunas and tuna-like species. When limiting factors were combined, managers have chosen between expending resources on lucrative target species such as tuna or bycatch such as sharks. As a result, chondrichthyans and other bycatch species were deprioritized by RFMOs (Simpfendorfer et al. 2002; Clarke et al. 2006, 2013; Fowler 2014; Dent & Clarke 2015). Despite this lower priority, several management measures for chondrichthyans (Figure 2.1, Table 2.1; (FAO 2019b)) have been introduced by RFMOs and some member nations responsible for domestically implementing measures decided at RFMOs (Shiffman & Hammerschlag 2016). Today RFMOs recognize the need for additional management actions for these species. The aim has been to reduce mortality of, and interactions with, key shark species that require conservation and management (Clarke et al. 2014).

There have been frequent observations of the shortcomings of interventions aimed at chondrichthyans. This study defines policy interventions here as any law, treaty, regulation, or convention (Figure 2.1, Table 2.1) formalized by one or more governing bodies for the purpose of establishing or defining conservation and management procedures. This study defines fishery management tools here as interventions that alter fishing techniques or activities or require reporting with the aim of achieving specific conservation and management outcomes. Although limitations of these interventions have been described, inconsistencies in the definitions and interpretation of terms underlying policy interventions have not been fully explored. How species qualify as “migratory”, for example, is subject to several published definitions, leading to variations in interpretation. Similarly, if “protection” afforded by policies is not defined clearly in terms of policy intent, interpretation is left to individual stakeholders, including policymakers, fishery managers, enforcement officers, and the fishing industry. Policy inconsistencies include species successfully meeting criteria for protection on some interventions but not others with a similar mandate, and overlapping tracts of ocean managed by two or more governing bodies with different policies. Such inconsistencies can allow continued, unsustainable exploitation by creating loopholes that make policies and resultant fishery management tools difficult to implement and enforce.

Policies adopted with incomplete or unclear definitions or loopholes could compromise significant conservation effort. The effort expended in formalizing inconsistent, incomplete, and unclear policy interventions diverts the already limited capacity for conservation and management of chondrichthyans. Just as “conservation science must remain objective and rigorous to achieve goals and retain impact” (Heupel & Simpfendorfer 2010), similar rigor should be applied when developing policy interventions. Without uniform definitions underlying policy, the interpretation of management decisions is likely to be based less on science and more on social values and political expediency (Butterworth 1992; Sutherland et al. 2004; Game et al. 2009; Simpfendorfer et al. 2011; Pressey et al. 2017; Cramp et al. 2018). The reasons for policy interventions being developed with unclear and inconsistent definitions are likely a mix of well-intentioned, though limited, attempts at protecting species, acceptance by managers of compromises in policy formulation, and deliberate avoidance of restrictions.

This chapter begins with an explanation of current policy and fishery management interventions for chondrichthyans followed by a summary of the limitations of these measures. Following the analysis, I make recommendations for consistent protection of chondrichthyans across policy interventions that, when implemented, would enhance the effectiveness of traditional fishery management tools in promoting the maintenance of populations.

The focus of this review was on multilateral instruments (regional and international) because this is where the inconsistency in language, criteria and resultant interpretation is the most complex. As such, the review is consequently biased away from reef-associated species because these species are primarily managed within national jurisdictions while pelagic species are primarily co-managed. The issues uncovered by this analysis, however, may still relate to national-scale conservation and management policy, which is highlighted in the Discussion.

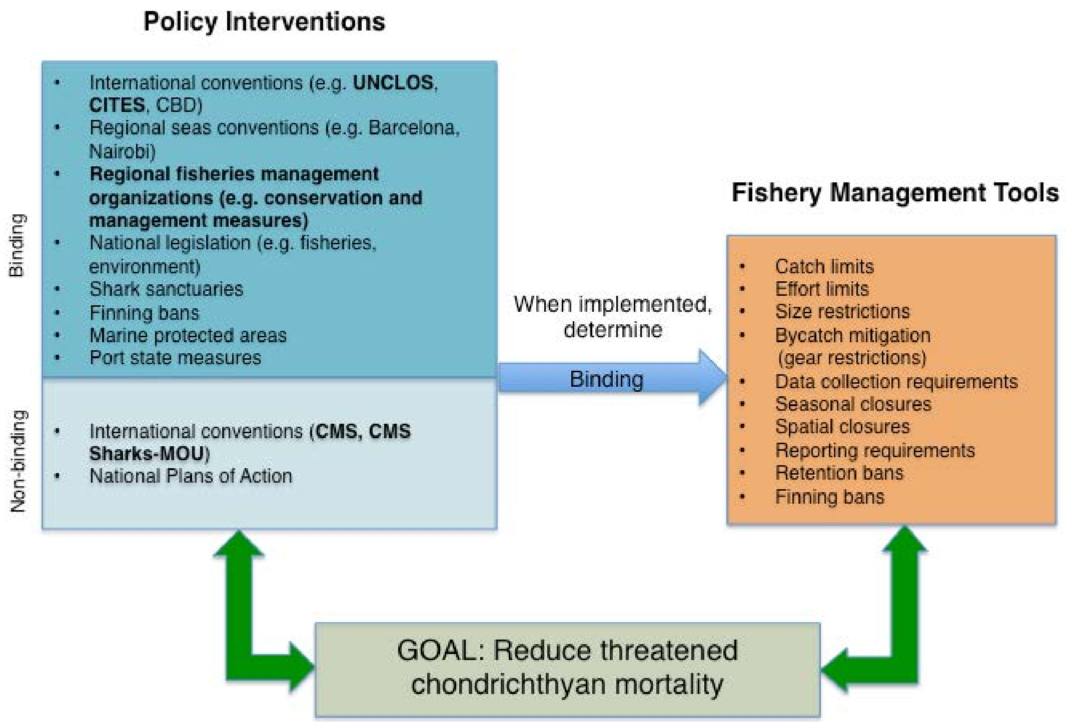
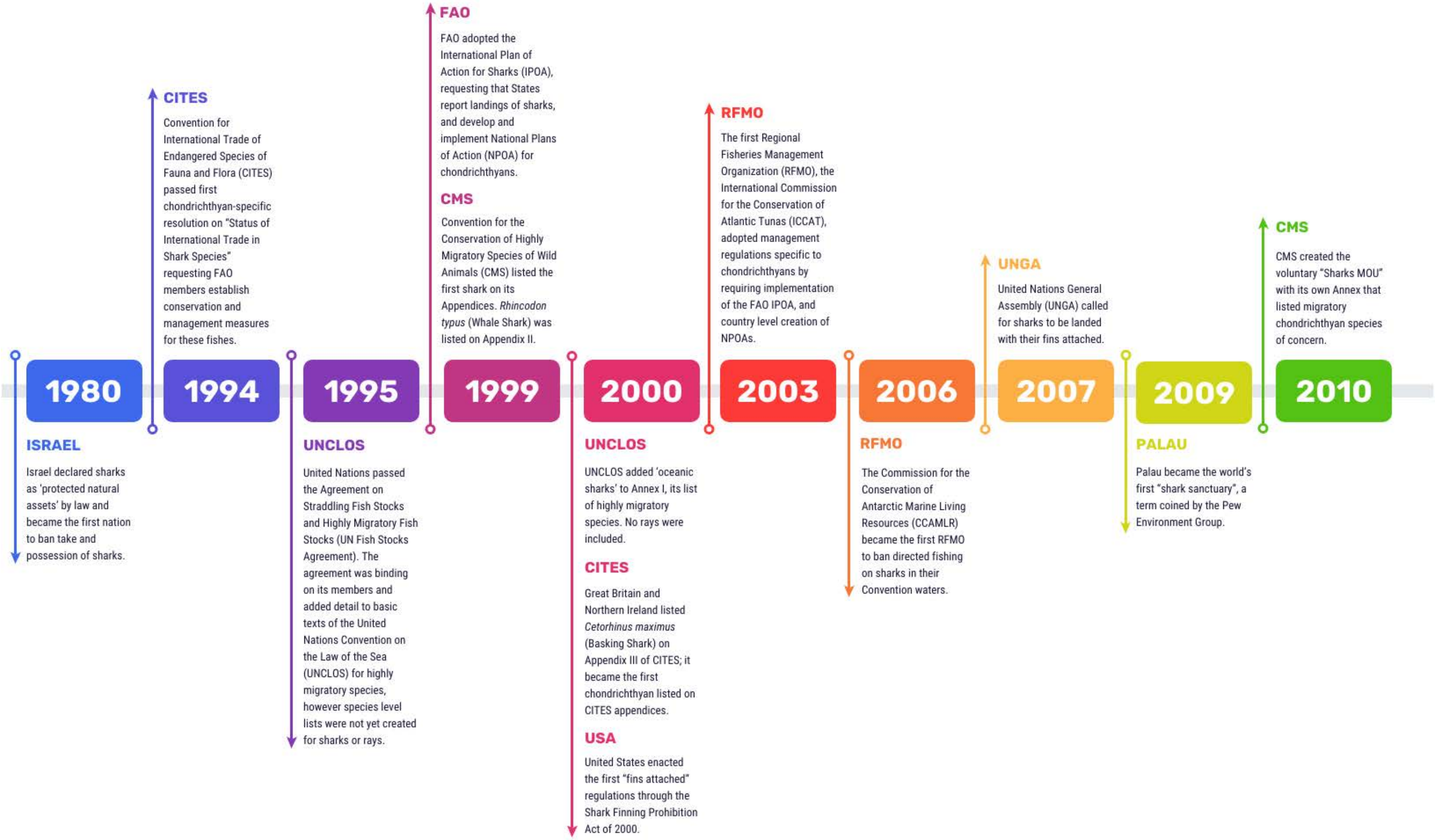


Figure 2.1: Interventions for reducing mortality of threatened chondrichthyans. Policies in bold were included in the analysis. (For detail on fishery management tools, see Table 2.1). Key to acronyms in Table 2.2.

Table 2.1: Fishery management tools applied to chondrichthyans

Type	Description
Catch limits	**Individual or group limits on daily/trip/annual catches**
Effort limits	Limits on numbers of fishers, vessels, amount of gear allowed on board, time spent fishing
Size restrictions	All sharks under/over specified size must be avoided and/or discarded
Bycatch mitigation	Gear restrictions such as banning the use of trace wire or requiring circle hooks
Data collection requirements	Trained observers on board, e-reporting in real time for quota management
Seasonal closures	Specified times (with or without geographic location) when certain species may not be retained. Also, a specified time when certain gear, such as fish aggregating devices may not be used.
Reporting requirements	Mandates on type and specificity of data collected such as time, depth, species identification, effort, weight of catch, as well as on the timing of report submissions to management organizations
Spatial closures	Geographic locations with permanent or seasonal restrictions, including no entry permitted or no retention of certain species
Retention bans	Prohibition of retention of certain species for a specified time period, usually until stock is capable of producing maximum sustainable yield
Finning bans	Prohibition of finning sharks at sea, requiring fins to be naturally attached or limits on proportion of shark fins vs. carcasses allowed on board

2.1.1 Policy and management interventions for chondrichthyans



1980

ISRAEL

Israel declared sharks as 'protected natural assets' by law and became the first nation to ban take and possession of sharks.

1994

CITES

Convention for International Trade of Endangered Species of Fauna and Flora (CITES) passed first chondrichthyan-specific resolution on "Status of International Trade in Shark Species" requesting FAO members establish conservation and management measures for these fishes.

1995

UNCLOS

United Nations passed the Agreement on Straddling Fish Stocks and Highly Migratory Fish Stocks (UN Fish Stocks Agreement). The agreement was binding on its members and added detail to basic texts of the United Nations Convention on the Law of the Sea (UNCLOS) for highly migratory species, however species level lists were not yet created for sharks or rays.

1999

FAO

FAO adopted the International Plan of Action for Sharks (IPOA), requesting that States report landings of sharks, and develop and implement National Plans of Action (NPOA) for chondrichthyans.

CMS

Convention for the Conservation of Highly Migratory Species of Wild Animals (CMS) listed the first shark on its Appendices. *Rhincodon typus* (Whale Shark) was listed on Appendix II.

2000

UNCLOS

UNCLOS added 'oceanic sharks' to Annex I, its list of highly migratory species. No rays were included.

CITES

Great Britain and Northern Ireland listed *Cetorhinus maximus* (Basking Shark) on Appendix III of CITES; it became the first chondrichthyan listed on CITES appendices.

USA

United States enacted the first "fins attached" regulations through the Shark Finning Prohibition Act of 2000.

2003

RFMO

The first Regional Fisheries Management Organization (RFMO), the International Commission for the Conservation of Atlantic Tunas (ICCAT), adopted management regulations specific to chondrichthyans by requiring implementation of the FAO IPOA, and country level creation of NPOAs.

2006

RFMO

The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) became the first RFMO to ban directed fishing on sharks in their Convention waters.

2007

UNGA

United Nations General Assembly (UNGA) called for sharks to be landed with their fins attached.

2009

PALAU

Palau became the world's first "shark sanctuary", a term coined by the Pew Environment Group.

2010

CMS

CMS created the voluntary "Sharks MOU" with its own Annex that listed migratory chondrichthyan species of concern.

Figure 2.2: Timeline of initial regulations specific to chondrichthyans in national, regional and multilateral polices

In 1994, the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) passed the first chondrichthyan-specific resolution requesting the Food and Agriculture Organization of the United Nations (FAO) and members of international fishery management bodies to establish programs for the conservation and management of these fishes (Vincent et al. 2014; CITES 2016). In 1994, FAO passed a resolution for "sharks", but it would take several years before "rays" were added to the "shark" category, meaning that when the term "shark" was used, it could include both sharks and rays. In 1995, the United Nations passed the Agreement on Straddling Fish Stocks and Highly Migratory Fish Stocks, hereafter called the "UN Fish Stocks Agreement". The UN Fish Stocks Agreement was binding on its members, meaning they were legally obligated to comply. The motivation was the inadequate protection of migratory fish by the 1982 United Nations Convention on the Law of the Sea (UNCLOS), a binding convention that required coastal states and those fishing on the high seas to cooperate for the conservation of straddling stocks (those that exist both within a nation's exclusive economic zone and the adjacent high seas) and highly migratory species. The UN Fish Stocks Agreement strengthened protection by adding detail to the basic texts of UNCLOS regarding straddling stocks and highly migratory species, categories that include many threatened chondrichthyans (United Nations 2013).

In 1999, FAO adopted the non-binding International Plan of Action for Sharks, requesting that States that reported landings of sharks, whether targeted or taken as bycatch, develop and implement National Plans of Action for chondrichthyan species (FAO 1999; Fischer, J. Erikstein, K. D'Offay, B. Guggisberg, S. Barone 2012; Fowler 2014) to ensure long-term sustainable take. Plans were to be based on shark assessment reports and embrace the precautionary approach (FAO 1999; Fowler 2014), expressed in the UN Fish Stocks Agreement as "States are required to use caution when information is uncertain or unreliable, and that the absence of adequate information cannot be used as a reason for postponing or failing to take conservation and management measures" (UN 1995). In 2000, UNCLOS added 'oceanic sharks' to its Annex I of highly migratory species, which required states to ensure that species listed on the Annex were not endangered by overexploitation. That same year, *Cetorhinus maximus* (Basking Shark), was listed on Appendix III of the Convention for International Trade of Endangered Species of Fauna and Flora (CITES) by Great Britain and Northern Ireland (CITES 2016). It was the first chondrichthyan species listed on any CITES appendix. However, Appendix III listings can be added unilaterally, meaning they do not require a vote by the Convention, and species listed on Appendix III do not require export permits (CITES 2016).

Following the implementation of the UN Fish Stocks Agreement in 2001, a subset of FAO-mandated regional fisheries bodies, including five tuna and 12 non-tuna RFMOs, adopted their first chondrichthyan-specific regulations between 2003 and 2005. RFMOs adopted policies called conservation and management measures that were binding on their members. Non-binding measures were adopted first and included in the UN's call for states that landed sharks to create and implement National Plans of Action.

Concurrent with increased public concern in the 1990s about the decline of sharks, and in particular, the practice of shark finning (removing the fins from the body and dumping the carcass (Clarke et al. 2013), regional- and national-level policy interventions expanded to include finning regulations. RFMOs mandated through binding measures that vessels have no more than a 5% ratio of the weight of shark fins to carcasses onboard. In addition to "fin-to-carcass" ratio regulations at regional levels, "fins attached" regulations were enacted at national levels, prohibiting the removal of shark fins at sea. The United States became the first country to enact "fins attached" regulations through the Shark Finning Prohibition Act of 2000 (Shark Finning Prohibition Act 2000). They later made amendments, resulting in the Shark and Fishery Conservation Act (Shark and Fishery Conservation Act 2011), that required all vessels to land shark carcasses with fins naturally attached until the first point of landing.

The RFMOs used several binding chondrichthyan-specific measures to reduce targeted or incidental catch of sharks. These include prohibiting the use of "shark lines," which are reinforced metal fishing wire that is difficult for sharks to bite through if incidentally captured, and prohibitions on targeting of sharks within convention areas, such as the shark targeting ban in CCAMLR. Additionally, RFMOs later enacted species-retention bans that required swift and careful release of hooked sharks. An example of the species-retention ban is the Oceanic Whitetip Shark "no retention measure" in WCPFC.

In addition to RMFO measures, several multi-lateral policy measures addressed concern over decreasing shark populations in the years 2000-2010, including a 2007 United Nations General Assembly call for sharks to be landed with their fins attached (non-binding), as well as species listings on international agreements such as the non-binding United Nations Environment Program's Convention for the Conservation of Highly Migratory Species of Wild Animals (CMS) Appendices. Appendix I listings encourage range states to prohibit take of any species on the list, with exceptions for scientific research and indigenous uses. CMS Appendix II listings are non-mandatory, but states are encouraged to enact conservation and management of listed species through cooperation with neighboring states. In 2010, the CMS Convention created a voluntary, non-binding "Sharks-MOU" with an Annex separated from the broader CMS Appendices, both of which listed migratory chondrichthyan species of concern. The species listed on the Sharks-MOU Annex I are intended to be afforded special conservation and management attention by the MOU's signatories (CMS Sharks MOU 2018).

2.1.2 Recognized limitations of protective measures

A brief overview of the known limitations of protective measures provides context for the questions addressed in this review. The ongoing exploitation of chondrichthyans is in stark contrast to protection of other marine taxa with similar life-history parameters such as cetaceans, all of which are exempted from the development of a sustainable fishery by the United Nations Convention on the Law of the Sea (Hoyt 2011) meaning there is no allowable targeted catch aside from small quotas for cultural or research uses. Additionally, all cetaceans are afforded protection from unregulated trade (Guggisberg 2015; CITES 2017). As a result of these conservation interventions, the decline of several cetacean species has been reversed (Ward-Paige et al. 2012). Despite the higher proportion of threatened chondrichthyans compared to cetaceans, chondrichthyans are not protected from the development of fisheries, nor are they afforded blanket listing, regardless of population threat level. Ultimately, cetaceans benefit from societal pressure to protect mammals; chondrichthyans do not.

The FAO State of World Fisheries and Aquaculture Report (2014) stated that much more effort was required to arrest and reverse declines in chondrichthyan populations through scientific research, catch documentation, and fisheries regulations (FAO 2014). Despite efforts to halt the downward trajectory of vulnerable chondrichthyans through policy interventions and fishery management tools, important limitations in both are well established. Limitations range from specific omissions of detail in policy and fishery management tools that create loopholes to widespread data deficiency that inhibits the establishment of protective measures and understanding of their effectiveness.

Pervasive data deficiency is worsened by limited financing that precludes increasing management capacity and thwarts data collection (Bräutigam et al. 2015). When combined with the lower priority chondrichthyans receive in RFMOs in comparison to high-value target species, lack of data exacerbates poor knowledge of species biology and undermines reporting (Simpfendorfer et al. 2002; Clarke et al. 2006, 2013). These gaps in data, or poor data quality, prevent accurate stock assessments needed to understand population trends and assess extinction risks that inform protective measures (Musick 1999). Stock assessments are especially difficult for pelagic species, which migrate across multiple national jurisdictions and into the high seas (Simpfendorfer et al. 2002; Dulvy et al. 2008, 2017; Costa et al. 2012; Lascelles et al. 2014). Management of threatened reef-associated and epipelagic species are not without complications either. These species, like pelagic species, can make continental-scale migrations (Heupel et al. 2015) and inhabit densely populated islands where catch records are sparse or non-existent, and where the sale of shark parts supports livelihoods (Mangubhai et al. 2012; Jaiteh et al. 2016; Mizrahi et al. 2019).

In addition to the difficulties of protecting largely unmanaged and unmonitored species, non-binding measures are often ignored (Fischer, J. Erikstein, K. D'Offay, B. Guggisberg, S. Barone 2012) or are not implemented, even by well-intentioned governments that lack the required capacity (Dulvy et al. 2017). Compounded by the need for collaboration across jurisdictions and stakeholder groups, management effectiveness for chondrichthyans is ultimately reduced in part because the definitions of "threatened" and "protected", and the terms on which definitions depend, such as "migratory" and "precautionary approach", vary across policy interventions by species, nation, region, and political motivation.

2.1.3 Questions addressed in this review

This review assessed the consistency of the definitions, interpretation, and application of the terms “threatened”, “protected”, “migratory”, and “precautionary approach” amongst a range of policy interventions aimed at guarding chondrichthyans from overexploitation and unsustainable trade. While other reviews have focused on aspects of shark sanctuaries (Ward-Paige 2017) or exposed flaws of incomplete species listings (Fowler 2014), this review adds to previous work by providing a detailed analysis broadly across species, policies, and jurisdictions. By assessing inconsistencies in levels of threat versus levels of protection and whether species, areas, penalties, and exemptions are consistent across multiple policy interventions, this review highlights gaps that limit management effectiveness. This review also identifies loopholes that allow continued exploitation, even when protective policy interventions are in place. “Protection” afforded to threatened species within these interventions is often misleading (Shiffman et al. 2020). From the perspective of non-specialists, what might seem to be minute differences in the definitions of key terms used in conservation and management of species such as “threatened” and “protected” actually create ambiguity, leaving opportunities for continued exploitation of threatened chondrichthyans, even when protective measures are in place. In the context of the limitations of conservation measures, I focus this review on problems arising from inconsistencies that contribute to reduced management effectiveness for chondrichthyans.

This review addresses five questions:

1. Were definitions for “threatened”, “migratory”, and “precautionary approach” consistent across interventions?

2. Were species listings, defined as species that have been added to a policy, consistent by threat level and were those listings consistent across interventions?

3. Were species listings on each policy consistent with the policy’s stated intent and species

listing criteria?

4. Was level of protection afforded by policies consistent across interventions?

5. Were species listed on binding or non-binding policies, and was policy language prescriptive for what governments and fishers were bound to do?

2.2 METHODS

This study restricted its analysis to policies with three characteristics: species-based; at least regional in scope; and specifying forms of protection for chondrichthyans. For the purposes of this review, “regional” refers to groupings of at least two national governments with neighboring jurisdictions and shared marine resources, “international” refers to groupings of at least two national governments whose jurisdictions are not neighboring, but whose governments are mandated with resource protections. Analyzing policies at least regional in scope allowed us to address and compare definitions of “migratory” that refer to animals that can cross national jurisdictions. I focused on chondrichthyan-specific policies for consistency in comparing interpretation of definitions in fit-for-purpose management. Many multilateral (international or regional policies) not designed for conservation and management of chondrichthyans offer direct and indirect benefits, such as the regional seas conventions. However, it is not possible to measure the specificity or effectiveness of terms in these policies against those designed specifically for chondrichthyans.

The policies included in this review (Table 2.2) fall into two categories: multilateral environmental agreements and regional policies administered by RFMOs. I reviewed all international and regional policies, treaties and conventions, with specific protections for chondrichthyans across fisheries and trade. I did not include the United Nations Convention on Biological Diversity (CBD) or Port State Measures Agreement because they did not specifically list protections for chondrichthyans. The 18 Regional Seas conventions of the United Nations Environment Program (UNEP) were not included because UNEP’s list of “key issues” for Regional Seas conventions did not specify chondrichthyans (UNEP 2019).

Table 2.2: List of policy interventions analyzed for this review. Those in bold type were included. Others did not have specific reference to chondrichthyans and were not analyzed further.

Multilateral environmental agreements

CITES	**Convention for International Trade in Endangered Species of Wild Fauna and Flora**
CMS	**Convention for the Conservation of Migratory Species of Wild Animals**
CMS Sharks MOU	**CMS Sharks Memorandum of Understanding**
UNCLOS	**United Nations Convention on the Law of the Sea**

Regional policies

Tuna RFMO

CCSBT	Commission for the Conservation of Southern Bluefin Tuna
IATTC	**Inter-American Tropical Tuna Commission**
ICCAT	**International Convention for the Conservation of Atlantic Tunas**
IOTC	**Indian Ocean Tuna Commission**
WCPFC	**Western and Central Pacific Fisheries Commission**

Regional policies

Non-tuna RFMO

CCAMLR	**Commission for the Conservation of Antarctic Marine Living Resources**
CCBSP	Convention on the Conservation and Management of Pollock Resources in the Central Bering Sea
GFCM	**General Fisheries Commission for the Mediterranean**
IPHC	International Pacific Halibut Commission
NAFO	**Northwest Atlantic Fisheries Organization**
NASCO	North Atlantic Salmon Conservation Organization
NEAFC	**North East Atlantic Fisheries Commission**
NPAFC	North Pacific Anadromous Fish Commission
PSC	Pacific Salmon Commission
SEAFO	**South East Atlantic Fisheries Organization**
SIOFA	South Indian Ocean Fisheries Agreement
SPRFMO	South Pacific Regional Fisheries Management Organization

International policies (multilateral environment agreements) were selected based on the authors' knowledge of shark conservation and management, but also by grey literature searches on Google, Google Scholar, Scopus, and James Cook University Library's One Search. I used the following key words: "shark protection", "shark protection policies", "shark protection laws", "shark conservation", "shark conservation policies", "shark conservation laws", "elasmobranch policies", "elasmobranch laws", "chondrichthyan policies", "chondrichthyan laws", "chondrichthyes policies" and "chondrichthyes laws". I assessed the policies and chondrichthyan-specific annexes, appendices, and memoranda (treaties and conventions) and noted listing criteria, species listed, level and type of protection afforded, and exemptions.

The list of relevant RFMOs was compiled using (FAO 2019a) and the Sea Around Us online RFMO tool (Cullis-Suzuki & Pauly 2010; Pauly & Zeller 2015). I examined five tuna- and 12 non-tuna RFMOs. For each RFMO, I recorded area covered, any overlapping jurisdictions with other RFMOs, and member nations upon which the conservation and management measures were binding. Keyword searches for conservation and management measures specific to chondrichthyans in RFMOs were conducted in the form of "recommendations" or "resolutions" for designated species. I noted "key species", species designated by the RFMO as requiring greater management attention, and the IUCN Red List status of the "key species." Also assessed were levels and types of protection afforded, and exemptions.

2.2.1 Analysis

I compiled a list of all chondrichthyans considered threatened on the IUCN Red List (i.e. Critically Endangered, Endangered and Vulnerable). Species listed as Near Threatened, Least Concern and Data Deficient were not considered. Then I noted which threatened species were gazetted in annexes, appendices, memoranda, legislation, or regulations of the policies that were examined. To the list, I added species that were not assessed by IUCN as threatened, but nonetheless listed on the policies and noted their threat levels per the IUCN Red List.

The list provided the basis of this analysis, which was applied across the range of policies. Methods used to answer the five questions are given below.

> *1. Were definitions for "threatened", "migratory" and "precautionary approach" clear and consistent across interventions?*

"*Threatened*": I noted each policy intervention's definition of "threatened" and compared those definitions to the IUCN Red List's definition of "threatened".

"*Migratory*": I compared policies to determine how those directed at protecting migratory species (UNCLOS, CMS and CMS Sharks MOU) defined "migratory".

"*Precautionary Approach*": I evaluated whether each policy referenced the "precautionary approach" as defined by the UN Fish Stocks Agreement (1995) or Rio Declaration (1996). Then, I evaluated whether the "precautionary approach" was adhered to, based on each policy's criteria and associated species that were listed (or missing) on each policy intervention.

2. Were species listings consistent by threat level and were those listings consistent across interventions with similar mandate?

Two kinds of comparisons were made. The first compared species listings across all interventions against the IUCN Red List threat levels. The second compared listings between policies within defined groups, such as those managing fisheries or migratory species. In the first, a comparison was made for all species listed as threatened on the IUCN Red List with species listed across multilateral environmental agreements and RFMOs, and then for species that were listed in the policies, but not considered threatened by IUCN. For the second comparison, species listed in appendices of CMS were compared with species listed on the CMS Sharks MOU. Species listed by RFMOs with similar mandate (i.e. tuna RFMOs) and by overlapping RFMOs were also compared. Species lists were compared across all policy groups, and inconsistencies and gaps were noted.

3. Were species listings on each policy consistent with the policy's stated intent and species listing criteria?

The species listing criteria of each policy intervention were examined to determine which species were eligible for listing as defined by the criteria per policy. Then, species listing criteria were compared with species listed on that policy to measure consistency. Inconsistencies were noted when a species met the listing criteria for a policy intervention based on the criteria for that specific policy but was not listed and, conversely, when a species was listed when it did not meet the criteria or threat level threshold for that policy intervention.

4. Was level of protection afforded by policies consistent across interventions?

Prohibited or banned activities defined within each policy were compared across policies with similar mandates, such as policies targeting migratory species or policies targeting protection of species interacting with pelagic fisheries. RFMOs' "key species" protection policies were compared amongst tuna and non-tuna RFMOs. Also, the levels of protection that were afforded to species listed in the tiered "Appendices" or "Annexes" of CITES and the international policies for migratory species were compared (UNCLOS, CMS, CMS Sharks MOU). For the international policies that were examined, it was inappropriate to compare prohibited activities between CITES and the rest because CITES was the only policy that represented trade.

> *5. Were species listed on binding or non-binding policies and was policy language prescriptive for what governments and fishers were bound to do?*

Species were assessed for whether they were listed on binding or non-binding policies. Then, each of the policies was examined for prescriptive language on what countries and vessels were bound to do, including clear definitions, reporting requirements, time-bound implementation requirements, and processes and penalties for non-compliance.

Further detail of policy analyses can be found in the Appendix 1.

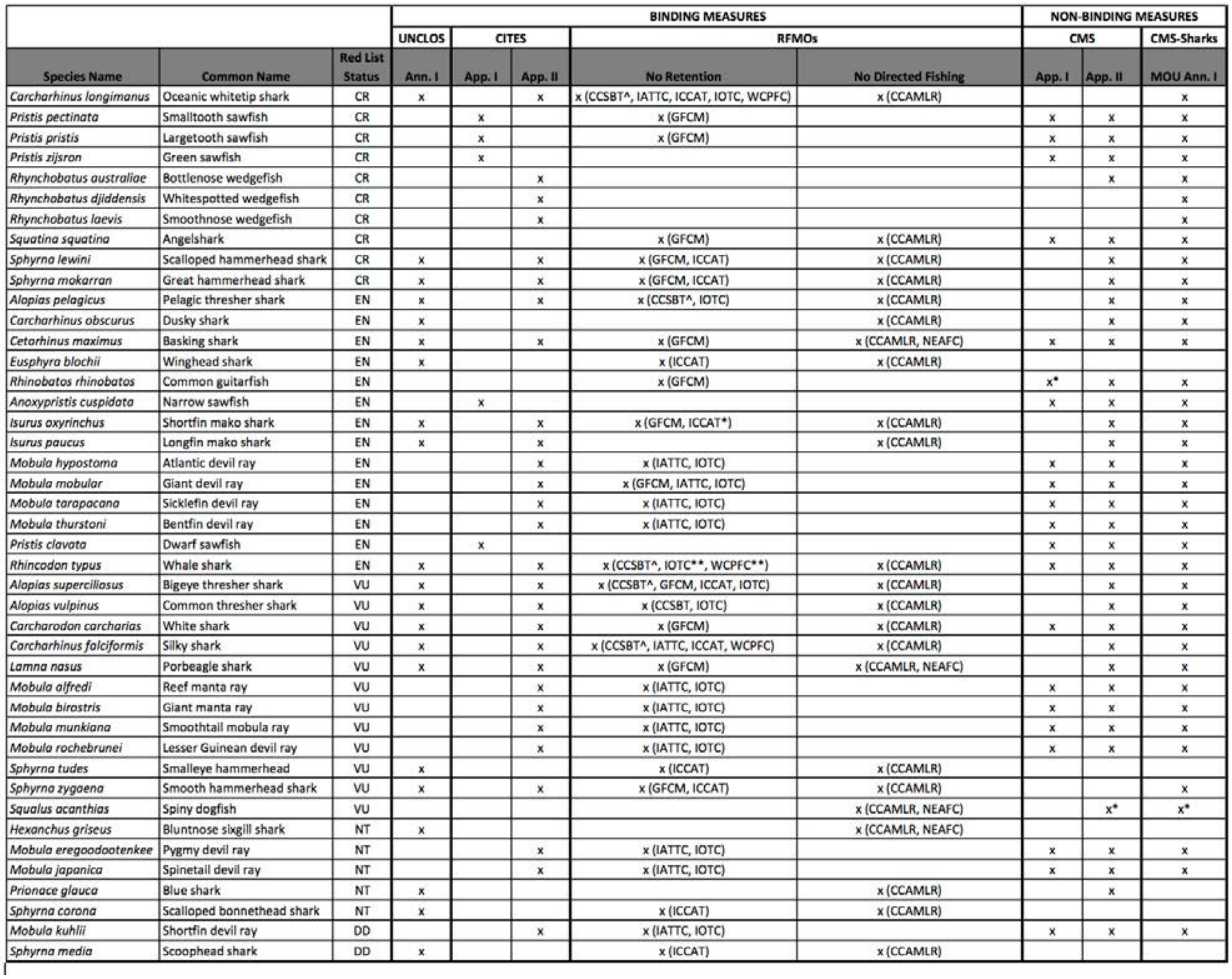
2.3. RESULTS

As of December 1, 2019 (Table 2.3), of the 1124 chondrichthyans assessed on the IUCN Red List, 206 species were globally threatened with extinction. CITES Appendices listed 46 species threatened by international trade (Appendices I and II). UNCLOS Annex I listed 72 species that were migratory with potential for overexploitation in high seas fisheries. CMS Appendices listed 35 species that were both migratory and threatened and the CMS Sharks MOU Annex listed 37 species. Ten RFMOs (tuna and non-tuna) had policies specific to sharks, six RFMOs determined that a total of 46 species in their mandates warranted specific conservation and management measures that banned retention in their fisheries.

Table 2.3: Number of listed species per policy by IUCN Red List assessment category. Grey boxes indicate threatened species.

IUCN Red List Category		**Critically Endangered**	**Endangered**	**Vulnerable**	**Near Threatened**	**Least Concern**	**Data Deficient**
Total numbers of chondrichthyan species in IUCN Red List	**1124**	**42**	**57**	**107**	**112**	**368**	**438**
Total # listed by UNCLOS (Ann. I)	72	8	12	12	19	13	8
Total # listed by CITES (App I)	5	3	2	0	0	0	0
Total # listed by CITES (App II)	41	18	9	10	3	0	1
Total # listed by CMS (App. I)	21	4	9	5	2	0	1
Total # listed by CMS (App. II)	34	5	15	10	3	0	1
Total # listed by CMS (Sharks MOU)	37	10	13	11	2	0	1
Total # Sharks listed as “no retention” by 1 RFMO	43	11	12	15	3	0	2
Total # Sharks listed as “no retention” by 2 RFMOs	20	3	6	8	2	0	1
Total # Sharks listed as “no retention” by 3 RFMOs	18	3	5	7	2	0	1
Total # Sharks listed as “no retention” by 4 RFMOs	3	1	1	1	0	0	0
Total # Sharks listed as “no retention” by 5 RFMOs	1	1	0	0	0	0	0

Table 2.4: Species listed on at least two international and regional chondrichthyan-specific policy interventions. CCAMLR has a ban on directed fishing for sharks, but no definition for which species are included. Therefore, I did not apply the CCAMLR ban to rays, wedgefishes, or sawfishes. However, I extended CCAMLR's ban to all sharks, whether or not the species were likely to occur in the CCAMLR convention area, because the policy said, "sharks".



			BINDING MEASURES					NON-BINDING MEASURES		
			UNCLOS	CITES		RFMOs		CMS		CMS-Sharks
Species Name	Common Name	Red List Status	Ann. I	App. I	App. II	No Retention	No Directed Fishing	App. I	App. II	MOU Ann. I
Carcharhinus longimanus	Oceanic whitetip shark	CR	x		x	x (CCSBT^, IATTC, ICCAT, IOTC, WCPFC)	x (CCAMLR)			x
Pristis pectinata	Smalltooth sawfish	CR		x		x (GFCM)		x	x	x
Pristis pristis	Largetooth sawfish	CR		x		x (GFCM)		x	x	x
Pristis zijsron	Green sawfish	CR		x				x	x	x
Rhynchobatus australiae	Bottlenose wedgefish	CR			x				x	x
Rhynchobatus djiddensis	Whitespotted wedgefish	CR			x					x
Rhynchobatus laevis	Smoothnose wedgefish	CR			x					x
Squatina squatina	Angelshark	CR				x (GFCM)	x (CCAMLR)	x	x	x
Sphyrna lewini	Scalloped hammerhead shark	CR	x		x	x (GFCM, ICCAT)	x (CCAMLR)		x	x
Sphyrna mokarran	Great hammerhead shark	CR	x		x	x (GFCM, ICCAT)	x (CCAMLR)		x	x
Alopias pelagicus	Pelagic thresher shark	EN	x		x	x (CCSBT^, IOTC)	x (CCAMLR)		x	x
Carcharhinus obscurus	Dusky shark	EN	x				x (CCAMLR)		x	x
Cetorhinus maximus	Basking shark	EN	x		x	x (GFCM)	x (CCAMLR, NEAFC)	x	x	x
Eusphyra blochii	Winghead shark	EN	x			x (ICCAT)	x (CCAMLR)			
Rhinobatos rhinobatos	Common guitarfish	EN				x (GFCM)		x*	x	x
Anoxypristis cuspidata	Narrow sawfish	EN		x				x	x	x
Isurus oxyrinchus	Shortfin mako shark	EN	x		x	x (GFCM, ICCAT*)	x (CCAMLR)		x	x
Isurus paucus	Longfin mako shark	EN	x		x		x (CCAMLR)		x	x
Mobula hypostoma	Atlantic devil ray	EN			x	x (IATTC, IOTC)		x	x	x
Mobula mobular	Giant devil ray	EN			x	x (GFCM, IATTC, IOTC)		x	x	x
Mobula tarapacana	Sicklefin devil ray	EN			x	x (IATTC, IOTC)		x	x	x
Mobula thurstoni	Bentfin devil ray	EN			x	x (IATTC, IOTC)		x	x	x
Pristis clavata	Dwarf sawfish	EN		x				x	x	x
Rhincodon typus	Whale shark	EN	x		x	x (CCSBT^, IOTC**, WCPFC**)	x (CCAMLR)	x	x	x
Alopias superciliosus	Bigeye thresher shark	VU	x		x	x (CCSBT^, GFCM, ICCAT, IOTC)	x (CCAMLR)		x	x
Alopias vulpinus	Common thresher shark	VU	x		x	x (CCSBT, IOTC)	x (CCAMLR)		x	x
Carcharodon carcharias	White shark	VU	x		x	x (GFCM)	x (CCAMLR)	x	x	x
Carcharhinus falciformis	Silky shark	VU	x		x	x (CCSBT^, IATTC, ICCAT, WCPFC)	x (CCAMLR)		x	x
Lamna nasus	Porbeagle shark	VU	x		x	x (GFCM)	x (CCAMLR, NEAFC)		x	x
Mobula alfredi	Reef manta ray	VU			x	x (IATTC, IOTC)		x	x	x
Mobula birostris	Giant manta ray	VU			x	x (IATTC, IOTC)		x	x	x
Mobula munkiana	Smoothtail mobula ray	VU			x	x (IATTC, IOTC)		x	x	x
Mobula rochebrunei	Lesser Guinean devil ray	VU			x	x (IATTC, IOTC)		x	x	x
Sphyrna tudes	Smalleye hammerhead	VU	x			x (ICCAT)	x (CCAMLR)			
Sphyrna zygaena	Smooth hammerhead shark	VU	x		x	x (GFCM, ICCAT)	x (CCAMLR)			x
Squalus acanthias	Spiny dogfish	VU					x (CCAMLR, NEAFC)		x*	x*
Hexanchus griseus	Bluntnose sixgill shark	NT	x				x (CCAMLR, NEAFC)			
Mobula eregoodootenkee	Pygmy devil ray	NT			x	x (IATTC, IOTC)		x	x	x
Mobula japanica	Spinetail devil ray	NT			x	x (IATTC, IOTC)		x	x	x
Prionace glauca	Blue shark	NT	x				x (CCAMLR)		x	
Sphyrna corona	Scalloped bonnethead shark	NT	x			x (ICCAT)	x (CCAMLR)			
Mobula kuhlii	Shortfin devil ray	DD			x	x (IATTC, IOTC)		x	x	x
Sphyrna media	Scoophead shark	DD	x			x (ICCAT)	x (CCAMLR)			

Indicates not a full retention ban in fishery: (ICCAT) Shortfin mako banned landing live animals only. (IATTC*) Silky shark retention banned in purse seine fishery, longline fishery limited to silky shark landings of 20% of total catch, of which 20% of number cannot be juveniles <100cm in length. (CMS App. II and CMS Sharks MOU) *Spiny Dogfish listing applies only to northern hemisphere populations. **Indicates protection in specific gear: (WCPFC**, IOTC **). Whale shark retention banned in purse seine fishery only. ^CCSBT registered vessels fishing within the Convention areas of IOTC, WCPFC and ICCAT must comply with Conservation and Management Measures of those RFMOs.

Twelve species were listed across the policies that were sampled (Table 2.4), meaning they occurred in at least one of the appendices/annexes (binding and non-binding) of each multilateral environmental agreement and in at least one RFMO (no retention or no targeted fishing). The species included, in no particular order: *Isurus oxyrinchus* (Shortfin Mako Shark), *Isurus paucus* (Longfin Mako Shark), *Rhincodon typus* (Whale Shark), *Sphyrna lewini* (Scalloped Hammerhead Shark), *Sphyrna mokarran* (Great Hammerhead Shark), *Alopias pelagicus* (Pelagic Thresher Shark), *Alopias superciliosus* (Bigeye Thresher Shark), *Alopias vulpinas* (Common Thresher Shark), *Carcharodon carcharias* (White Shark), *Carcharhinus falciformis* (Silky Shark), *Cetorhinus maximus (*Basking Shark) and *Lamna nasus* (Porbeagle Shark).

Although species were listed in a number of policies, levels of protection within the policies varied. Despite their global distribution, none of the species were listed in conservation and management measures of all RFMOs. No single species was afforded protection, binding or non-binding, throughout its range. While the Oceanic Whitetip, for example, is listed by all tuna RFMOs as a no retention species, it is not protected from high seas fishing, nor is it listed as no retention in all non-tuna RFMOs. Additionally, there are country-level exemptions creating gaps in protective coverage.

Table 2.5: The percentages of threatened chondrichthyans listed in each policy intervention (e.g. 12.5% of the 42 CR species are listed by UNCLOS). Only species listed as "no retention" in RFMOs were included in the table. CR= Critically Endangered; EN= Endangered; VU= Vulnerable. The bottom row combines figures for the other three rows. Note that not all species are globally distributed, nor are all of the IUCN threatened species eligible for listing on each of the interventions, so 100% is not achievable. CCAMLR has a ban on directed fishing for sharks, but no definition for which species are included. Therefore, I did not apply the CCAMLR ban to rays, skates, chimaeras, wedgefishes, or sawfishes. For the same reason, I excluded the same groups from the SEAFO ban on directed fishing for deepwater sharks.

# Species	Threat Level	UNCLOS	CITES App. I	CITES App. II	CMS App. I	CMS App. II	CMS Sharks MOU	By 1 RFMO	By 2 RFMOs	By 3 RFMOs	By 4 RFMOs	By 5 RFMOs
42	**CR**	19.1%	7.1%	42.9%	9.5%	11.9%	23.8%	26.2%	7.1%	7.1%	2.4%	2.4%
57	**EN**	21.1%	3.5%	15.8%	15.8%	26.3%	22.8%	21.1%	10.5%	8.8%	1.8%	-
107	**VU**	11.2%	-	9.4%	4.7%	9.4%	10.3%	14.0%	7.5%	6.5%	0.9%	-
206	**Threatened**	**15.5%**	**2.4%**	**18.0%**	**8.7%**	**14.6%**	**16.5%**	**18.5%**	**8.3%**	**7.3%**	**1.5%**	**0.5%**

2.3.1. Were definitions clear and consistent?

Threatened: The definition of 'threatened' for species was not consistent and varied amongst the policies that were examined. When assessing a species against its selection criteria, CITES used the IUCN definition of 'threatened''. CMS did not specify a definition of threatened, but used its own definition of 'endangered', which was a migratory species with elevated extinction risk, and a second-tier classification for a species with 'unfavorable conservation status'. CMS's 'endangered' species definition lacked specific criteria for a species to qualify and therefore required fewer rigors to achieve 'endangered' status than IUCN. UNCLOS's text did not specifically define 'threatened' but noted that species "must not be in danger of overexploitation," which relied on that species' ability to produce maximum sustainable yield. UNCLOS did clearly define fishery-specific terms including 'passage', 'innocent passage' and 'piracy'. The RFMOs were mandated by the FAO to keep species populations "above levels at which their reproduction may become seriously threatened." However, they did not specifically or quantitatively define ‘threatened’. CITES Appendix I listings, as included in the Convention text, “shall include all species threatened with extinction which are or may be affected by trade.” While CITES has taxon-specific decline criteria, no quantitative definition of ‘threatened’ or ‘endangered’ was given and no quantitative assessment criteria were defined to measure an effect by trade.

Migratory: The definitions for “migratory” varied between policies. No quantitative distance or documented range thresholds were used to define ‘migratory’ by UNCLOS, CMS, or the CMS Sharks MOU, which are the policies focused on migratory species. Rather, animals were classified as ‘migratory’ if they crossed jurisdictional boundaries, which was consistent across the policies. However, the areas within jurisdictional boundaries are highly variable. For example, a species might not be classified as migratory in Australia, but could be in Asia because of the variations in sizes of the exclusive economic zones. UNCLOS did not specifically define ‘migratory’ or ‘highly migratory’, but created a list of highly migratory species in Annex I that, it stated, “crossed international jurisdiction and the high seas.” The CMS Convention Text defines ‘migratory species’ as “the entire population or any geographically separate part of the population of any species or lower taxon of wild animals, a significant proportion of whose members cyclically and predictably cross one or more national jurisdictional boundaries.” CMS Sharks MOU did not list a specific definition for migratory, although it listed specific definitions for 15 other terms in the MOU Text. However, it listed specific orders in its Annex I of Migratory Sharks, four of which were not listed by UNCLOS’s Convention, including Orectolobiformes, Squaliformes, Pristiformes, and Myliobatiformes.

Precautionary approach*:* Specific reference to either the UN Fish Stocks Agreement (Article 6, Annex II) or the Rio Declaration (Principle 15) definition for ‘precautionary approach’ was found in nine of the fourteen convention texts examined in this review or within amendments to those texts. The definition of ‘precautionary approach’ was consistent amongst those convention texts. UNCLOS preceded the UN Fish Stocks Agreement and the Rio Declaration, and has not been amended since. CMS made no reference to the precautionary approach. CMS Sharks MOU referenced the precautionary approach, not as a measure of when to add species to its Annex, but rather for what signatories are meant to do as part of a conservation plan for species on Annex I.

While CITES referenced the importance of the Rio Declaration precautionary approach (Res 9.24), it created its own language for its application in trade contexts stating that “Parties shall act in the best interest of the conservation of the species.” Of the ten RFMOs that were examined with specific measures for chondrichthyans, no reference to the precautionary approach was found in multiple RFMO texts (e.g. ICCAT, CCSBT, CCAMLR). However, CCAMLR’s Convention texts explicitly defined conservation, rather than sustainable harvest, as a primary objective, which is a precautionary approach that means any extractive activity will be compared to the conservation objective of the Convention area.

For the RFMOs, adherence to the precautionary approach is mandatory, but Tables 2.4 and 2.6 illustrate several examples of sharks that are threatened by and overlap with fisheries but are not listed as protected or no retention species, which is inconsistent with the UN Fish Stocks Agreement’s definition of the precautionary approach. A lack of adherence to the precautionary approach and lack of consistency by RFMOs was also evident in the varying protections for closely related species, or “lookalike” species, for Thresher Sharks, Hammerheads, Makos, and Devil Rays and Manta Rays. Examples of inconsistency included IOTC’s mention of difficulty in differentiating the three species of Thresher Sharks and therefore extending “no retention” policies to all as a precautionary measure, while ICCAT extended protection only to the Bigeye Thresher Shark. Conversely, ICCAT extended protection to all but one Hammerhead Shark because of difficulties in differentiating between species, but IOTC did not list Hammerheads. Further, the precautionary approach was not upheld in the areas of overlap between RFMOs, when similar fishing was occurring (longline and purse seine) and species were protected in one RFMO but not the other. Examples of these species are Silky Shark, Whale Shark, and Giant Manta Ray in the IATTC/WCPFC overlap (Table 2.7 b-c). In RFMOs CCAMLR and SEAFO, all directed fisheries on deep sea sharks were banned until sufficient data showed a sustainable level of take, which was consistent with the precautionary approach definition by UN Fish Stocks. Similarly, NAFO required all sharks to be released alive, which varied with ICCAT’s interpretation of precautionary, in which it allowed take of North Atlantic Shortfin Mako Shark until sufficient data unequivocally showed any take was detrimental to the persistence of the species.

2.3.2. Were species listings consistent by threat level and were those listings consistent across interventions with similar mandate?

Appendix 1, Table A1.1 shows all chondrichthyans that were listed to species level on each of the policies that were examined, and their IUCN Red List threat level.

The percentage of species listed by policies (Table 2.5) was related to threat level for species listings in CITES Appendix I and II, CMS Sharks MOU, and for species listed as no retention by at least 1 RFMO and by at least 4 RFMOs, meaning that the highest percentage of listed species were Critically Endangered (CR), then Endangered (EN), then Vulnerable (VU). Species listed as no retention by at least 1 RFMO had the highest overall percentage of listings, but these listings were not in the same RFMO; rather they were spread across different RFMOs. CMS Appendix II listed the highest total percentage of threatened chondrichthyans (26.3%), whereas CITES Appendix II listed the highest percentage of any threat level category with 42.9% of the 42 Critically Endangered (CR) species, noting, however, that threat level does not necessarily equal threat by trade. Regionally, listings by at least two or more RFMOs were fairly consistent with threat level, noting that not all species listed as threatened by IUCN Red List overlapped with RFMO areas of jurisdiction.

Of the policies that were examined in this study, no single instrument listed more than 20% of the combined threatened species (all three threat level categories, bottom line of 2.5) and less than 10% of all threatened species were listed by two or more RFMOs, even though many (but not all) threatened migratory species overlapped with these fisheries. Gaps in species threat level and policy listings were evident in all threat level categories. Several species were assessed as globally threatened on the IUCN Red List, but not listed consistently across policies, or in any policy, while others were less threatened (lower threat level categories), but were more commonly listed on policies (Table 2.4).

Two Critically Endangered species (*Sphyrna lewini, Sphyrna mokarran*) were listed across the policy categories (i.e. a species listed in at least one RFMO, appendix or annex of each of the policy types) (Table 2.3). Five of 57 Endangered species (*Alopias pelagicus, Cetorhinus maximus, Isurus oxyrinchus, Isurus paucus, Rhincodon typus,*) and five of 107 Vulnerable species (*Alopias superciliosus, Alopias vulpinas, Carcharodon carcharias, Carcharhinus falciformis, Lamna nasus*) were listed across all five policy categories that I examined (Table 2.4). Levels of protection varied for species listed across all five policy categories.

Several chondrichthyan species that were not globally threatened with extinction were listed more frequently than threatened species. Three species of mobulid rays (two Near Threatened and one Data Deficient) were listed in CITES Appendix II, CMS Appendices I and II, CMS Sharks MOU, and as no retention species in the RFMOs IATTC and IOTC, which were the only tuna RFMOs to list rays as no retention species. The mobulids were listed in CITES, CMS and IATTC because of “lookalike” provisions, which provide justification for listing species that closely resemble listed species or are difficult to distinguish as listed species. However, similar provisions were not consistently made for other threatened species in the policies, including wedgefishes, Hammerhead Sharks, Thresher Sharks or Mako Sharks (Table 2.4).

Inconsistencies across interventions with similar mandates were similar to those uncovered by threat level. In some cases, species with higher threat levels were left off interventions while species with lower threat levels were included. There was no consistency or pattern for listing lookalike species. Reciprocal listings between interventions for species were uncommon, such as overlapping RFMOs listing the same species for protections, even when gears, target species (e.g. tuna), and chondrichthyan species distributions were similar. Inconsistent species listings occurred across overlapping tuna and non-tuna RFMOs in every ocean. Reciprocal listings were also inconsistent for CITES-listed species between CITES and the RFMOs.

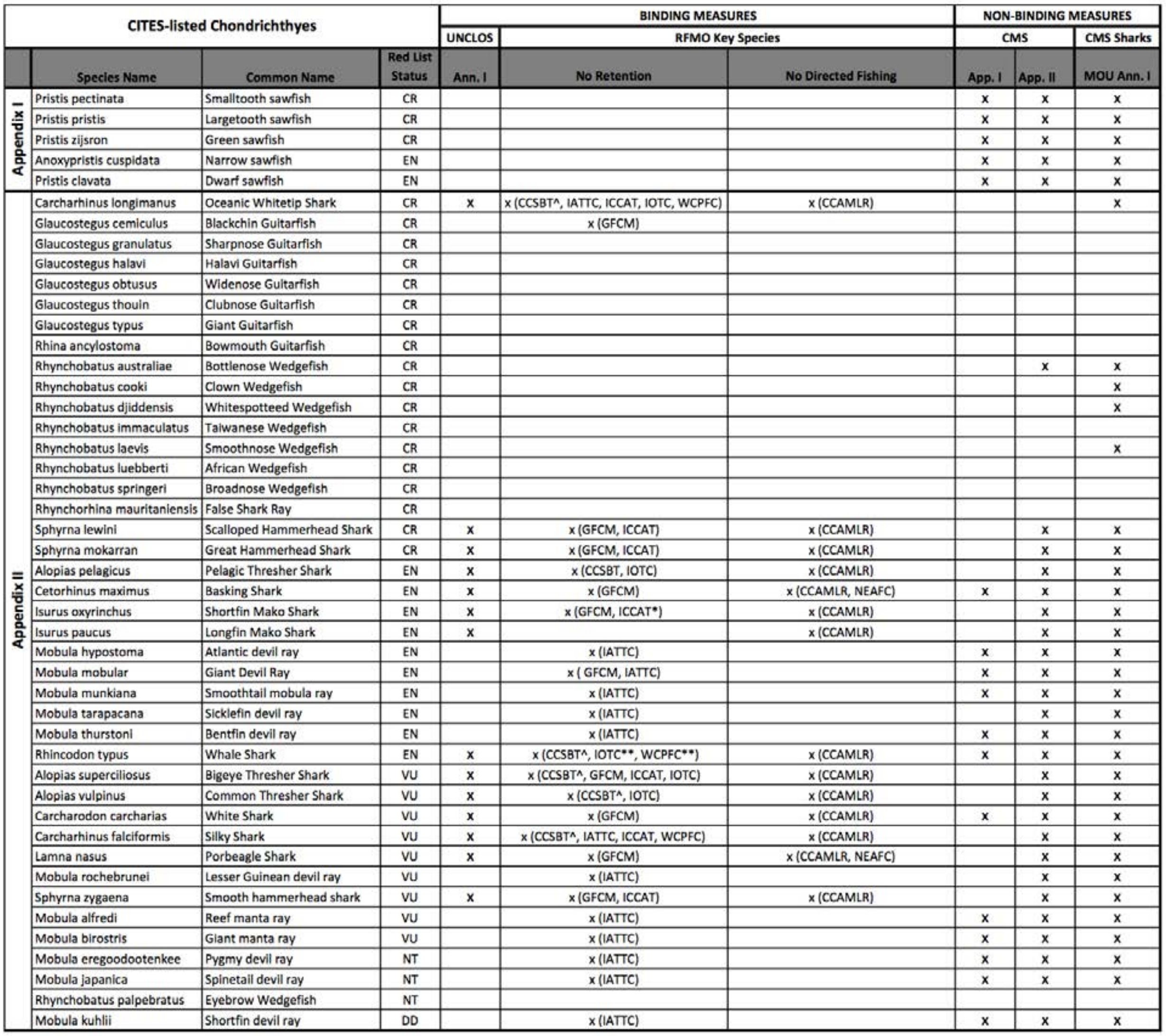
Among the migratory species interventions (UNCLOS, CMS, and CMS Sharks MOU), several Critically Endangered and Endangered species were missing while species in lower threat levels were listed. It should be noted that the UNCLOS list was not compiled based on threat level, but was meant to be updated regularly. For example, the Critically Endangered Oceanic Whitetip Shark (*Carcharhinus longimanus*) and Endangered Winghead Shark (*Eusphyra blochii*) were listed in Annex I of Highly Migratory Species on UNCLOS (Table 2.3). Neither shark was listed by the CMS Appendices and the CMS Sharks MOU did not list the Endangered Winghead Shark. However, all three species of Thresher sharks (*Alopias* spp.), two of which are categorized in a lower threat level (Vulnerable), were consistently listed on the same three policies. There was no taxon-specific pattern as to which species were listed, nominated or rejected for inclusion on interventions, except that UNCLOS listed no rays.

In fisheries interventions (RFMOs, both tuna and non-tuna, UNCLOS) there were inconsistent listings of "no retention" species amongst tuna RFMOs and RFMOs that overlapped spatially. For example, while the Oceanic Whitetip Shark was listed by all five tuna RFMOs, no tuna RFMO listed the globally Endangered Shortfin Mako Shark as a no retention species, despite its elevated global threat level and vulnerability to the same gears as the Oceanic Whitetip. The tuna RFMO IOTC listed all three species of Thresher sharks (one Endangered, two Vulnerable) as no retention species due to difficulties in telling them apart (lookalikes). However, ICCAT and GFCM listed only the Vulnerable Bigeye Thresher Shark (*Alopias superciliosus*) as no retention despite morphological similarities of the other two Thresher Sharks. ICCAT did list all Hammerheads (except *S. tiburo*) as no retention under lookalike clauses, which was inconsistent with its own listings by not listing all Thresher Sharks.

In several RFMOs, taxon-specific species lists were missing, making taxon-specific comparisons difficult. For several RFMOs that spatially overlapped, there were no instructions on how the RFMO handled areas of overlapping jurisdiction and reciprocal species listings. In the CCSBT overlap with other RFMOs, CCSBT had reciprocal protections for non-target species. However, for other areas of overlap, species listings were inconsistent. For example, Whale Sharks are globally Endangered and listed as no retention species for purse seine vessels by WCPFC, but not by IATTC. Conversely, Giant Manta Rays (*Mobula birostris*) are globally Vulnerable and listed as no retention species (all gears) by IATTC, but not by WCPFC. In the area of overlap, vessels are allowed to choose which regulations by which they will abide, for a period of not less than three years.

This review sampled only one policy intervention that focused on trade in chondrichthyans (CITES), so it was impossible to compare other listings for consistent protections from threat by trade. Therefore, I analyzed policies that influenced trade and looked for inconsistencies between those listings and the CITES listings (Table 2.6 and Appendix 1 Table A1.1). CITES-listed species were listed inconsistently in fisheries and migratory species interventions and I found the inconsistencies similar to those uncovered within migratory species and fisheries interventions. For example, eighteen Critically Endangered species were listed on CITES Appendix II, rather than Appendix I which has the strictest trade regulations, noting that three of the sharks (*Carcharhinus longimanus, Sphyrna lewini, Sphyrna mokarran)* were reassessed as Critically Endangered after the most recent CITES meeting. I also noted species that were listed by CITES but not in other interventions. Specifically, 12 CITES Appendix II species were not listed elsewhere. Notably, of the seven Critically Endangered wedgefishes most recently listed on CITES Appendix II, only one (*Rhynchobatus australiae*) was listed on both CMS Appendix II and CMS Sharks MOU (Table 2.6).

Table 2.6: CITES Appendix I and II listed chondrichthyans and their listings in fisheries and migratory species policies. CCAMLR has a ban on directed fishing for sharks, but no definition for which species are included so I did not apply the CCAMLR ban to rays, wedgefishes, or sawfishes. However, I extended CCAMLR's ban to all sharks, whether or not the species were likely to occur in the CCAMLR convention area, because the policy said, "sharks".



CITES-listed Chondrichthyes				BINDING MEASURES			NON-BINDING MEASURES		
				UNCLOS	RFMO Key Species		CMS		CMS Sharks
	Species Name	Common Name	Red List Status	Ann. I	No Retention	No Directed Fishing	App. I	App. II	MOU Ann. I
Appendix I	Pristis pectinata	Smalltooth sawfish	CR				x	x	x
	Pristis pristis	Largetooth sawfish	CR				x	x	x
	Pristis zijsron	Green sawfish	CR				x	x	x
	Anoxypristis cuspidata	Narrow sawfish	EN				x	x	x
	Pristis clavata	Dwarf sawfish	EN				x	x	x
Appendix II	Carcharhinus longimanus	Oceanic Whitetip Shark	CR	x	x (CCSBT^, IATTC, ICCAT, IOTC, WCPFC)	x (CCAMLR)			x
	Glaucostegus cemiculus	Blackchin Guitarfish	CR		x (GFCM)				
	Glaucostegus granulatus	Sharpnose Guitarfish	CR						
	Glaucostegus halavi	Halavi Guitarfish	CR						
	Glaucostegus obtusus	Widenose Guitarfish	CR						
	Glaucostegus thouin	Clubnose Guitarfish	CR						
	Glaucostegus typus	Giant Guitarfish	CR						
	Rhina ancylostoma	Bowmouth Guitarfish	CR						
	Rhynchobatus australiae	Bottlenose Wedgefish	CR					x	x
	Rhynchobatus cooki	Clown Wedgefish	CR						x
	Rhynchobatus djiddensis	Whitespotteed Wedgefish	CR						x
	Rhynchobatus immaculatus	Taiwanese Wedgefish	CR						
	Rhynchobatus laevis	Smoothnose Wedgefish	CR						x
	Rhynchobatus luebberti	African Wedgefish	CR						
	Rhynchobatus springeri	Broadnose Wedgefish	CR						
	Rhynchorhina mauritaniensis	False Shark Ray	CR						
	Sphyrna lewini	Scalloped Hammerhead Shark	CR	x	x (GFCM, ICCAT)	x (CCAMLR)		x	x
	Sphyrna mokarran	Great Hammerhead Shark	CR	x	x (GFCM, ICCAT)	x (CCAMLR)		x	x
	Alopias pelagicus	Pelagic Thresher Shark	EN	x	x (CCSBT, IOTC)	x (CCAMLR)		x	x
	Cetorhinus maximus	Basking Shark	EN	x	x (GFCM)	x (CCAMLR, NEAFC)	x	x	x
	Isurus oxyrinchus	Shortfin Mako Shark	EN	x	x (GFCM, ICCAT*)	x (CCAMLR)		x	x
	Isurus paucus	Longfin Mako Shark	EN	x		x (CCAMLR)		x	x
	Mobula hypostoma	Atlantic devil ray	EN		x (IATTC)		x	x	x
	Mobula mobular	Giant Devil Ray	EN		x (GFCM, IATTC)		x	x	x
	Mobula munkiana	Smoothtail mobula ray	EN		x (IATTC)		x	x	x
	Mobula tarapacana	Sicklefin devil ray	EN		x (IATTC)			x	x
	Mobula thurstoni	Bentfin devil ray	EN		x (IATTC)		x	x	x
	Rhincodon typus	Whale Shark	EN	x	x (CCSBT^, IOTC**, WCPFC**)	x (CCAMLR)	x	x	x
	Alopias superciliosus	Bigeye Thresher Shark	VU	x	x (CCSBT^, GFCM, ICCAT, IOTC)	x (CCAMLR)		x	x
	Alopias vulpinus	Common Thresher Shark	VU	x	x (CCSBT^, IOTC)	x (CCAMLR)		x	x
	Carcharodon carcharias	White Shark	VU	x	x (GFCM)	x (CCAMLR)	x	x	x
	Carcharhinus falciformis	Silky Shark	VU	x	x (CCSBT^, IATTC, ICCAT, WCPFC)	x (CCAMLR)		x	x
	Lamna nasus	Porbeagle Shark	VU	x	x (GFCM)	x (CCAMLR, NEAFC)		x	x
	Mobula rochebrunei	Lesser Guinean devil ray	VU		x (IATTC)			x	x
	Sphyrna zygaena	Smooth hammerhead shark	VU	x	x (GFCM, ICCAT)	x (CCAMLR)		x	x
	Mobula alfredi	Reef manta ray	VU		x (IATTC)		x	x	x
	Mobula birostris	Giant manta ray	VU		x (IATTC)		x	x	x
	Mobula eregoodootenkee	Pygmy devil ray	NT		x (IATTC)		x	x	x
	Mobula japanica	Spinetail devil ray	NT		x (IATTC)		x	x	x
	Rhynchobatus palpebratus	Eyebrow Wedgefish	NT						
	Mobula kuhlii	Shortfin devil ray	DD		x (IATTC)		x	x	x

Indicates not a full retention ban in fishery: (ICCAT) Shortfin mako banned landing live animals only. (IATTC*) Silky shark retention banned in purse seine fishery, longline fishery limited to silky shark landings of 20% of total catch, of which 20% of number cannot be juveniles <100cm in length. (CMS App II and CMS Sharks MOU) *Spiny Dogfish listing applies only to northern hemisphere populations. **Indicates protection in specific gear:

(WCPFC**, IOTC **) Whale shark retention banned in purse seine fishery only. ^CCSBT registered vessels fishing within the Convention areas of IOTC, WCPFC and ICCAT must comply with Conservation and Management Measures of those RFMOs.

2.3.3. Were species listings on each policy consistent with the policy's stated intent and species listing criteria?

I did not find any listing criteria for the families of species listed in UNCLOS' Annex I of Highly Migratory Species, nor were any criteria available from RFMOs to designate species as requiring special management, such as listing them as no retention species or setting catch limits. The tuna RFMO WCPFC, however, described a qualitative process for prioritizing key species that required conservation and management measures. The listing criteria for CMS and CITES were defined and available online. CITES' listing criteria were the most prescriptive and included biological thresholds and quantitative taxon-specific decline criteria. However, both CMS and CITES lacked quantitative thresholds for terms upon which their criteria depended (additional description can be found in Appendix 1 Text A1.1). For example, CMS lacked quantitative thresholds for how species were classified as 'migratory' or 'endangered'. Further, in CMS's migratory definition, a "significant proportion" of a population must cross boundaries, but there was no definition for what constituted "significant". Similarly, CITES did not quantitatively define how species qualified as 'threatened' or 'endangered' by trade, but CITES did have quantitative taxon-specific decline criteria. Several RFMOs (ICCAT and IOTC) discussed species' vulnerability, but no quantitative threshold was outlined for how species qualified as 'vulnerable.' For CMS, CITES, and the RFMOs that relied on terms identical to those used in the IUCN Red List process, none specifically referenced or adopted IUCN's quantitative assessment criteria associated with its threat level listings, or discussed how the evidentiary standard used by IUCN related to the terms in their respective policies. For example, while CITES had quantitative taxon-specific decline criteria, it was unclear how it identified a species as Endangered. Whether species were listed on the appendices and annexes of CMS and CITES or by any of the RFMOs did not depend solely on species meeting listing criteria; rather, listings depended first on nominations and then votes by the membership.

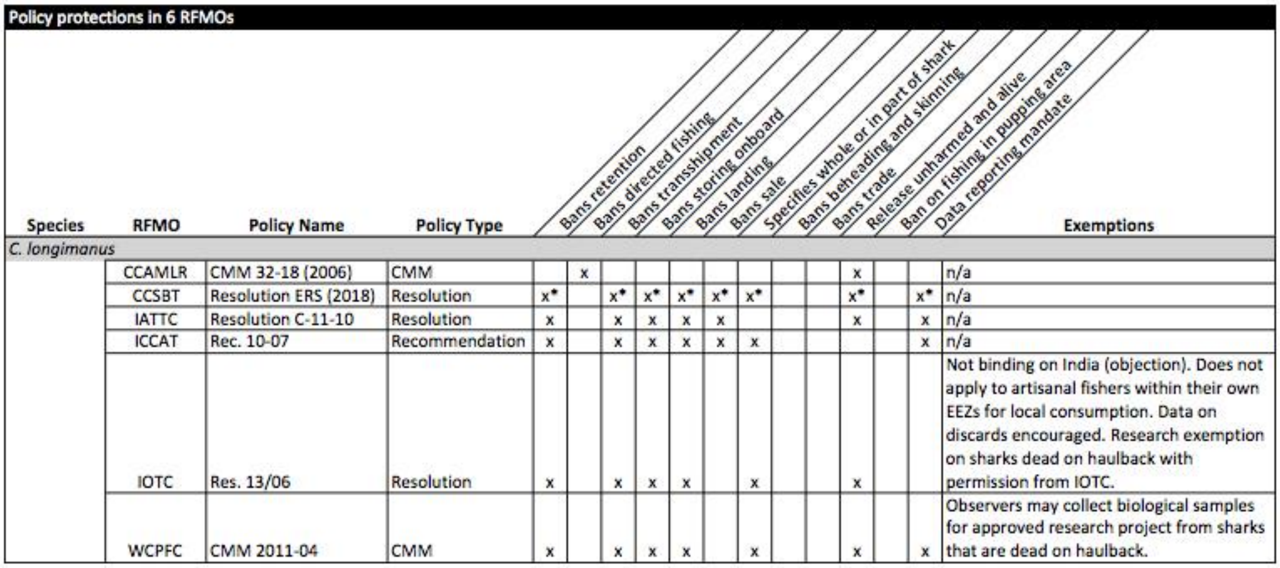
Despite the missing criteria or lack of quantitative thresholds for terms upon which criteria depend, gaps and inconsistencies in species listings and policy listing criteria were evident in all of the policies that were examined. For example, CITES Appendices did not list two Critically Endangered species, *Squatina squatina* and *Rhinobatos rhinobatos* (Table 2.4). Parts of these species may be internationally traded (Dent & Clarke 2015; CMS Sharks MOU 2018), but I was unable to determine whether their Critically Endangered status was the result of trade. In CMS, CITES and amongst the RFMOs, vague criteria enabled flexibility and inconsistent application. The Vulnerable White Shark (*Carcharodon carcharias*) was listed in CMS Appendix I, which calls for no take, while Endangered Mako Sharks and several Endangered hammerheads were listed on CMS Appendix II, which does not ban take (Table 2.4), which also highlighted the lack of consistency between criteria and listings for lookalike species. Finally, several species were proposed but not listed, and the absence of sufficient data was used as the reason to stall conservation measures while other species were listed when similar data restrictions were present. For example, ICCAT did not list the Shortfin Mako Shark as no retention, stating a lack of sufficient data, but it did list all hammerhead sharks, despite lacking data on all species. Conversely, GFCM listed all species that were in the Barcelona Convention as no retention, in the absence of stock assessment data, and all deepwater sharks were listed by SEAFO and NEAFC as species prohibited from directed fishing efforts, despite a lack of quantitative data on their catch histories. These inconsistencies highlighted the role of politics in species listings.

2.3.4. Was level of protection afforded by the policies consistent across interventions?

Levels of protection were not consistent across interventions. First, policy type names (Table 2.7 A) were used interchangeably and were either binding or non-binding, depending on the RFMO. For example, ‘Resolutions’ are binding in IOTC and IATTC, but non-binding in WCPFC, which overlaps with IATTC. Similarly, this review found inconsistent protections by species, gear type and amongst prohibited activities for “no retention” species in RFMOs. The Porbeagle Shark (*Lamna nasus*) was listed by several RFMOs as a species requiring special management, but levels of protection within the RFMOs varied. ICCAT and NEAFC mandated data reporting and swift release of hooked Porbeagle Sharks. NEAFC added a directed fishing ban. GFCM prohibited the most activities and also banned landing, retention, storing onboard, transshipment or sale of Porbeagle Shark parts (Table 2.7 B). Similarly, inconsistent activities were found amongst tuna RFMOs that designated species as no retention, even when the no retention measures were directed at vessels fishing with the same gear, such as longline or purse seine vessels. Some had data reporting mandates, some had artisanal fisher exemptions, and some banned retention in one gear and not another (Table 2.7 A-B, Appendix 1 Tables A1.2 A-C). For example, Silky Sharks (*Carcharhinus falciformis*) were banned from retention by IATTC on purse seine vessels, but catch was permitted on some longline vessels (Table 2.7 B). However, the bordering (and spatially overlapping) RFMO WCPFC banned Silky Shark retention in both gears. This review also found that prohibited activities varied within a single RFMO. Different activities were prohibited/mandated for two species listed as no retention in IOTC, *Carcharhinus longimanus* (Oceanic Whitetip Shark, Table 2.7 A) and *Alopias superciliosus* (Bigeye Thresher Shark, Appendix 1 Table A1.2 A), with more restrictions mandated for the Bigeye Thresher Shark.

Table 2.7: Species-specific protections for chondrichthyans in RFMOs (a) Policy protections for species listed in 6 RFMOs. (b) Policy protections for species listed in 5 RFMOs. The policy protections for species in four, three and two RFMOs, are in Appendix I Tables A1.2 a-c.

(a) Policy protections for species listed in 6 RFMOs.

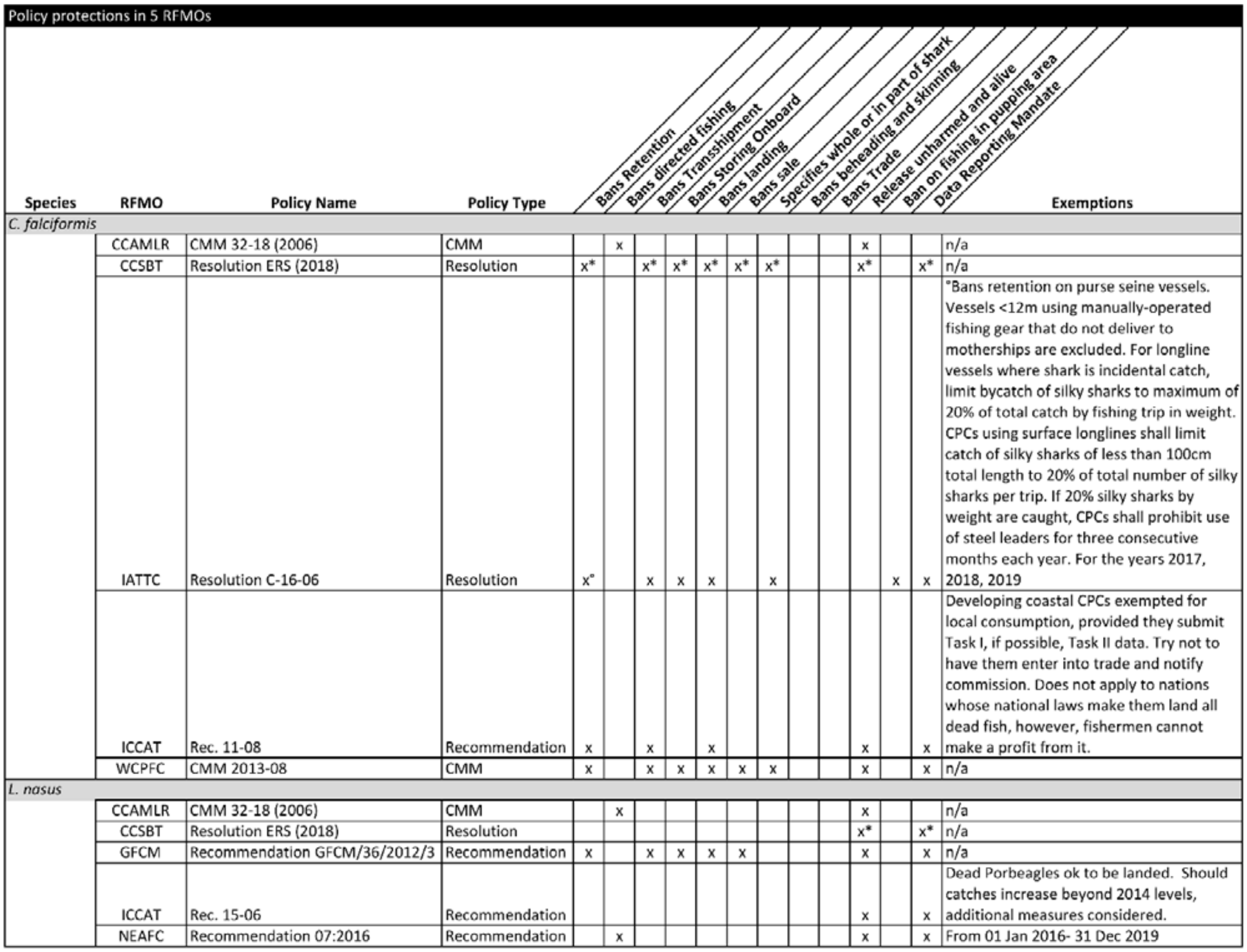


Policy protections in 6 RFMOs

Species	RFMO	Policy Name	Policy Type	Bans retention	Bans directed fishing	Bans transshipment	Bans storing onboard	Bans landing	Bans sale	Specifies whole or in part of shark	Bans beheading and skinning	Bans trade	Release unharmed and alive	Ban on fishing in pupping area	Data reporting mandate	Exemptions
C. longimanus																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	CCSBT	Resolution ERS (2018)	Resolution	x*		x*	x*	x*	x*	x*			x*		x*	n/a
	IATTC	Resolution C-11-10	Resolution	x		x	x	x	x				x		x	n/a
	ICCAT	Rec. 10-07	Recommendation	x		x	x	x	x	x					x	n/a
	IOTC	Res. 13/06	Resolution	x		x	x	x		x			x			Not binding on India (objection). Does not apply to artisanal fishers within their own EEZs for local consumption. Data on discards encouraged. Research exemption on sharks dead on haulback with permission from IOTC.
	WCPFC	CMM 2011-04	CMM	x		x	x	x		x			x		x	Observers may collect biological samples for approved research project from sharks that are dead on haulback.

x* CCSBT Resolution ERS (2018) mandates that vessels fishing in the overlapping RFMO must abide by the conservation and management measures of the overlapping RFMO. In the case above, vessels must abide by either ICCAT or WCPFC conservation and management measures when operating in the respective area of overlap. CMM: Conservation and Management Measure

(b) Policy protections for species listed in 5 RFMOs.



Policy protections in 5 RFMOs

Species	RFMO	Policy Name	Policy Type	Bans Retention	Bans directed fishing	Bans Transshipment	Bans Storing Onboard	Bans landing	Bans sale	Specifies whole or in part of shark	Bans beheading and skinning	Bans Trade	Release unharmed and alive	Ban on fishing in pupping area	Data Reporting Mandate	Exemptions
C. falciformis																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	CCSBT	Resolution ERS (2018)	Resolution	x*		x*	x*	x*	x*	x*			x*		x*	n/a
	IATTC	Resolution C-16-06	Resolution	x°		x	x	x		x				x	x	°Bans retention on purse seine vessels. Vessels <12m using manually-operated fishing gear that do not deliver to motherships are excluded. For longline vessels where shark is incidental catch, limit bycatch of silky sharks to maximum of 20% of total catch by fishing trip in weight. CPCs using surface longlines shall limit catch of silky sharks of less than 100cm total length to 20% of total number of silky sharks per trip. If 20% silky sharks by weight are caught, CPCs shall prohibit use of steel leaders for three consecutive months each year. For the years 2017, 2018, 2019
	ICCAT	Rec. 11-08	Recommendation	x		x		x					x		x	Developing coastal CPCs exempted for local consumption, provided they submit Task I, if possible, Task II data. Try not to have them enter into trade and notify commission. Does not apply to nations whose national laws make them land all dead fish, however, fishermen cannot make a profit from it.
	WCPFC	CMM 2013-08	CMM	x		x	x	x	x	x			x		x	n/a
L. nasus																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	CCSBT	Resolution ERS (2018)	Resolution										x*		x*	n/a
	GFCM	Recommendation GFCM/36/2012/3	Recommendation	x		x	x	x	x				x		x	n/a
	ICCAT	Rec. 15-06	Recommendation										x		x	Dead Porbeagles ok to be landed. Should catches increase beyond 2014 levels, additional measures considered.
	NEAFC	Recommendation 07:2016	Recommendation		x								x		x	From 01 Jan 2016- 31 Dec 2019

x* CCSBT Resolution ERS (2018) mandates that vessels fishing in the overlapping RFMO must abide by the conservation and management measures of the overlapping RFMO. In the case above, vessels must abide by either ICCAT or WCPFC conservation and management measures when operating in the respective area of overlap.

2.3.5. Were species listed on binding or non-binding policies and was policy language prescriptive for what governments and fishers were bound to do?

A detailed synopsis per policy intervention is available in Appendix 1 Text A1.3.

Of the policy interventions and related binding and non-binding appendices and annexes that were sampled, 156 chondrichthyans were listed to species level on at least one policy, including 74 listed as threatened: Critically Endangered (CR) = 32, Endangered (EN) = 21, Vulnerable (VU) = 24, Near Threatened (NT) = 27, Least Concern (LC) = 28, and Data Deficient (DD) = 24. Of the chondrichthyans listed to species level, all were listed on at least one binding policy examined, which included UNCLOS, the CITES Appendices, or by a binding RFMO conservation and management measure. Thirty-eight species were also listed on the non-binding CMS Appendices and CMS Sharks MOU (Appendix 1 Table A1.1)

All policies, whether binding or non-binding, required implementation by states to be effective (see Appendix 1 Text A1.3 for breakdown per policy). CITES Appendices I and II were binding, clear, and prescriptive on what states were bound to do. UNCLOS and the RFMOs lacked prescription for effective implementation, and had no clear guidelines for enforcement and compliance. The non-binding nature of the CMS Appendices and CMS Sharks MOU meant that there was no legal culpability for states that did not comply. Still, prescription was lacking in binding and non-binding policies. UNCLOS, CMS (Appendix II) and the CMS Sharks MOU directed states to work together to design conservation plans, but no standards were set as to how states were meant to work together or what plans should contain or aim to achieve. Prescription amongst the RFMOs varied, with few binding policies providing prescription necessary for effective implementation, such as clear spatial and temporal restrictions, clear and consistent fishing gear restrictions, described banned activities, taxon-specific definitions, or clear instructions on data collection and safe release guidelines. Policies also lacked definitions upon which implementation depended. SEAFO and NEAFC had binding resolutions that prohibited targeted fishing for deepwater sharks. However, no definition for ‘targeted fishing’ was given, meaning that no gear, depth, or spatial or temporal limits were specified. SEAFO did not list species names to determine which species constituted ‘deep water sharks’, nor was a depth limit specified. Similarly, ICCAT's binding resolution for no retention on hammerhead sharks (Table 2.7 c) stated that states, "should try not to increase catch", but with no prescription or quantitative catch limits to guide implementation, enforcement, or compliance. While resolutions existed within RFMOs and their basic texts called on the roles of compliance committees to review implementation of the policies, no specific reference was made by any RFMO in any chondrichthyan-specific binding protective measure to define the compliance process of either the Commission or member states, or describe the process and any associated penalties for non-compliance.

With the exception of CITES's Review of Significant Trade, no policy outlined or referenced punitive measures for lack of implementation, enforcement, or compliance of the binding policies that were examined. While the process for compliance committees' reviews of implementation might have been written into Convention texts or other associated documents, no policy directly referenced them in the policies that listed chondrichthyans. It was unclear what course of action would follow should vessels, member states, or flag states contravene the binding policy, whether by lack of implementation or lack of enforcement or compliance.

2.4. DISCUSSION:

Some of the shortcomings of multilateral environment agreements and RFMO policies have been discussed previously. These include data gaps (Camhi et al. 2009; Clarke et al. 2013, 2014; Bräutigam et al. 2015; Davidson et al. 2016; Dent & Clarke 2015; Dulvy et al. 2017), lack of funding (Clarke et al. 2013; Fowler 2014; Bräutigam et al. 2015; Dent & Clarke 2015), lack of capacity (Hanich & Tsamenyi 2009; Lack & Sant 2011; Bräutigam et al. 2015), too few species listed (Camhi et al. 2009; Fowler 2014; Vincent et al. 2014), need for consensus for species listings (Gjerde et al. 2008, 2013), lack of transparency at RFMOs (Hanich & Tsamenyi 2009; Lack & Sant 2011), lack of central enforcement (Gjerde et al. 2008; Camhi et al. 2009), political interference (Butterworth 1992; Sutherland et al. 2004; Hanich & Tsamenyi 2009; Pressey et al. 2017; Cramp et al. 2018), and lack of compliance (Gjerde et al. 2008; Dulvy et al. 2008; Lack & Sant 2011; Clarke et al. 2013, 2014; Bräutigam et al. 2015; Trouwborst 2015). This analysis examined the specifics of the policies and the species listings themselves and uncovered the underlying factors of many of the issues uncovered by others. The gaps and inconsistencies found by this analysis led not only to uncertainty over levels of protection, but create loopholes that are detrimental to conservation outcomes for chondrichthyans. These deficiencies create challenges in the listing process, make effective implementation difficult, allow continued exploitation, and, importantly, leave many threatened species without adequate management. This situation is exacerbated by limited capacity in many organizations to quantitatively assess the number of species requiring management and the levels of required management, but also by the role of politics in species listings. When species listings are determined by nominations and votes, as is the case in all RFMOs, CITES, CMS, and the CMS Sharks MOU, the political motivations of stakeholders must be considered as a limitation when decision-making requires consensus. I found that, even when species are listed, the inconsistencies and vague definitions applied could thwart protections by allowing flexibility in implementation and compliance. This review highlights areas that, if amended, could reduce the shortcomings uncovered by this and other reviews, thereby strengthening conservation outcomes for chondrichthyans.

2.4.1 Inconsistent or incomplete definitions and criteria

Vague and unclear definitions in policies and their listing criteria not only prevented species listings, but also created gaps in listings and loopholes in the policies, precluding effective implementation and protection by allowing for continued exploitation. This analysis highlighted the absence of quantitative criteria, which contributed to confusion over whether species should be considered for listing, and which level of listing was most appropriate. Similarly, based on this analysis, the terms "threatened" and "endangered" were used interchangeably among listing criteria, which can create further confusion for stakeholders over appropriate conservation and management measures required for species, including stakeholders tasked with voting on species listings. For policies without adequate definitions in terms or listing criteria, interpretation and decisions are left to the people in the room on the day, which is less rigorous and defensible through time. For example, species that previously qualified for listing as "endangered" or "threatened" might not qualify today, resulting in a shifting baseline for listing criteria and increasing resistance to species listings. Conversely, species could be listed today that would not have qualified, or not have been advocated for, in the past. Too few species have conservation and management measures in place (McClenachan et al. 2012; Bräutigam et al. 2015) and the lack of rigor in listing widens the inconsistencies between policies and IUCN Red List threat levels. I found a lack of consistency in how and when species were listed by multilateral environment agencies and RFMOs, which was consistent with the outcome from the study by Lawson and Fordham (2019) during their analysis of CMS Appendix I listings.

There were also major inconsistencies related to the listing of species when data were lacking on conservation status. Despite the proclaimed adherence to the precautionary approach by nine of the policies that were examined, I found inconsistencies in its application by RFMOs and multilateral environment agencies. The precautionary approach calls for species under threat to be listed in the absence of adequate data (FAO 1995; UN 1995), and a precedent exists in RFMOs that support this approach, including lookalike clauses for species. I found different responses to uncertainty, not just between policies with similar mandates, such as policies directed at migratory species or at fisheries, but also within a single management forum, meaning the individual agencies have not yet established their own standards for species-specific policy protections.

Wang *et al* (Wang 2011) questioned what level of uncertainty in data is required by management agencies before the precautionary approach is applied, or in the case of this analysis, before nominating and voting for species listings on conservation and management interventions. Similar inconsistencies existed in each of the policies that were examined, which aligned with previous studies that noted the inconsistent interpretation and inadequate application of the precautionary approach (Davies & Polacheck 2007; Wang 2011). It might be difficult in the short term to reverse limited capacity and funding in fisheries management related to non-target or bycatch species like chondrichthyans. However, implementation, enforcement and compliance problems are worsened when critical definitions upon which policy criteria depend are left vague, intentionally or unintentionally. Multilateral environment agencies should formalize how they respond to uncertainty, including when the precautionary approach will be applied. Based on the results of this analysis, I conclude that, when interpretation is left to individual stakeholders, economic incentives or political motives can prevail over the need for species protection. Importantly, states and/or individuals can also choose whether or not to be precautionary, to nominate or vote for species, or to comply with listing criteria.

2.4.2 Unclear levels of protection

As a result of this analysis, the lack of rigor and attention to detail in policy language led to questions about actual levels of protection afforded or intended for listed chondrichthyans. When coupled with missing definitions and inconsistent species listings, the lack of prescription about protection can facilitate political interference and encourage inconsistent interpretation of policy intent. Examples are vague, non-transparent or missing implementation guidelines and compliance protocols, inconsistent protections within and across policies, a lack of effective deterrents, and the absence of monitoring and evaluations of effectiveness (Camhi et al. 2009; Clarke et al. 2013). There are numerous barriers to conservation and management of chondrichthyans that might be difficult to change, including limited financing, capacity, and political will (Ferraro & Pattanayak 2006; Gjerde et al. 2008; Dulvy et al. 2008; Hanich & Tsamenyi 2009; Clarke et al. 2013; Bräutigam et al. 2015). However, I believe that several of the underlying policy problems, including clarity around levels of protection, could be overcome with limited effort, reducing the weaknesses in implementation, enforcement, and compliance.

The success of multilateral environment agreements and conservation and management measures by RFMOs relies on implementation, enforcement, and compliance by member and flag states (Gjerde et al. 2008; Hanich & Tsamenyi 2009; Trouwborst 2015), many of which are limited in capacity (Chakalall et al. 2007; Hanich & Tsamenyi 2009; Hanich et al. 2010; Lawson & Fordham 2019). As others have recommended, this review underscores the importance of states to implement their international obligations (Dulvy et al. 2008; Camhi et al. 2009; Clarke et al. 2013; Gjerde et al. 2013; Fowler 2014; Trouwborst 2015), but I believe, by clarifying definitions, criteria, and enforcement and compliance mechanisms, that listings, consistency between policies and implementation will be more straightforward, leading to a greater understanding of levels of protection afforded by each policy intervention.

Similarly, when policies are implemented through fishery management tools, which regulate the activities of fishers directly responsible for reducing chondrichthyan mortality at-vessel, ambiguity can be problematic. Ambiguous terms from RFMOs include which species are "sharks" or "deep water sharks", what constitutes "targeting" species, and how vessels "should make every effort to minimize harm" to species, or to release "juveniles". The terms "should" and "encourage", and phrases such as "minimize harm" are not concrete, measureable, or enforceable when directing states to implement actions in binding policies. Likewise, artisanal exemptions without explicitly defining which fishers are artisanal, or stating that pupping grounds are off limits without providing coordinates or spatial or temporal restrictions, create loopholes and restrict states' ability to effectively implement and enforce chondrichthyan protections. Fishers, enforcement officers, fisheries managers, and legal teams can interpret loosely defined terms and phrases differently, potentially increasing challenges of enforcement and compliance (Arias et al. 2014) and ultimately reducing the effectiveness of the policies or fishery management tools.

Additionally, a mandate to collect data, but without a plan for which data to collect and how to collect them, can result in limited data or the wrong data being submitted to management agencies, thereby widening data gaps that already exist (Simpfendorfer et al. 2002; Pressey 2004; Dulvy et al. 2008; Clarke et al. 2013, 2015).

Whether or not policy detail is left vague intentionally, lack of prescription reduces the likelihood of effective implementation, compromises mortality reduction of listed species, and wastes already limited resources on ineffective protections for chondrichthyans. Providing time-bound policies with clear definitions and direction on how to reduce chondrichthyan mortality would reduce ambiguity for fishers and states that might otherwise comply. Examples of required clarifications include clear definitions for key terms such as migratory, endangered, and artisanal, taxon-specific species lists, clear guidelines for data collection, gear restrictions, handling measures, size limits, depth limits, soak times, and spatial and temporal restrictions (Cullis-Suzuki & Pauly 2010).

In addition to vagueness about prohibited activities, this analysis highlighted that prescribed levels of protection varied within and amongst multilateral environment agreements and RFMOs. Chondrichthyan protection is weakened when one agency lists an animal for prohibition of take or trade, but a parallel or overlapping agency does not. Uniformity amongst RFMOs for which activities are prohibited, or mandated, as part of a “no retention” measure, would not only promote periodic discussion on best available information, such as handling measures to reduce post-release mortality (Hutchinson et al. 2015, 2017), but would limit confusion and ambiguity for fishers and implementing agencies, which could strengthen conservation outcomes for chondrichthyans.

Compliance processes for all policies were either missing or difficult to locate and interpret. With the exception of CITES’ ability to enforce trade sanctions on nations (CITES n.d.), multilateral environment agreements and RFMOs are unable to enforce policy restrictions or impose fines on vessels because enforcement is the responsibility of member- or flag-states. Clear and transparent compliance processes, including effective deterrents for non-compliance, could increase conservation impact from policies for chondrichthyans, even within capacity limitations at state and regional levels (Gjerde et al. 2008; Dulvy et al. 2008; McClenachan et al. 2012; Arias et al. 2014; Ban et al. 2014). It is important to mandate periodic reviews (Gilman et al. 2008; Cullis-Suzuki & Pauly 2010; Lack & Sant 2011; Clarke et al. 2013) to understand not only if policies are clear and effective, but also which policies are effective and if amendments would result in real change (Ferraro & Pattanayak 2006; Dulvy et al. 2008; Clarke et al. 2013; Pressey et al. 2017; Cramp et al. 2018). To achieve this, the same rigor needs to be applied to policy writing that is applied to stock assessments and other biodiversity or ecological research (Ferraro & Pattanayak 2006).

2.4.3 Role of politics in listings

The review results showed that policies for chondrichthyan conservation and sustainable management left room for significant political interference from inception through species listings, implementation, enforcement, and compliance. The current structure, capacity, and funding for chondrichthyan management still relies on a piecemeal approach of nomination and voting for a few individual species. At the outset, the species nomination process requires species advocates, which presents problems because some scientists are unwilling to step into an advocacy role. Subsequently, the need for conservation can be represented or misrepresented by activists without an adequate factual basis, potentially reducing nominations for species more in need of conservation and better management, and wasting limited time, money, and political will on less-threatened species (Challender & MacMillan 2019; Friedman et al. 2020). Once species are nominated, the voting process at the multilateral environment agreement meetings and RFMOs allows states with a vested interest in exploitation to block science-based recommendations for species protections (Gjerde et al. 2013). When consensus is required, a block precludes species listings on annexes and appendices at multilateral environment agreement meetings, as well as on catch limits or no retention measures at RFMOs. The consequent lack of management action means that states can continue exploiting threatened species, largely unabated. When a two-thirds majority vote is required (e.g. CITES) and passed, states may file an exemption to continue exploitation of a listed species, even when other states implement the binding policy. Non-binding policies are largely ignored, either because of a lack of political will, lack of implementation guidelines, or lack of capacity (Camhi et al. 2009; Lawson & Fordham 2019). Although states are legally bound to uphold the precautionary approach through either their association with UNCLOS, CITES, CMS, or membership and participation in an FAO regional fishery body, many nations that have the institutional arrangements and capacity to implement protection ignore their international obligations with little consequence (Trouwborst 2015).

2.4.4 Towards a systematic process for listing and effective management

I understand that capacity limitations and data gaps are hard to overcome without financial support, and that effectiveness of any policy must include supportive political will. However, in the context of limitations highlighted by this analysis, I believe that chondrichthyan conservation and management can be strengthened without complete legislative reform. A number of the problems uncovered by this analysis can be addressed by injecting rigor into the policy process through deliberate planning. Specifically, I recommend that a revised species-specific systematic planning process (Pressey & Bottrill 2009) be created to replace the ad hoc approach that is currently used. As part of the process, the adoption of explicit, uniform definitions for threatened, endangered, and protected are required. Additionally, a clear and agreed set of conservation goals is needed for chondrichthyans, and should be uniform across management works. Thresholds for assessments and species listings need to be quantified in criteria, including when exemptions are not appropriate. Decisionmaking in response to uncertainty should be alleviated by the deliberate adoption of the precautionary approach, with a clear definition that agencies will err on the side of caution in the absence of adequate data. For species that are listed by multilateral environment agreements or states for conservation, I also recommend the creation of a systematic conservation process that progresses chondrichthyans from listings on policies directly into implementation, enforcement, compliance, and evaluations of effectiveness. Implementing this process and ensuring the inclusion of species at all stages should lead to reduction in mortality. Importantly, I also recommend that progression of species along the conservation process be communicated to all stakeholders at regular intervals. In addition, a multi-stage definition of "protected" would provide the necessary framework to deliberately address the issues uncovered by this analysis, working to reduce both the ambiguity in policies and political interference that hinders mortality reduction for sharks and their relatives.

If adopted, a systematic conservation process framework with a staged approach would not only inject necessary rigor into the policy process, but would reflect some of the complexities in conservation and management. This approach could reduce ambiguity; assist in identifying gaps, funding restraints, capacity issues, political interference, or other bottlenecks to conservation effectiveness, and provide accountability to all stakeholders, including the public. I expect that each stage of this framework would afford an opportunity for transparent communication with all stakeholders, which could provide milestones for all stakeholders to both report on and follow progress. Transparency could create opportunities and levers for continued support, assistance and engagement by communities, NGOs, donors, fishers, fisheries managers, scientists, and politicians. Deliberately defining the steps necessary for species to progress along a process aimed at mortality reduction will provide a better understanding of the effectiveness of policies for each species and any amendments necessary to increase conservation impact.

Chapter 3:

Predictors of elasmobranch abundance on Pacific reefs

ABSTRACT:

Reef elasmobranchs (sharks and rays) are often managed at national and local scales because of restricted movements, but the scarcity of baseline data hinders effective conservation and management. To establish locally relevant baselines, this chapter examined the impacts of environmental and anthropogenic factors that affect reef elasmobranch abundance from 5,647 Baited Remote Underwater Video Stations (BRUVS) deployments across 18 nations across the western and central Pacific Ocean between five and 40 m depths. A total of 7,065 individual elasmobranchs were recorded, comprising 42 species. No elasmobranchs were observed on 24% of deployments. Separate generalized linear mixed models were fit to the relative abundance of total elasmobranchs (all sharks and rays) and the three most abundant shark species (*Carcharhinus amblyrhynchos, Carcharhinus melanopterus, Triaenodon obesus*). The predictor variables included environmental variables (minimum monthly sea surface temperature, primary productivity, depth, coral reef relief and habitat type) and anthropogenic factors (market gravity, which is a measure of the size of a human population and their distance from the reef, and presence of shark sanctuaries). Minimum monthly sea surface temperature was the only variable that significantly consistently related to the relative abundance of all species or groups, with more elasmobranchs recorded in warmer waters. Abundances of total elasmobranchs, *C. amblyrhynchos* and *T. obesus* decreased with increasing market gravity. The presence of a shark sanctuary was a positive influence on all species except *T. obesus*. The central Pacific had higher abundances of reef elasmobranchs than the western Pacific, even under similar environmental and anthropogenic conditions, highlighting the need to investigate local conditions and management. BRUVS provided a low-cost methodology to examine factors affecting reef elasmobranch abundances that can assist managers with conservation and management of these species.

3.1. INTRODUCTION:

Populations of elasmobranchs (sharks and rays) have declined across a wide range of ecosystems including rivers, bays, estuaries, open ocean environs, deep sea, continental shelves and coral reefs (Camhi et al. 2009; Dulvy et al. 2014; Weigmann 2016). These declines are largely driven by anthropogenic mortality, through causal effects that are direct (e.g. fishing) and indirect (e.g. pollution, habitat destruction, climate change) (Chin et al. 2010; Dulvy et al. 2014). Like other groups of elasmobranchs, reef-associated species are under significant pressure from fishing (MacNeil et al. 2020). Unlike many pelagic elasmobranchs, which fall under the mandate of regional fisheries management organization (RFMO) bodies and therefore receive support additional to national-level management, reef-associated species are typically managed by individual nations. In developing countries, elasmobranch management is often limited by a lack of data, funding, and capacity. However, in some Pacific Island countries, customary land and marine tenure underpinning community-based management may support local protection or exploitation of these species (Johannes 1978; Macintyre & Foale 2007; Friedlander 2018; Mangubhai et al. 2020). Additionally, the sale of elasmobranch products contributes to culture, livelihoods, and food security in developing coastal and island communities, meaning that ineffective management could be especially detrimental to local populations (Mangubhai et al. 2012; Jaiteh et al. 2016; Mizrahi et al. 2019).

The recognized limitations of elasmobranch management in developing countries have resulted in widespread advocacy for spatial management among tropical nations, including marine protected areas (MPAs) and closures to commercial retention of sharks (defined as shark sanctuaries) (Bond et al. 2012; Ward-Paige 2017; MacKeracher et al. 2018). Spatial management is a critical component for effective conservation and management of reef elasmobranchs because it reduces fishing pressure on these species by reducing interactions of elasmobranchs with fishing gear (Knip et al. 2012; Espinoza et al. 2014). MPAs have demonstrated benefits to site-attached reef elasmobranchs (Ward-Paige et al. 2010; Bond et al. 2012; Goetze & Fullwood 2013; Espinoza et al. 2014; MacNeil et al. 2020), but sizes of MPAs are important, with larger, no-take MPAs necessary to protect more mobile species (Dwyer et al. 2020; MacNeil et al. 2020). Shark sanctuaries have typically been established where local reliance on shark fishing was already low, and have been criticized for exempting artisanal fishers who are primarily interacting with reef species, as well as inconsistencies in size, species protections, punitive measures, and reporting requirements (Davidson 2012; Ward-Paige 2017; Cramp et al. 2018). However, MacNeil et al. (2020) concluded that countries with shark sanctuaries had higher relative abundances of reef sharks than countries without sanctuaries, whether or not sanctuaries were responsible for the increased abundances. Yet, the vast majority of tropical countries have incomplete species lists, lacking baseline evidence for whether conservation and management measures (e.g. MPAs, sanctuaries, fisheries policies) need implementation or improvement.

Several studies have examined factors affecting reef shark abundance at various scales including: protected areas and zoning (Ward-Paige et al. 2010; Espinoza et al. 2014; Vianna et al. 2016); impacts of environmental and oceanographic factors (Nadon et al. 2012; Espinoza et al. 2014); human population density and socioeconomic conditions (Ward-Paige et al. 2010; Nadon et al. 2012; Jaiteh et al. 2016; Mizrahi et al. 2019; MacNeil et al. 2020); and the effects of fishing and fishing gears (Ward-Paige et al. 2010; Cinner et al. 2016; Vianna et al. 2016; Goetze et al. 2018). Studies concluded that well enforced MPAs resulted in higher reef shark abundances (Ward-Paige et al. 2010; Espinoza et al. 2014; Jaiteh et al. 2016; MacNeil et al. 2020), but the effects of remoteness, coastal human populations, and oceanographic and environmental conditions varied. For example, contrary to others, Vianna et al. (2016) found that, within the Palau Shark Sanctuary, remote uninhabited reefs held lower densities of reef sharks, likely because of illegal fishing. Contrasting results on factors affecting reef shark abundance mean that management decisions based on transferability from studies in other regions might not be effective.

The influence of environmental and anthropogenic factors were examined across a gradient of human influence and environmental conditions on presence and abundance of western and central Pacific Ocean reef elasmobranchs. This study expanded upon work by Nadon et al. (2012) by examining a larger number of reefs in 18 nations and territories, which also vary in governance, and on MacNeil et al. (2020) by exploring the effects of environmental variables on total elasmobranchs (sharks and rays) and species-level data n the Pacific region, which was shown to have high abundances than other locations.

3.2. METHODS:

3.2.1. Site selection

This research used data collected in the Pacific region as part of the Global FinPrint project. Sampling locations represented 18 nations and territories in the western and central Pacific Ocean. The 18 nations included 58 sites, comprised of 117 individual reefs, on which 6,648 individual Baited Remote Underwater Video Stations (BRUVS) were deployed (Figure 3.1). Deployments occurred between 2010 and 2018.

3.2.2. BRUVS deployments

Elasmobranchs were recorded by BRUVS consisting of a weighted frame, an underwater housing containing an action camera, and bait pole extended 1−1.5 m in front of the camera including a perforated container holding approximately 500 g−1 kg of oily fish (e.g. *Sardinops sagax*.). Due to the remoteness of many of the sites, bait types and bait canisters varied. Studies demonstrated that variations in bait type and quantity did not influence diversity or abundance estimates (Dorman et al. 2012; Hardinge et al. 2013; Wraith et al. 2013) The number of deployments varied with size of reef; where possible a minimum number of 50 drops were deployed per reef, and a deployment duration of 60 minutes was demonstrated to be sufficient to survey reef elasmobranchs (Currey-Randall et al. 2020).

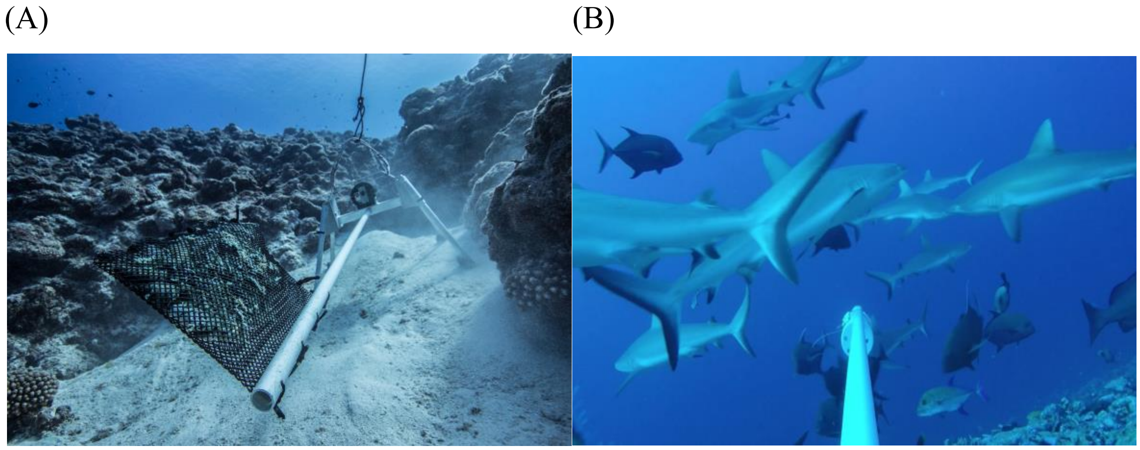


Figure 3.1: BRUVS deployment. (A) BRUVS unit on the benthos. Photo courtesy Manu San Felix. (B) Video screen grab from BRUVS in Cook Islands, showing MaxN = 10 elasmobranchs.

BRUVS were deployed from small boats and set at depths of 5−40 m. Units were deployed a minimum of 500 m apart to reduce likelihood of overlapping bait plumes and double counting individuals. The maximum distance between adjacent BRUVS was 1 km. BRUVS were deployed for a minimum of 60 minutes during daylight hours.

3.2.3. Video analysis

Each video was reviewed for 60 minutes, with time equal to zero (t = 0) beginning when the unit settled on the benthos (Currey-Randall et al. 2020). All footage was analyzed using FinPrint Annotator (v.1.1.44.0) or EventMeasure (www.seagis.com v.4.43) software. Two independent reviewers analyzed videos. The number, time of arrival, and species of each elasmobranch present on screen were recorded. The maximum number of individuals of each species in a single frame (MaxN) was recorded for all elasmobranch species in each video and used as an index of relative abundance. A senior annotator validated species identification and MaxN.

Environmental variables recorded during video analysis included: the percentage composition of broad habitat types (hard coral, soft coral, macroalgae, consolidated, unconsolidated, etc.); reef type (reef slope or lagoon); depth; and benthic relief. Benthic relief and habitat data were analyzed in BenthoBox (www.benthobox.com) software using methods outlined by Sherman et al. (2020). A 20-square grid was placed over an image from each deployment and squares were scored. Benthic relief was calculated by first assigning a value from 0 (flat) to 5 (complex) for each square in the grid (Polunin & Roberts 1993; Wilson et al. 2007). Then, the average relief was calculated per drop. Habitat type was identified by first labeling each square in the grid with the habitat type that represented the greatest proportion per square. Then the percentage of habitat type was calculated by the number of squares in the 20-square grid per habitat type at $t = 0$.

3.2.4. Market gravity data

To examine anthropogenic effects on reef elasmobranchs, I used the market gravity data provided in the supplementary materials of Cinner et al. (2016). Total market gravity was calculated by dividing the human population of the nearest port by the squared travel time between the port and the reef. I tested the hypothesis that elasmobranch abundance decreased with increasing market gravity. Gravity values ranged from 3.55×10^{-6} at remote and uninhabited Beveridge Reef in Niue, to 3756.02 at densely populated Tahiti in French Polynesia, which also holds the nation's capital and major port.

3.2.5. Oceanographic and environmental data

I used remotely sensed oceanographic data to examine the potential influences of oceanic productivity and sea surface temperature (SST) on densities of reef elasmobranchs (Appendix 2 Table A2.1). I obtained monthly oceanic primary productivity ($\text{mg C} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$) between 2010 and 2018 from the vertically generalized production model (VGPM; Behrenfeld & Falkowski 1997) at a spatial resolution of 1/6º. The VGPM estimates net primary production from chlorophyll and available light using a temperature-dependent description of photosynthetic efficiency (Figure 3.2). The average monthly SST was obtained from the global Multi-scale Ultra-high Resolution (MUR) SST Analysis (v4.1, NASA JPL[1]), which combines infrared, microwave and *in situ* SST data sources. Using monthly average MUR SST, mean minimum

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[1] Data were obtained from the NASA EOSDIS Physical Oceanography Distributed Active Archive Center (PO.DAAC) at the Jet Propulsion Laboratory, Pasadena, CA (http://dx.doi.org/10.5067/GHGMR-4FJ01).

monthly temperature was calculated over the dates of deployment at each site. Environmental covariates were calculated as a single value per sampling site (mean primary productivity and minimum temperature) by averaging over a region that extended 50 km from the outermost extent of an island (or other site) after removing a 10 km buffer closest to shore.

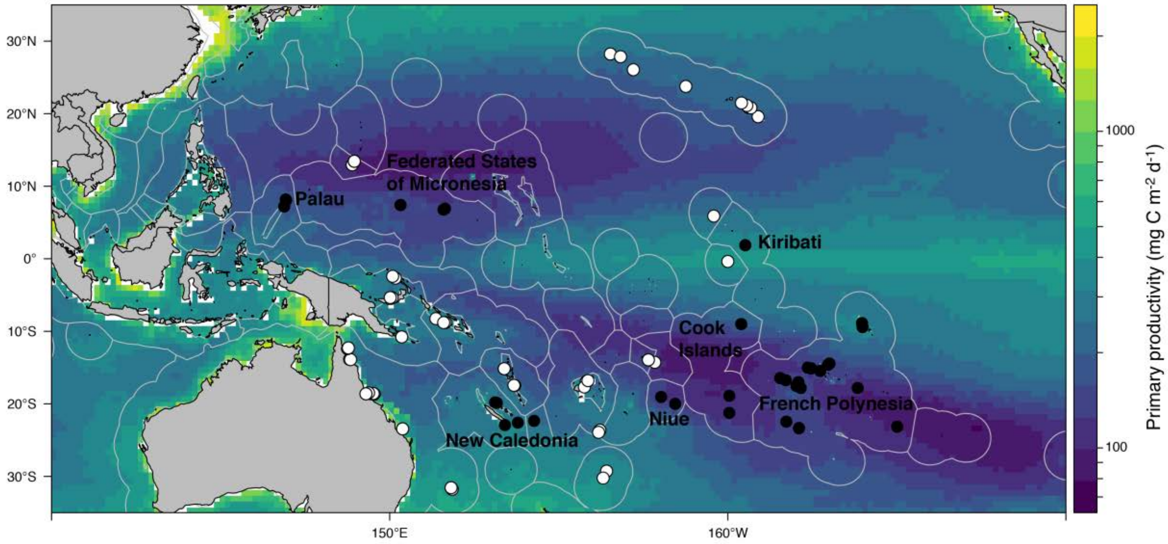

Figure 3.2: Average monthly primary productivity for 2017 from the VGPM model with sampling sites marked as dots inside of exclusive economic zones. Sanctuary countries are marked with black points, non-sanctuary locations in white points.

3.2.6. Policy data

Countries and territories were labeled as a shark sanctuary if they had active legislation during the time of sampling that banned landing elasmobranchs (sharks, rays, or both) throughout their exclusive economic zones. Sanctuary locations included sites in Cook Islands (est. 2012), Federated States of Micronesia (est. 2015), French Polynesia (est. 2006 *except *Isurus* spp., which were added in 2012), Kiribati (est. 2015), New Caledonia (est. 2013), Niue (est. 1996), and Palau (est. 2009) (Figure 3.2).

3.2.7. Data filtering

Video data were filtered to include “open” and “limited” sets, meaning the cameras not facing either up or down, and there was minimal obstruction in front of the camera obscuring its ability to record. Sets with “limited” vision were retained because elasmobranchs could still be observed. Further filters were used for reef type to select for “slope” and “lagoon” habitats. Analyses excluded “back reef”, “reef crest” and “reef flat” habitats because there were limited sites within these reef types. If multiple datasets were present for a single reef over different years, I retained the most recent year’s data, unless a previous year had a significantly higher number of drops. Only the five habitat types with the highest mean coverage were included in the analysis. A total of 5,647 BRUVS deployments (85%, 6,648 total) were included in analysis after data filtering.

3.2.8. Analysis of relative abundance

After filtering, the data were split into two datasets and analyzed separately. The first dataset included all elasmobranchs and was analyzed with total MaxN as the response variable. Total MaxN was calculated by summing the MaxN recorded per species, per deployment. The second dataset was separated by species and filtered to retain only the 10 most abundant elasmobranch species recorded across all Pacific deployments, which were analyzed independently against environmental and anthropogenic variables in the models. The response variable in the species dataset was species MaxN.

Collinearity was tested between the five most extensive habitat variables by using a variance inflation factor (VIF) threshold less than 3.0 (Appendix 2 Tables A2.2 a-c). Habitat categories “unconsolidated” and “consolidated” were collinear with “hard coral”, “soft coral”, and “macroalgae” in both data sets (total MaxN and species MaxN). Therefore, “unconsolidated” and “consolidated” were removed and “hard coral”, “soft coral” and “macroalgae” were used in both data sets. After removing “consolidated” and “unconsolidated”, a second VIF was run and all values were below 3.0.

The response variables were in the form of MaxN counts. The mean MaxN counts were modeled with the Poisson and negative binomial distributions, and their zero-inflated counterparts, using R statistical software (R Core Team 2020, version 3.4.1). Data were analyzed at the reef level; however, reef was nested within a site as a random effect. A hierarchical generalized linear mixed effects model was developed using template model builder R package: glmmTMB (Brooks et al. 2017). In both data sets, continuous variables included percentage habitat type, depth, relief, minimum monthly sea surface temperature, mean monthly primary productivity, and total market gravity. Categorical variables included reef type (slope or lagoon) and sanctuary (yes or no). Oceanographic data were grouped by site to ensure any effects of sea surface temperature or primary productivity were not missed because of the distance between sites in various nations. Various configurations of fixed and random variables were explored, including hierarchy and centered versus scaled continuous variables, and zero-inflated models. The models with the lowest Akaike Information Criterion (AIC) of >2 points of difference were selected. In the total elasmobranchs dataset, the final model included scaled continuous variables using the hierarchy of reef nested within site as the random slope (Appendix 2 Table A2.3 a). The zero-inflated negative binomial model was the best fit for the total elasmobranchs dataset. Based on the total elasmobranchs model design and selection, candidate models were developed and then run separately on each of the 10 most abundant species.

The zero-inflated negative binomial model, which was the best fit for the total elasmobranchs dataset, would not converge for the three species with highest abundance in all deployments (i.e. *Carcharhinus amblyrhynchos, Carcharhinus melanopterus, Triaenodon obesus*). The number of zeroes on each of the most abundant 10 species was checked to determine whether zero-inflated models were necessary. Models were considered a good fit if the deviance was >1.0. Poisson and negative binomial distributions were tested with continuous and categorical variables in each of the species models and then the model with the lowest AIC, with greater than two points of difference, was selected. Only the most abundant three species in the analysis were included due to insufficient data for the remaining species to fit the models. The models that converged and were selected were not the ideal models, but provided the best result with the limited species-level data in the dataset. Model detail is in the supplementary materials (Appendix 2 Table A2.3 b-d).

3.3. RESULTS:

A total of 7,065 individual elasmobranchs were recorded in 5,647 individual BRUVS deployments. This study identified a total of 42 species (Table 3.1), representing 14 families, 27 genera and 5 orders. The most abundant three species were *Carcharhinus amblyrhynchos* (recorded in 21% of the deployments), *Carcharhinus melanopterus* (22% of the deployments), and *Triaenodon obesus* (14% of the deployments) (Table 3.1). No elasmobranchs were sighted in 24% of deployments. The mean MaxN of all Pacific sites combined was 1.8 elasmobranchs per hour, which ranged by site from 0 (Molokai Island, Hawaii) to 10.1 (Jarvis Island, USA Pacific). In 38% of sites, the mean MaxN was 1.0 or less. A mean MaxN of greater than 5.0 was found in 7% of sites (Figure 3.3). The three sites with the highest mean MaxN (Figure 3.4) were within protected areas: Jarvis Island within the Pacific Remote Islands National Marine Monument; Penrhyn in the Cook Islands; and Beveridge Reef in Niue, the latter two within national shark sanctuaries. Of the three, only Penrhyn in the Cook Islands is inhabited.

Table 3.1: All elasmobranch species recorded during deployments. The most abundant ten species are indicated above the black line. Several species were identifiable only to genus level and "Unknown spp." were unidentifiable to genus level. "No sharks" indicates no elasmobranchs were sighted during the hour-long deployment.

Family	Genus	Species	Common Name	Total MaxN	Highest MaxN	# Nations
Carcharhinidae	*Carcharhinus*	*amblyrhynchos*	Grey Reef Shark	2,687	21	17
Carcharhinidae	*Carcharhinus*	*melanopterus*	Blacktip Reef Shark	1,968	13	15
Carcharhinidae	*Triaenodon*	*obesus*	Whitetip Reef Shark	939	18	17
Carcharhinidae	*Carcharhinus*	*galapagensis*	Galapagos Shark	429	13	3
Unknown	Unknown spp.			250	5	18
Dasyatidae	*Neotrygon* spp.			94	2	7
Carcharhinidae	*Negaprion*	*acutidens*	Sharptooth Lemon Shark	92	3	6
Aetobatidae	*Aetobatus*	*ocellatus*	Ocellated Eagle Ray	89	20	14
Ginglymostomatidae	*Nebrius*	*ferrugineus*	Tawny Nurse Shark	81	3	8
Aetobatidae	*Aetobatus* spp.			60	8	8
Dasyatidae	*Taeniura*	*lymma*	Bluespotted Fantail Ray	45	1	5
Carcharhinidae	*Galeocerdo*	*cuvier*	Tiger shark	41	2	6
Mobulidae	*Mobula spp.*			41	2	8
Dasyatidae	*Taeniurops*	*meyeni*	Blotched Fantail Ray	38	2	5

Dasyatidae	*Pateobatis*	*fai*	Pink Whipray	30	3	8
Sphyrnidae	*Sphyrna*	*lewini*	Scalloped Hammerhead	28	10	4
Carcharhinidae	*Carcharhinus*	*albimarginatus*	Silvertip Shark	25	2	8
Dasyatidae	*Urogymnus*	*granulatus*	Mangrove Whipray	13	1	5
Mobulidae	*Mobula*	*alfredi*	Reef Manta Ray	12	1	3
Carcharhinidae	*Carcharhinus*	*tilstoni or limbatus*	Australian/ Blacktip	10	2	3
Mobulidae	*Mobula*	*birostris*	Giant Manta Ray	10	2	2
Sphyrnidae	*Sphyrna*	*mokarran*	Great Hammerhead	9	1	3
Carcharhinidae	*Carcharhinus*	*limbatus*	Blacktip Shark	8	1	4
Hemiscylliidae	*Chiloscyllium*	*punctatum*	Grey Carpetshark	8	1	1
Dasyatidae	*Pastinachus*	*ater*	Broad Cowtail Ray	7	1	3
Dasyatidae	*Bathytoshia*	*lata*	Brown Stingray	6	2	2
Carcharhinidae	*Carcharhinus*	*macloti*	Hardnose Shark	6	2	1
Sphyrnidae	*Sphyrna* spp.			4	3	2
Carcharhinidae	*Carcharhinus*	*leucas*	Bull Shark	3	1	2
Hemigaleidae	*Hemipristis*	*elongata*	Snaggletooth Shark	3	1	2
Hemiscylliidae	*Hemiscyllium*	*ocellatum*	Epaulette Shark	3	1	1

Rhinidae	*Rhynchobatus* spp.			4	1	3
Stegostomidae	*Stegostoma*	*fasciatum*	Zebra Shark	3	1	2
Carcharhinidae	*Carcharhinus*	*dussumieri*	Whitecheek Shark	2	1	1
Carcharhinidae	*Carcharhinus*	*plumbeus*	Sandbar Shark	2	1	1
Hemigaleidae	*Hemigaleus*	*australiensis*	Australian Weasel Shark	2	1	1
Rhinidae	*Rhynchobatus*	*australiae*	Whitespotted Wedgefish	2	1	1
Dasyatidae	*Urogymnus*	*asperrimus*	Porcupine Ray	2	1	2
Myliobatidae	*Aetomylaeus*	*vespertilio*	Ornate Eagle Ray	1	1	1
Alopiidae	*Alopias* spp.			1	1	1
Dasyatidae	*Bathytoshia*	*brevicaudata*	Short-tail Stingray	1	1	1
Carcharhinidae	*Carcharhinus*	*sorrah*	Spottail Shark	1	1	1
Lamnidae	*Carcharodon*	*carcharias*	White Shark	1	1	1
Dasyatidae	*Dasyatis*	*thetidis*	Thorn-tail Stingray	1	1	1
Dasyatidae	*Himantura*	*australis*	Reticulate Whipray	1	1	1
Triakidae	*Mustelus* spp.			1	1	1
Dasyatidae	*Taeniura*	*lessoni*	Oceania Fantail Ray	1	1	1
N/A	no elasmobranchs			0	0	18

Figure 3.3: Mean MaxN counts (points) and standard errors across all deployments at each site for: (A) *Carcharhinus amblyrhynchos,* (B) *Carcharhinus melanopterus,* (C) *Triaenodon obesus,* (D) total elasmobranchs.

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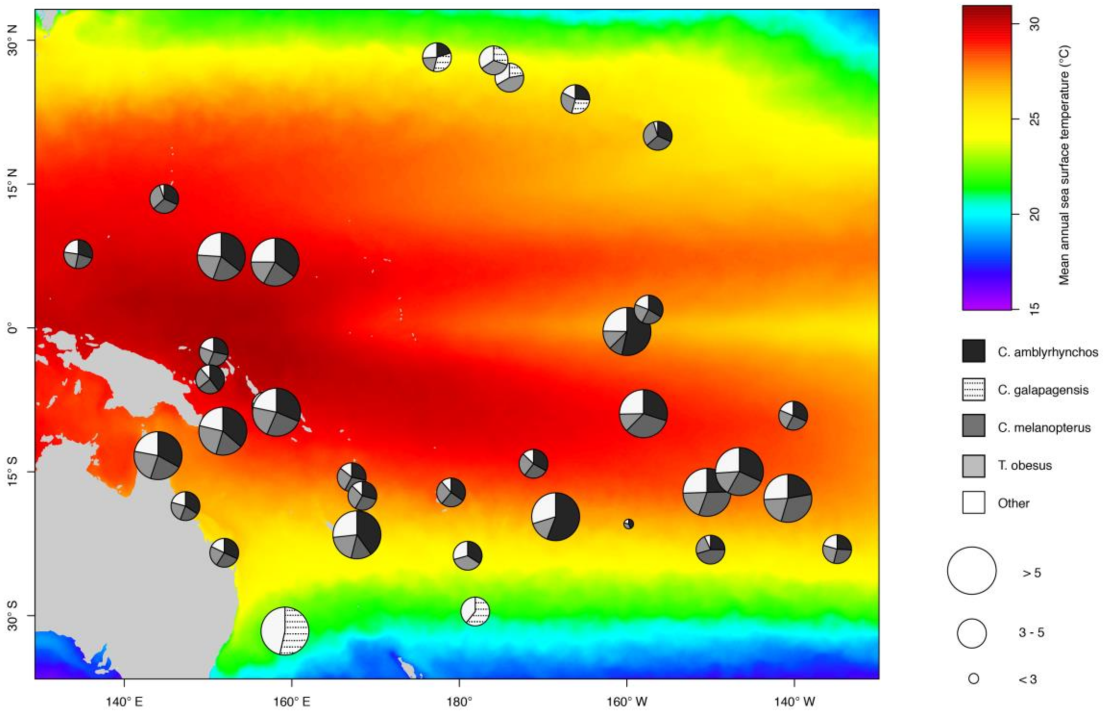

Figure 3.4: Species composition by location, displaying MaxN and mean annual sea surface temperature (SST). The size of each pie chart represents MaxN of total elasmobranchs. The wedges show the species composition of the sites (four most abundant species, plus others).

3.3.1 Total elasmobranch abundance

Environmental and anthropogenic factors substantively influenced the relative abundance of total elasmobranchs observed at sites (Table 3.2). Mean relative abundance was strongly negatively related to total market gravity (Figure 3.5 A), positively related to minimum monthly sea surface temperature (Figure 3.5 B), and positively related to the presence of a shark sanctuary (Figure 3.5 C). There was little evidence for an effect of reef type (slope or lagoon), primary productivity, depth, relief, or substrate (hard coral, soft coral, macroalgae,).

Table 3.2: Modeled effects of variables on abundance of total elasmobranchs combined, and species-specific models for *Carcharhinus amblyrhynchos*, *Carcharhinus melanopterus*, and *Triaenodon obesus*. Effects in bold did not overlap zero. SST was the minimum monthly sea surface temperature during the month of BRUVS sampling and it was scaled by location. Chl-a was the mean monthly primary productivity, also scaled by location. Sanctuary meant that a sanctuary was in place during the time of sampling. Reef types were slope and lagoon.

Variable	Chisq	Df	p-value
Total elasmobranchs			
Reef type	3.171	1	0.0750
Sanctuary	**7.383**	**1**	**0.0066**
Log(Gravity)	**7.269**	**1**	**0.0070**
SST	**25.649**	**1**	**<0.0001**
Log(Chl-a)	0.3413	1	0.5591
Depth	1.141	1	0.2854
Relief	0.2632	1	0.6079
Hard coral	2.801	1	0.0942
Macroalgae	1.374	1	0.2411
Soft coral	0.0043	1	0.9475
Grey Reef Sharks (*C. amblyrhynchos*)			
Reef type	**3.916**	**1**	**0.0478**
Sanctuary	**10.261**	**1**	**0.0014**
Log(Gravity)	**5.6713**	**1**	**0.0173**
SST	**9.8234**	**1**	**0.0017**
Log(Chl-a)	0.0000	1	0.9970
Depth	**23.4091**	**1**	**<0.0001**
Relief	0.8771	1	0.3490
Hard coral	0.6694	1	0.4132
Macroalgae	1.4869	1	0.2222
Soft coral	0.0033	1	0.9540

Blacktip Reef Sharks (*C. melanopterus*)			
Reef type	0.2664	1	0.6057
Sanctuary	**11.6729**	**1**	**0.0006**
Log(Gravity)	0.5645	1	0.4525
SST	**13.3726**	**1**	**0.0003**
Log(Chl-a)	0.1630	1	.06864
Depth	**77.0053**	**1**	**<0.0001**
Relief	2.3610	1	0.1244
Hard coral	0.1409	1	0.7074
Macroalgae	3.4779	1	0.0622
Soft coral	0.0005	1	0.9817
Whitetip Reef Sharks (*T. obesus*)			
Reef type	0.3626	1	0.5471
Sanctuary	0.2704	1	0.6031
Log(Gravity)	**8.7257**	**1**	**0.0031**
SST	**7.7576**	**1**	**0.0053**
Log(Chl-a)	0.8192	1	0.3654
Depth	0.6143	1	0.4332
Relief	**7.8645**	**1**	**0.0050**
Hard coral	2.5065	1	0.1134
Macroalgae	1.1475	1	0.2841
Soft coral	0.7440	1	0.3884

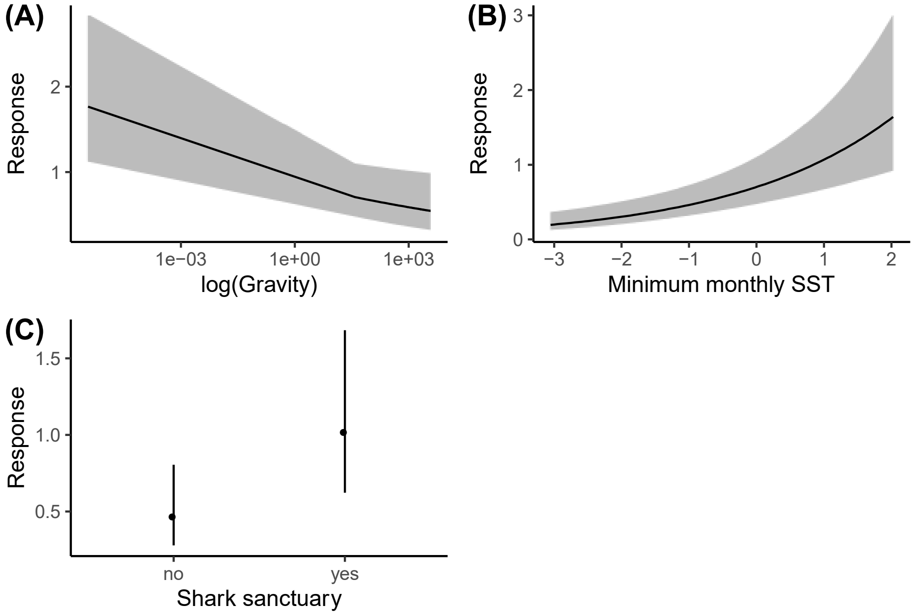

Figure 3.5: Variables that substantively influenced the relative abundance of total elasmobranchs: (A) total market gravity; (B) minimum monthly sea surface temperature, scaled by location; (C) presence of a shark sanctuary. Grey bands or error bars represent 95% confidence intervals.

3.3.2. Grey Reef Sharks

Grey Reef Sharks comprised more than 50% of all sighted elasmobranchs at two sites: the uninhabited atolls of Jarvis Island (USA) and Beveridge Reef (Niue) (Figure 3.4). No Grey Reef Sharks were recorded on the Hawaiian Islands of Molokai, Maui, Lanai, or Hawaii, the United States Pacific Islands of Lisianski and Pearl and Hermes, or on Orpheus Island, Australia. Grey Reef Sharks were also not recorded on Lord Howe Island (Australia) or on Kermadec Islands (New Zealand), but in these areas Galapagos Sharks were recorded (Figure 3.4).

The negative binomial model without zero inflation was the best fit (dev = 1.73) (Appendix 2 Table A2.3 b). Several factors were positively associated with the relative abundance of Grey Reef Sharks (Table 3.2, Figure 3.6). Higher abundances were found in shark sanctuaries. A pairwise Tukey's test was run on the reef type variables (slope and lagoon), which showed that there were 62% more Grey Reef Sharks in slope habitats than in lagoon habitats. Abundances were also positively associated with greater depth, higher relief, and higher minimum monthly SST. Total market gravity was negatively associated with abundance. There were no detectable effects of primary productivity, relief, or substrate (hard coral, macroalgae, soft coral) (Table 3.2).

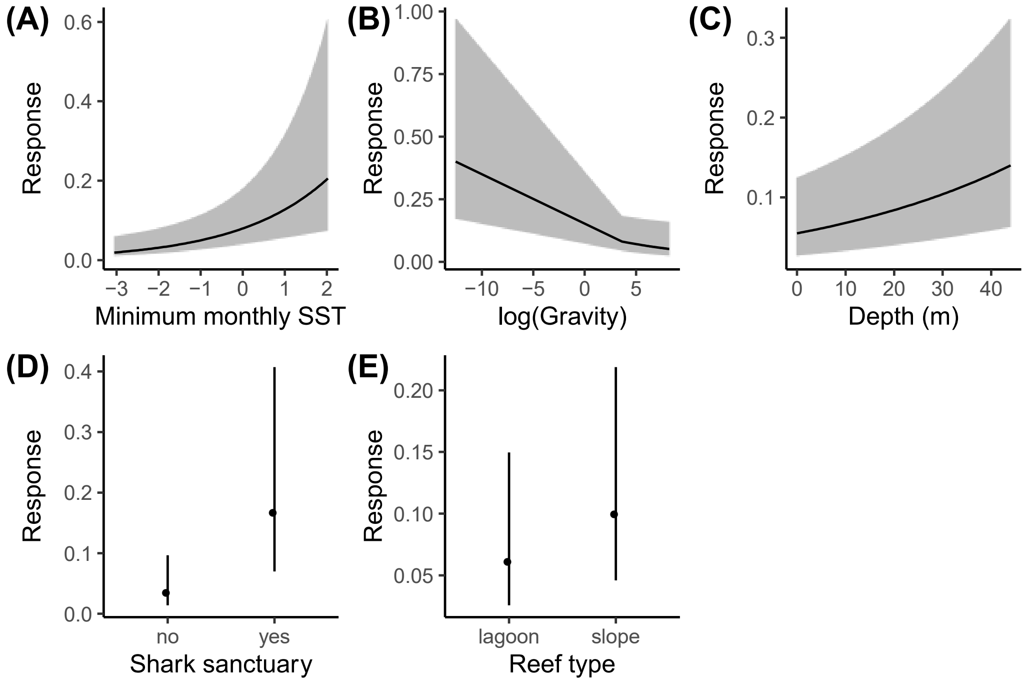

Figure 3.6: Variables that substantively influenced the abundance of Grey Reef Sharks (*Carcharhinus amblyrhynchos*) in the species dataset: (A) minimum monthly sea surface temperature, scaled by location; (B) total gravity; (C) depth; (D) presence of a shark sanctuary; (E) reef type. Grey bands or error bars represent 95% confidence intervals.

3.3.3. Blacktip Reef Sharks

A mean MaxN of greater than two Blacktip Reef Sharks per hour was recorded at only two sites: Penrhyn in Cook Islands, and Rangiroa in French Polynesia (Figure 3.3 B). Both sites are inhabited and within shark sanctuaries (Figure 3.2). At both sites, the mean MaxN for Blacktip

Reef Sharks was higher than for Grey Reef Sharks. There were no Blacktip Reef Sharks recorded in: Niue’s waters; Rarotonga or Aitutaki in Cook Islands; Minerva Reef in Tonga; the United States’ Pacific Minor Islands, including French Frigate Shoals, Lisianski, Midway, Pearl, and Hermes; the Hawaiian Islands of Oahu, Molokai, Maui and Hawaii; or the Australian islands of Lord Howe and Orpheus (Figure 3.3 B).

The Poisson model without zero inflation was the best fit (dev = 1.399) (Appendix 2 Table A2.3 c). The strongest variables included sea surface temperature, depth, and the presence of a shark sanctuary (Table 3.2; Figure 3.7). Similar to Grey Reef Sharks, the presence of a shark sanctuary and miminum monthly sea surface temperature were positively associated with mean abundance. However, abundance of Blacktip Reef Sharks decreased with depth (Figure 3.7 B). There were no detectable effects of market gravity, primary productivity, reef type, relief, or substrate type (Table 3.2).

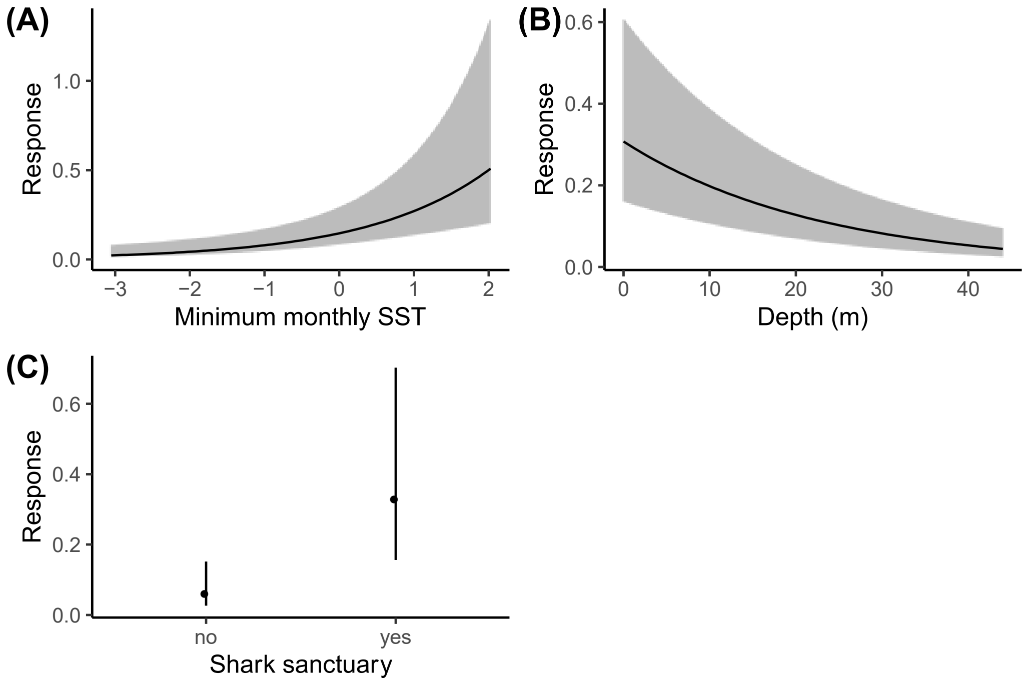

Figure 3.7: Variables that substantively influenced the abundance of Blacktip Reef Sharks (*Carcharhinus melanopterus*) in the species dataset: (A) minimum monthly sea surface temperature, scaled by location; (B) depth; (C) the presence of a shark sanctuary. Grey bands or error bars represent 95% confidence intervals.

3.3.4. Whitetip Reef Sharks

In sites where the most abundant three elasmobranch species were recorded, densities of Whitetip Reef Sharks were lower than Blacktip Reef and Grey Reef Sharks everywhere except for Minerva Reef (Figure 3.3 D). Jarvis Island had the highest mean MaxN of *T. obesus* (mean MaxN = 1.24) (Figure 3.3 D). Whitetip Reef Sharks were not recorded in: New Zealand's Kermadec Islands; Lord Howe Island in Australia; Tubuai in French Polynesia; or in the Hawaiian Islands of Lanai, Maui, Molokai and Oahu.

The Poisson model without zero inflation was the best fit (dev = 1.07) (Appendix 2 Table A2.3 d). Substantive variables were gravity, sea surface temperature, and coral reef relief (Table 3.2;

Figure 3.8). Gravity was negatively associated with abundance, whereas sea surface temperature and relief were positively associated with abundance (Figure 3.8). Unlike Blacktip Reef and Grey Reef Sharks, an effect of shark sanctuaries was not detected on the abundance of Whitetip Reef Sharks. There were also no detectable effects of reef type, depth, primary productivity, or substrate (hard coral, soft coral or macroalgae).

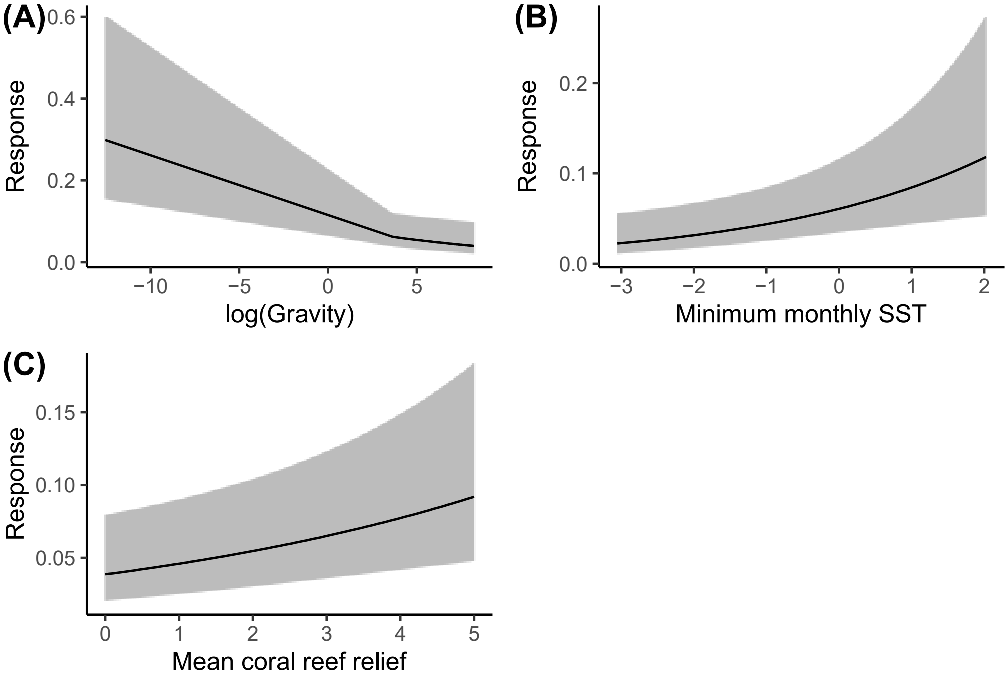

Figure 3.8: Variables that substantively influenced the abundance of Whitetip Reef Sharks (*Triaenodon obesus*) in the species dataset: (A) total gravity. (B) minimum monthly sea surface temperature, scaled by location. (C) mean coral reef relief. Grey bands represent 95% confidence intervals.

3.4. DISCUSSION:

Results showed that the abundance of reef elasmobranchs was related to both human and environmental variables, but that minimum monthly SST was the only variable that had a consistent effect across all species or groups examined. The Pacific region as a whole, which included inhabited sites without formal protections for elasmobranchs, had higher relative abundances than many no-take marine reserves in other parts of the world. The mean MaxN of total elasmobranchs per hour (1.8) across sites in this study was only slightly lower than the mean abundance of elasmobranchs in the British Indian Ocean Territory Marine Reserve (1.96) (Tickler et al. 2017). While MacNeil et al. (2020) found that sites in the Western Pacific require additional shark management measures because of low abundances; they also found that Central Pacific sites had high abundances of reef sharks and rays. Nadon et al. (2012) reported higher densities of sharks in remote, uninhabited sites in the Central Pacific than in inhabited sites. The top three species recorded during this study (*C. amblyrhynchos, C. melanopterus, T. obesus*) were the same top species as other studies that included Pacific nations, although the rank order of species abundances varied (Nadon et al. 2012; Goetze et al. 2018; MacNeil et al. 2020).

Of the thirty-nine species that were not modeled individually due to low abundances, only *Aetobatus ocellatus* was recorded in more than 10 nations, with spatial distribution from Australia to the easternmost nation in this study, French Polynesia. Conversely, 33% of species were recorded in only one nation; 10 of these were recorded only in Australia. Interestingly, *Neotrygon* spp., was recorded in seven nations, but was not recorded east of American Samoa. Meanwhile, *Pateobatis fai* and *Pateobatis meyeni*, both rays larger in size than *N. kuhlii*, were recorded in fewer nations but were distributed from Australia to French Polynesia. The larger sizes of *P. fai* and *P. meyeni* might enable them to transit the vast distances between reefs in the Pacific Ocean.

3.4.1. Environmental drivers:

Sea surface temperature (SST) was an important factor for each species or group, while primary productivity was not in any model. This contrasted with the results of Nadon et al. (2012) that showed both SST and primary productivity were significant drivers of abundance. While the majority of sites in this study were located on islands, similar to those studied by Nadon et al. (2012), we also included continental shelf areas, which could have masked the effect of primary productivity. Studies have also shown contrasting effects of primary productivity on the richness of elasmobranch species, with Tittensor et al. (2010) finding that SST was the most important predictor of species richness across 13 taxa globally, including coastal and oceanic sharks, with no significant effect of primary productivity on oceanic sharks and weak significance for coastal sharks. Yet, Guisande et al. (2013) found no significant effect of primary productivity on elasmobranch richness in marine habitats. These results showed high abundances of reef elasmobranchs in areas with both high and low primary productivity, such as Beveridge Reef (low) and Jarvis Island (high). At the species level, Nadon et al. (2012) found no significant effect of SST for Whitetip Reef Sharks, but significant effects for Grey Reef Sharks and Blacktip Reef Sharks. I found a positive effect for all three species, with abundances increasing with increasing SST. The contrasting result for Whitetip Reef Sharks could be due to the larger sample size in this study and inclusion of sites across a broader gradient of SST. Understanding how elasmobranchs respond to their environment is increasingly important as the global climate changes (Heupel & Simpfendorfer 2014). The importance of SST as a predictor of elasmobranch abundance suggests a need to examine their vulnerability to a warming ocean due to climate change (Chin et al. 2010; Tittensor et al. 2010; Heupel et al. 2019). Latitudinal separations in species presence were also found, with Galapagos Sharks present only at higher-latitude reefs where Grey Reef Sharks were absent.

Blacktip Reef Sharks were not found in Tonga or Niue, or on any island site south of 18°S latitude, with the exceptions of Tubuai and Mangareva in French Polynesia and the Great Barrier Reef. SST was an important predictor of relative abundance, but this species' distribution ranged from 23−30°C. Several island nations that fell within this temperature range were also shark sanctuaries, such as the reefs of Aitutaki, Beveridge Reef, and Minerva Reef, but no Blacktip Reef Sharks were recorded at these sites. The observed patchy distribution of this species could be due to the large distances (>50 km) to other islands separated by deep ocean, or a lack of suitable habitats for juveniles (Papastamatiou et al. 2009; Chin et al. 2013, 2016; Mourier & Planes 2013; Vignaud et al. 2014).

The importance of habitat for reef-associated elasmobranchs has been well documented (Chin et al. 2012; Espinoza et al. 2014; Heupel et al. 2018, 2019). Depth was an important driver for individual species in this study, but not for the total number of elasmobranchs. As expected, Grey Reef Sharks were more prevalent and Blacktip Reef Sharks less prevalent as depth increased. Results also indicated Grey Reef Sharks preferred reef slopes to lagoons. These findings are consistent with other studies that showed clear depth and habitat differences for these species (Heupel et al. 2018). Benthic relief was a predictor for Whitetip Reef Sharks, but not for other species or for total elasmobranchs. This pattern is supported by other studies showing that this species uses complex habitat for foraging and refuge (Randall 1977; Whitney et al. 2012; Heupel et al. 2018).

3.4.2. Human drivers:

Proximity of reefs to human populations and their associated pressures, as indicated by market gravity, was negatively associated with the total abundance of elasmobranchs, but not as strongly as studies have shown for other reef fishes, especially those species that support livelihoods (Cinner et al. 2018). Jaiteh et al. (2016) showed that, in areas of both high abundance of elasmobranchs and human dependence on elasmobranchs for food, governance was more important than proximity of humans to the resource. While some elasmobranchs in the Western Pacific are harvested (Glaus et al. 2015; Jaiteh et al. 2016; Goetze et al. 2018), cultural traditions of some nations in this study limit the use of sharks (Goetze & Fullwood 2013; Torrente et al. 2018; Puniwai 2020), which could explain the reduced impact of market gravity for elasmobranchs when compared with other reef fishes. Yet, the association with market gravity was not consistent across the individual species examined: an association was found for Grey Reef and Whitetip Reef Sharks, but not for Blacktip Reef Sharks, possibly because the latter occurs at shallower depths (Chin et al. 2013) and might be less exposed to fishers targeting reef fish. This finding is consistent with studies from the Great Barrier Reef that reported lower catch per unit effort and lower rates of interaction by line fishers with Blacktip Reef Sharks than Whitetip Reef Sharks and Grey Reef Sharks (Heupel et al. 2009). Further, future investigations on the impact of human population should occur at the reef level to determine whether negative effects to elasmobranchs are limited by proximity of enforcement officers (Goetze et al. 2018), human access to the site (e.g. vessel availability, rough weather), or whether gear limitations or currents limit the ability to target elasmobranch species (Cinner et al. 2018; MacNeil et al. 2020).

Like MacNeil et al. (2020), the presence of a shark sanctuary had a significant substantial, positive effect on abundance in the combined elasmobranchs dataset. Sanctuary was also positively related to Grey Reef Sharks and Blacktip Reef Sharks, but not Whitetip Reef Sharks, were positively related to shark sanctuaries. While sanctuary regulations prohibit the targeting, retention, and transshipment of sharks (and sometimes rays) by industrial vessels, most regulations exempt artisanal fishers, which are local recreational and subsistence fishers, who primarily target other reef species (Ward-Paige 2017). When considering the slow recovery rates of shark populations (Roff et al. 2018), the relatively recent implementation of shark sanctuaries suggests that reef elasmobranchs in these locations might have been abundant prior to implementation. The absence of baseline data prior to sanctuary implementation makes it difficult to understand the true influence of the sanctuary on reef elasmobranch abundance. However, sanctuaries may encourage local fishers to limit their impacts on reef elasmobranchs. Despite the lack of baseline data prior to sanctuary implementation, the presence of sanctuaries and the associated campaigns that were run for their implementation could benefit reef elasmobranchs as part of a suite of spatial management tools. Governments that enacted national-level sanctuaries have already exhibited political will to conserve elasmobranchs, and so they might be more likely to consider species-, habitat- or fisheries-specific management measures for elasmobranchs in the future.

3.4.3 Hotspots:

A number of locations performed better or worse than expected. Beveridge Reef in Niue was second only to Jarvis Island for the total abundance reef-associated elasmobranchs. Beveridge Reef, while remote and uninhabited like Jarvis Island, has colder water and substantially lower primary productivity than many sites in this study. Yet there is little to no fishing pressure on Beveridge Reef (B. Pasisi, pers. comm.) or in the surrounding national waters (Gillett 2016), which likely explains high elasmobranch abundances, even in suboptimal environmental conditions. Areas with high minimum monthly SST and low gravity were expected to have high abundance. Kiritimati Atoll in Kiribati and Kubulau District in Fiji had less than one shark per hour recorded, despite having high SST and low gravity. Kiritimati Atoll is part of a shark sanctuary (although only enacted in 2016), was a significant driver of total abundance of elasmobranchs, and it is remote with high primary productivity, which were shown in other studies to positively affect abundance (Ward-Paige et al. 2010; Nadon et al. 2012). The low abundances in these areas are likely a result of overfishing and poaching. This study did not examine the levels of fishing in this study directly, but fishing has proved to be the primary driver of mortality in elasmobranchs, even within protected areas and sanctuaries (Stevens et al. 2000; Dulvy et al. 2014; Vianna et al. 2016; Bradley et al. 2018). Only two sites with gravity greater than 1.0 had relative abundances of elasmobranchs greater than the mean abundance of all the Pacific sites: Zaira Village in the Western Province of Solomon Islands and Chuuk Lagoon in Federated States of Micronesia. The above-average abundance of reef-associated elasmobranchs in these locations could result from local management, remoteness, or a combination of both. Goetz et al. (2018) showed that sites in the Western Province of the Solomon Islands had higher abundances of sharks as a result of remoteness and the strong trade winds and waves making access difficult for fishers. Chuuk has a large lagoon that provides ample habitat for elasmobranchs, which might explain the high abundances; it is also part of the Micronesia shark sanctuary, but the Chuuk state law banned shark fishing several years prior, in 2014. These results highlight the need for investigation of local issues and drivers of abundance.

3.4.4. Possible bias

Although study sites were widely distributed across the Pacific, funding and logistical constraints prevented sampling at a greater number of islands within each nation. Several of the countries in this study are comprised of numerous islands, spread across latitudes with varying sea surface temperatures, gravity metrics, and local governance (e.g. Cook Islands, Kiribati, Federated States of Micronesia). For this reason, national-level results should be interpreted with caution because of the relationship between these variables and the presence and abundance of reef-associated elasmobranchs. Some sites were also represented by fewer than optimal deployments (e.g. Oahu, Lanai, Molokai), so additional sampling is needed before the status of elasmobranchs at these sites can be fully assessed. Additional biases attributed to BRUVS in this study parallel those described by others (Bond et al. 2012; Espinoza et al. 2014; Jaiteh et al. 2016). Sampling occurred during daylight hours and therefore might have missed species that are more active at night, or missed higher abundances that might occur at night, especially for species that exhibit diel behavior changes (Vianna et al. 2013; Espinoza et al. 2014; Jaiteh et al. 2016). Additionally, although study sites were generally in areas of high visibility, I could have underestimated the abundance of benthic species, such as Whitetip Reef Sharks (Nadon et al. 2012), and species not attracted to bait such as mobulids and Eagle Rays. It is also possible that I overestimated Grey Reef Shark abundances in relation to other elasmobranchs because of their attraction to bait, and potential to influence behavior of other species (Espinoza et al. 2014; Sherman et al. 2020a). Metadata on factors that might affect abundance at local levels such as tidal state, time of day, and seasonal effects were not available on all deployments and were therefore not tested in the models. Future studies should collect fine-scale data to account for additional drivers of abundance for some species, however, given the residency of reef species, seasonal effects may not be relevant (Sherman et al. 2020b). Sampling biases were consistent across study sites meaning that patterns in the data should be reliable. While a combination of fishery-dependent and fishery-independent methodologies might better characterize reef elasmobranch abundances, these are not practical in capacity- and resource-limited locations. Despite the potential biases, this is the most comprehensive survey of an extensive region where many nations are capacity-limited and where previous assessments of elasmobranch abundance are lacking.

3.5. CONCLUSION:

This chapter presents baseline data for several islands that had never been sampled for elasmobranch abundance (e.g. sites in Cook Islands, French Polynesia, Niue), and provides new insights into the patterns of occurrence and abundance of reef-associated elasmobranchs across the Pacific Ocean. The results demonstrate the importance of minimum monthly SST and the presence of sanctuaries as predictors of abundance. The importance of examining results in local contexts was demonstrated, which is important because reef elasmobranchs are managed at national and local scales. Additional studies in these regions, including seasonal sampling and social science, could provide insights that could be beneficial to the persistence of reef-associated elasmobranch populations in the presence of fishing. Management for Pacific countries might vary because of reduced capacity and resources, and varying levels of local governance that includes traditional tenure. BRUVS data can help inform management. As a fishery-independent, non-invasive way to sample reef-associated elasmobranch populations, new insights into factors affecting elasmobranch abundances can be gained. These data highlight areas where increased management might be beneficial. BRUVS are easy to implement in resource- and capacity-limited sites, meaning that data can be readily collected for local management and can assist spatial planning, customary management, fisheries management, and in planning for the impacts of climate change.

Chapter 4:

Effect of implementing the Cook Islands Shark Sanctuary on commercial fishing activities

ABSTRACT:

Industrial fisheries are responsible for precipitous declines in oceanic sharks. While regional fisheries management organizations have banned retention of some sharks, several nations have created shark sanctuaries, banning retention of all sharks (and sometimes rays) throughout their exclusive economic zones. The number of shark sanctuaries expanded quickly over the past decade, however, no study has quantified their effectiveness. This chapter examined the effect of the Cook Islands Shark Sanctuary on industrial fishers' behavior by examining catch records from longline and purse seine vessels before and after sanctuary implementation**.** No reductions were apparent in the number of sharks captured by vessels in the years following sanctuary implementation, however a peak in retention coincided with sanctuary announcement in 2012. Changes to species composition were not consistent following sanctuary implementation, but records indicated that identification and reporting of sharks to species-level improved over time because the number of species in records increased. Shark retention decreased in logbook and observer records of the longline dataset, indicating a change in fisher behavior following implementation of the Shark Sanctuary regulations that likely reduced shark mortality in Cook Islands waters. However, scarcity of data in the purse seine records did not support a strong conclusion of decreased shark retention. The sanctuary was beneficial to species that were released following implementation of the regulations, but better reporting is required to assess extent of impacts of sanctuary implementation on fisher behavior in all fisheries.

4.1. INTRODUCTION:

Fisheries are the primary driver of population decline in elasmobranchs (hereafter sharks) contributing to over one quarter of all sharks being classified as threatened with extinction (Dulvy et al. 2014; IUCN 2019). Sharks are captured in coastal and offshore fisheries to fulfill demand for their fins, meat, liver oil or other parts (Clarke et al. 2006; Dent & Clarke 2015; Dulvy et al. 2017). They are also captured incidentally in industrial fisheries for other species where they are often termed bycatch (Molina & Cooke 2012; Worm et al. 2013; Clarke et al. 2014; Clarke 2015). Oceanic shark populations have decreased 77% over the past 50 years which resulted from an 18-fold increase in fishing effort (Pacoureau et al. 2021). Additionally, movement studies recently suggested that oceanic sharks have little spatial refuge from commercial longline vessels (Queiroz et al. 2019).

Management of sharks that interact with industrial longline and other fisheries that target highly migratory species requires targeted efforts from Regional Fisheries Management Organizations (RFMO) and their member nations (FAO 2019a). Ten of 17 RFMOs have created management measures for sharks, including all five tuna RFMOs (t-RFMO) which manage the tuna fisheries responsible for the highest oceanic shark mortality (Davidson et al. 2016; BMIS 2021; Chapter 1). Management interventions include regulations to enforce finning bans, and prohibitions on species retention and specific fishing gear such as reinforced fishing line (Clarke et al. 2013, 2014; Gilman et al. 2016b). However, RFMO measures have been criticized for lacking implementation, enforcement, transparency and compliance, and failing to reduce capture-induced mortality, leading to inadequate protections for many species (Gjerde et al. 2008; Gallagher et al. 2014; Tolotti et al. 2015b; Juan-Jordá et al. 2018; Queiroz et al. 2019; Pacoureau et al. 2021; Wang et al. 2021).

Several country members of RFMOs have national level shark conservation and management regulations in national waters to complement or fill the gaps in RFMO measures (Ward-Paige 2017). While developed countries have capacity and resources to implement sophisticated fisheries management that can result in sustainable fishing (Simpfendorfer & Dulvy 2017), developing countries may rely on measures that appear easy to implement, such as shark sanctuaries (Davidson 2012). Shark sanctuaries are described as nationwide bans on commercial retention of sharks, and have been enacted in 18 countries globally, with half located in the Pacific islands where sharks have low economic value in local communities and may hold cultural importance (Ward-Paige 2017). Sanctuaries are not bans on fisheries targeting tuna or other species; rather, sanctuaries ban the retention of sharks on fisheries operating within sanctuary waters meaning that if effective, regulations result in the release of sharks when incidentally captured. While sanctuaries were enacted by likely well-intentioned governments, they are criticized for exempting artisanal fishers, being located in areas where the potential for impact is low due to previously low shark catch, moving funds away from traditional fisheries management, containing loopholes that make continued exploitation possible, and for lacking evaluations of effectiveness (Davidson 2012; Ward-Paige 2017; Ward-Paige & Worm 2017; Cramp et al. 2018).

Previous studies have examined aspects of shark sanctuaries including anomalies in policy (Ward-Paige 2017; Cramp et al. 2018), potential for impact based on shark landings and citizen science diver surveys (Ward-Paige & Worm 2017), changes in shark fishing mortality (Gilman et al. 2016a), and the space-use of reef-associated sharks inside sanctuaries (Gallagher et al. 2021). However, no study has evaluated the effectiveness of sanctuary policy on behavior of commercial fishers.

Using a case study in the Cook Islands, which established a shark sanctuary on December 12, 2012, this chapter examined whether fisher behavior changed as a result of the implementation of a shark sanctuary by examining commercial fisheries observer and logbook reports. This study aimed to examine: (1) whether shark catch declined after sanctuary implementation; (2) whether shark retention reduced after sanctuary implementation; and (3) whether species composition and reporting changed after sanctuary implementation.

4.2. METHODS

4.2.1 Data Sources

All research was carried out under Cook Islands Government Research Permit 06/16. The Cook Islands are a member of the Western and Central Pacific Fisheries Commission (WCPFC) RFMO and receive technical support, including commercial fisheries and database housing and maintenance, from the Oceanic Fisheries Program at the Secretariat of the Pacific Community (SPC) (Allain et al. 2018). Commercial fisheries records were downloaded from SPC databases and provided by the Ministry of Marine Resources, Cook Islands Government and came in four separate datasets: (1) aggregated logbook data from longline vessels for years 1960-2013; (2) operational level logbook data from longline vessels from 2009-2018; (3) operational level observer data from longline vessels from 2009-2018; and (4) operational level data from purse seine vessels from 2009-2018. Data were filtered to include aggregated and operational level shark reporting data from vessels fishing within the Cook Islands Exclusive Economic Zone (EEZ). Aggregated data are the summed reports from all vessels within a fleet over larger spatial scales, whereas operational level data are at the vessel level, and include finer spatial scales as well as vessel specific information such as date and time of set and gear configurations (Langley 2007). The spatial scales, latitudes, longitudes, gear configurations, and other vessel or fleet details were not provided with the data sets, however all data were from vessels operating within the EEZ. The aggregated data set included only six species plus a general "shark" category; operational level logbooks and observer reports recorded species to species level, but also to genus level only and into a general "shark" category when observers or crew did not identify species. Observer coverage on longline vessels in the Cook Islands EEZ ranged from 6.0% to 12.8% compared to >98% logbook coverage in the operational dataset (MMR 2019). Purse seine observer coverage in the Cook Islands EEZ was unable to be obtained, however, the observers are placed by the regional observer program, whose guidelines state that 100% coverage is a requirement for vessels fishing between 20°N and 20°S (WCPFC 2019).

4.2.2 Data Analysis

The four datasets were analyzed separately and results plotted using R Statistical Software (version 3.4.1). In the aggregated logbook data, total catch was reported in metric tons (mt) per year and ended in 2013, which limited my ability to use these data. Data on the fate of individual sharks was not provided (e.g. retention or discard) for logbook data. In the operational datasets for longline and purse seine vessels, data was reported in metric tons and number of sharks caught. Fate of animals was recorded as number of sharks retained or discarded by species. No data on weights of retained sharks or discards were provided, therefore catch was analyzed using number of individual sharks captured, retained and/or discarded per year. Datasets were analyzed to species level where possible. Because aggregated data were reported by weight, the operational dataset was used for species level analyses so that comparisons could be made between logbook and observer reports (count data). Fishing vessel effort data was not available to compare catch records with fishing effort, nor were the data provided for number of observed trips. Percent change in pre- and post- sanctuary retention was calculated, and Chi-squared tests were used to determine if the differences in proportions of retention pre-and post- sanctuary were significant in the logbook and observer operational level data sets.

4.3. RESULTS:

4.3.1. Overview of Shark Catch Data

Shark catch records began in 1960 from longline logbooks; however, zero sharks were recorded from 1960 to 1984 and in 1996, 1997 and 2000. The aggregated dataset for longline vessels (1960-2013) reported six species (Blue Shark, Silky Shark, Scalloped Hammerhead Shark, Oceanic Whitetip Shark, thresher spp., mako spp. and a general “shark” category, which included animals not identified to genus or species level (Table 4.1). Reported total shark catch in the aggregated dataset peaked in 2012 at 379 mt (Figure 4.1). Between 2009 and 2018, based on the operational level datasets, reported shark capture from longline vessels for the three most frequently reported species (Blue Shark, Silky Shark, Oceanic Whitetip Shark) was more than five times higher than in purse seine vessels over the same period. In the operational level datasets for longline and purse seine vessels (2009-2018), 21 species were reported, four to genera level, and the general “shark” category for unidentified species (Table 4.2). Blue Sharks were the most commonly reported species overall and in the operational level longline dataset (Table 4.2). Blue Shark catch in the operational level dataset was three times that of the second most frequently reported species overall, Silky Sharks, which dominated purse seine vessel reports at 98% of all recorded species (Table 4.2). Oceanic Whitetip Sharks were the third most frequently reported species overall, but second most common in both the longline and purse seine datasets (Table 4.2).

Table 4.1: Total sharks reported in metric tons (ordered by weight) by longline vessels in the aggregated dataset (1960-2013). * Indicates that species were reported only to family level.

Species	**Common Name**	**LL/logbook (metric tons)**
Sphyrna lewini	Scalloped Hammerhead Shark	919.3
Sharks (Unidentified)	Sharks (Unidentified)	570.3
Prionace glauca	Blue Shark	238.2
Isuridae spp.*	Mako Sharks*	67.2
Carcharhinus longimanus	Oceanic Whitetip Shark	30.6
Carcharhinus falciformis	Silky Shark	8.7
Alopiidae spp.*	Thresher Sharks*	4.3

Table 4.2: Total number of sharks (individuals) reported in the operational level dataset by gear, ordered alphabetically by Latin name. Longline vessel data is broken down by logbook versus observer. Only observer data is presented for purse seine vessels. * Indicates that species were reported only to family level. Species with >10 individuals reported are indicated in bold.

Species	**Common Name**	**LL/observer (individuals)**	**LL/logbook (individuals)**	**PS/observer (individuals)**
Alopias pelagicus	**Pelagic Thresher Shark**	**16**	**11**	**3**
Alopias superciliosus	**Bigeye Thresher Shark**	**102**	**0**	**2**
Alopiidae* spp.	**Thresher Sharks***	**0**	**247**	**0**
Carcharhinus albimarginatus	Silvertip Shark	2	0	5
Carcharhinus altimus	Bignose Shark	2	0	0
Carcharhinus amblyrhynchos	Grey Reef Shark	2	0	0
Carcharhinus brachyurus	**Bronze Whaler Shark**	**11**	**0**	**2**
Carcharodon carcharias	Great White Shark	2	0	0
Carcharhinus falciformis	**Silky Shark**	**649**	**1852**	**5524**
Carcharhinus limbatus	Blacktip Shark	2	0	2
Carcharhinus longimanus	**Oceanic Whitetip Shark**	**253**	**5608**	**61**
Cetorhinus maximus	**Basking shark**	**0**	**11**	**1**
Carcharhinus melanopterus	**Blacktip Reef shark**	**7**	**5**	**0**
Carcharhinus plumbeus	Sandbar Shark	3	0	0

Galeocerdo cuvier	Tiger Shark	0	0	2
Isuridae* spp.	**Mako Sharks***	**3**	**565**	**0**
Isurus oxyrinchus	**Shortfin Mako Shark**	**196**	**0**	**0**
Isurus paucus	**Longfin Mako Shark**	**127**	**0**	**0**
Lamna nasus	**Porbeagle Shark**	**0**	**112**	**0**
Lamnidae spp.*	Mackerel Sharks*	0	1	0
Prionace glauca	**Blue Shark**	**1179**	**23654**	**8**
Rhincodon typus	Whale Shark	0	0	5
Sharks (Unidentified)	**Sharks (Unidentified)**	**26**	**5870**	**0**
Sphyrna mokarran	Great Hammerhead Shark	0	0	1
Sphyrna zygaena	Smooth Hammerhead Shark	0	0	1
Sphyrnidae* spp.	**Hammerhead Sharks***	**0**	**73**	**0**
Zameus squamulosus	Velvet Dogfish	2	0	0

4.3.2. Shark Catch and Sanctuary Implementation

In the aggregated longline logbook dataset (1960-2013), recorded shark catch peaked in 2012 at 379 mt and decreased the following year to 162 mt, which coincided with sanctuary implementation in 2013 (Figure 4.1). No data was available beyond 2013, which limited the interpretation of the effect of sanctuary implementation using this data set.

Shark catch (number of sharks hooked and not necessarily retained) peaked in different years in the operational dataset (2009-2013), depending on the vessel and record type (Figure 4.2). The total number of hooked individual sharks caught by gear can be found in Appendix 3 Table A3.1. In the longline logbook records, a decrease in reported catch was seen from 2012 to 2013 (Figure 4.2). However, then number of sharks reported in longline logbooks generally increased through time, from <2000 individuals before 2012 to >5000 in most years thereafter. Similarly, in the purse seine vessels observer records, reported shark catch halved from 2012 to 2013. However, catch increased to >1000 individuals in 2014 where it peaked and did not decrease to 2013 levels in subsequent years.

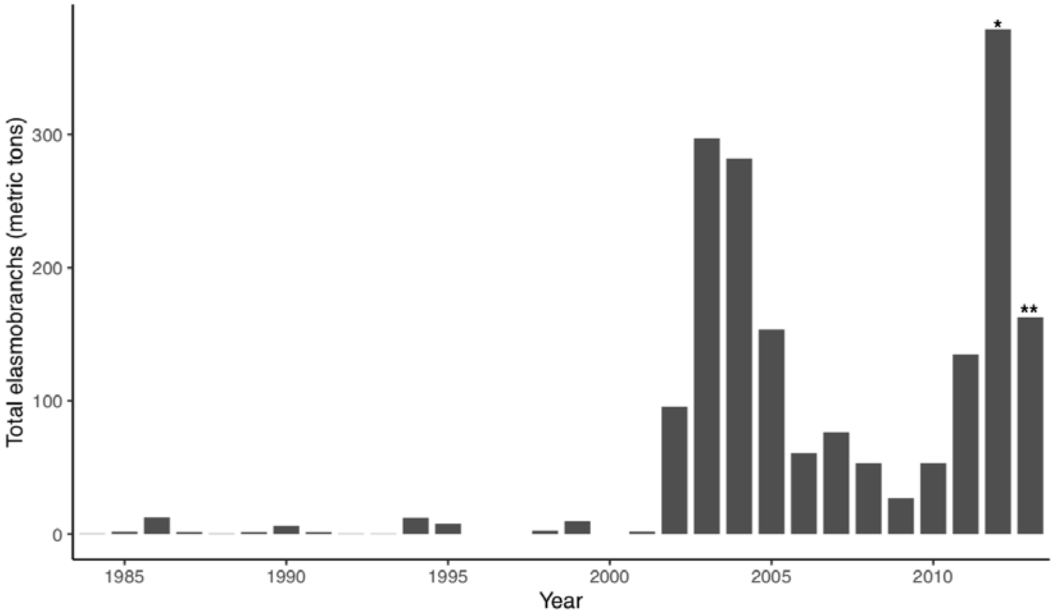

Figure 4.1: Shark catch (in mt) reported in the aggregated longline logbook dataset (1984-2013). * Indicates year sanctuary was declared (2012). ** Indicates year sanctuary was implemented on all vessels (2013).

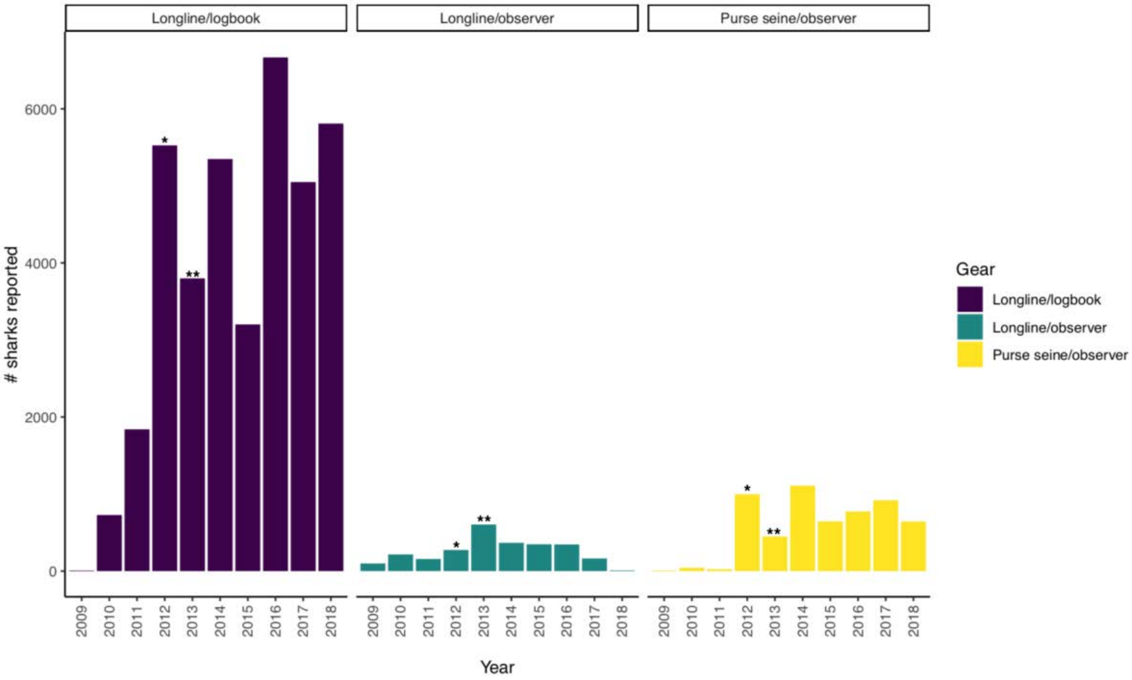

Figure 4.2: Number of sharks reported as captured in the operational level longline and purse seine datasets, broken down by gear and record type (2009-2018). * Indicates year sanctuary was declared (2012). ** Indicates year sanctuary was implemented on all vessels (2013).

4.3.3. Shark Retention and Sanctuary Implementation

There were no data on shark retention in the aggregated longline dataset (1960-2013). In the operational level dataset, total shark retention peaked in 2012 in the longline logbook and observer records (Figures 4.3, 4.4). Longline logbooks reported a 100-fold increase in retention in 2012 (Figure 4.3). There were significant changes in proportions of sharks discarded before and after sanctuary implementation. Logbooks showed a 11-fold decrease in retention (Chi-square df=1, $p < 0.001$). Observer records showed a 28-fold decrease in retention (Chi-square df = 1, $P<0.002$). Longline observers reported fewer than 10 sharks retained throughout the data reporting period (Figure 4.4). However, 693 sharks were reported as retained in 2013 by logbooks, but only 1 shark was reported as retained by observers. Observers reported much lower numbers of sharks retained than the logbooks, except in 2018 when zero sharks were reported as retained in both datasets (Figures 4.3, 4.4). This mismatch is likely the result of the differences in fishing effort that each of the data sets represent because logbooks represent higher fishing effort than observers, who were present on limited numbers of fishing trips.

Shark retention in purse seine observer records was reported at fewer than five individual sharks each year for the duration of the reporting period (Figure 4.5). Retention peaked in 2012 with four Silky Sharks and decreased to zero in 2013. Few sharks were reported as retained in 2017 and 2018 (Figure 4.5).

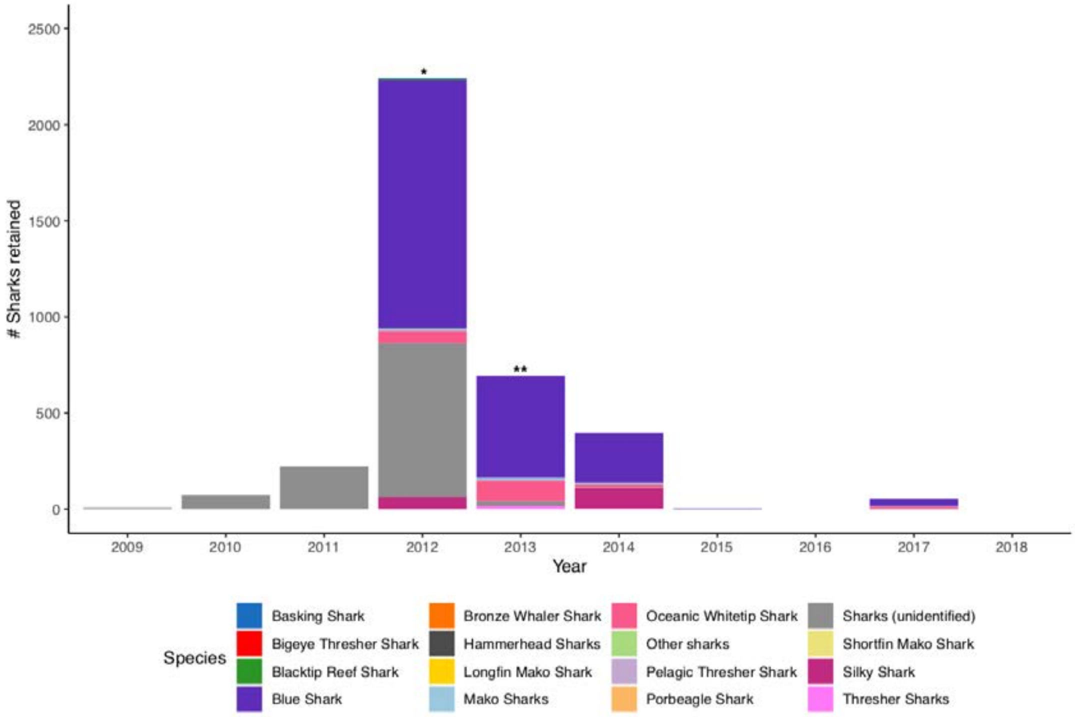

Figure 4.3: Top 15 species of sharks plus “Other sharks”, which includes all species outside of the top 15, reported as retained in the operational level longline logbook records, broken down by species (2009-2018). * Indicates year sanctuary was declared (2012). ** Indicates year sanctuary was implemented on all vessels (2013).

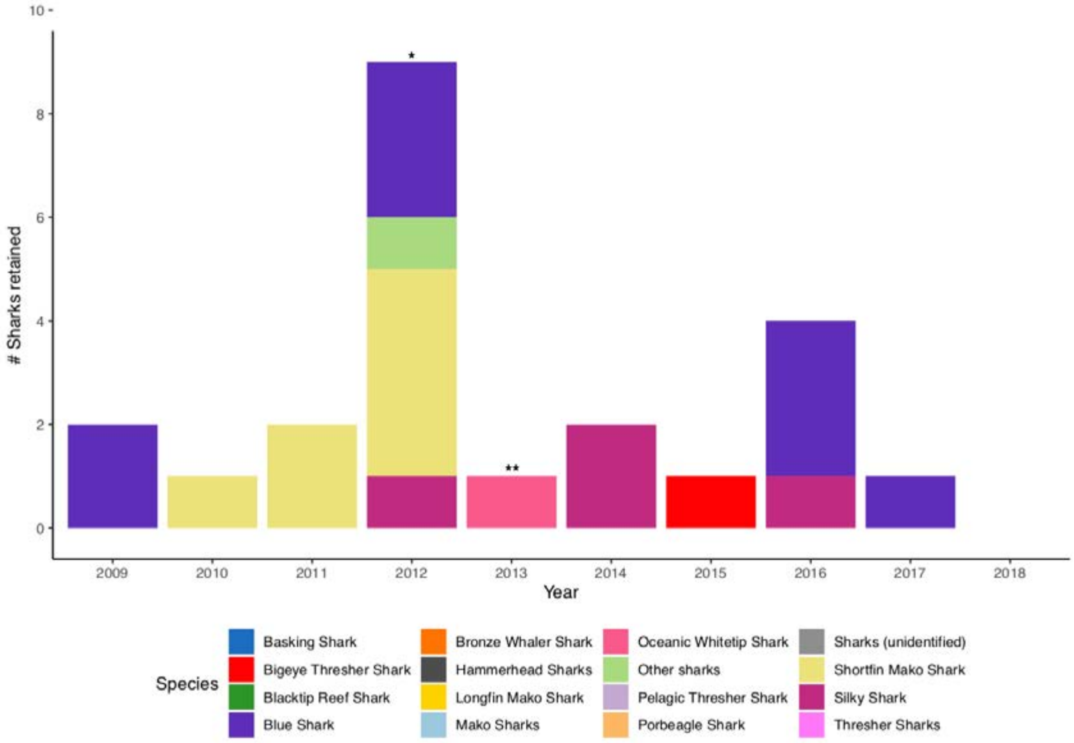

Figure 4.4: Top 15 species of sharks plus "Other sharks", which includes all species outside of the top 15, reported as retained in the operational level longline observer records, broken down by species (2009-2018). * Indicates year sanctuary was declared (2012). ** Indicates year sanctuary was implemented on all vessels (2013).

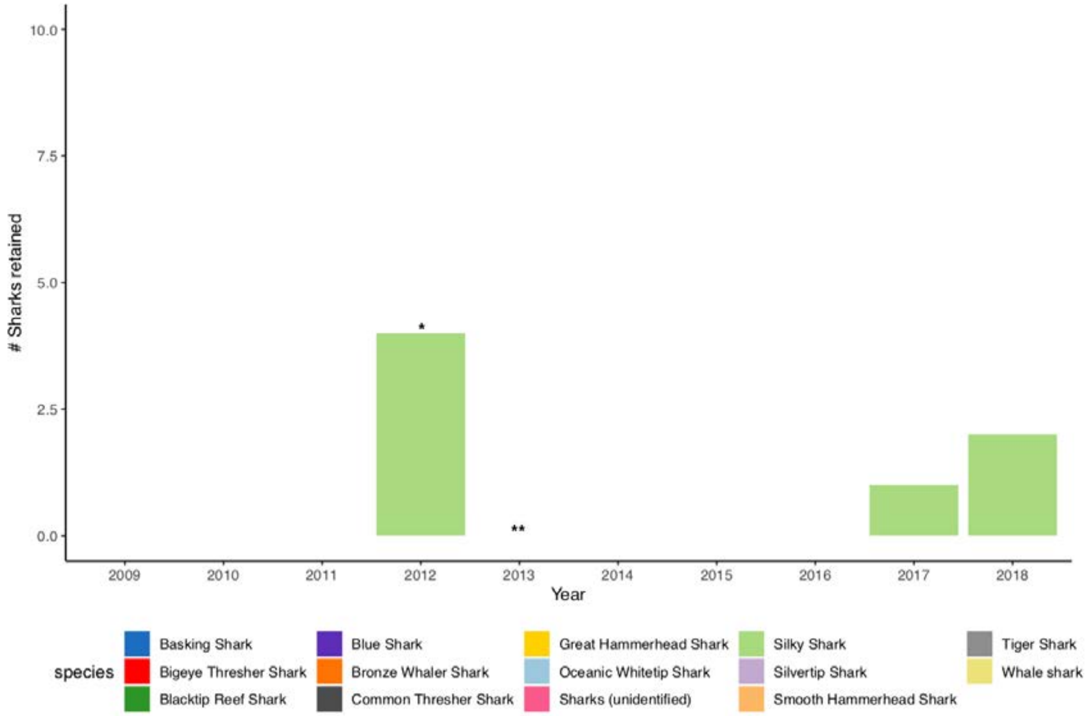

Figure 4.5: Number of sharks (all species) reported as retained in the operational level purse seine observer data, broken down by species (2009-2013). * Indicates year sanctuary was declared (2012). ** Indicates year sanctuary was implemented on all vessels (2013).

4.3.4. Species Composition and Reporting and Sanctuary Implementation

The aggregated longline dataset was not used for species level analyses because of the absence of count data for comparisons. The species composition of the longline operational level dataset was dominated by Blue Sharks, which represented >50% of the catch from 2013-2017, and unidentified sharks, which represented >50% of the catch 2010-2012 (Figure 4.6, 4.7). The number of species reported increased from seven in 2010, to 11 in 2011 and 14 in 2012 and 2013, remaining between 12-14 species for the remainder of the period. Similar to the purse seine data, no major species composition changes were observed following the implementation of the sanctuary. Species identification varied between logbook and observer data in the operational level dataset (Figure 4.6, 4.7). Basking Sharks were reported in the logbook data, but not in the observer data, likely due to low levels of observer coverage, suggesting logbook data represented more fishing effort (Figure 4.8 (#14)). Similarly, zero hammerhead sharks (*Sphyrna* spp.) were reported in the observer data, but were included in the logbook data (Figure 4.8 (#11)). Different species peaked at different times, and reporting to species level was more prevalent in observer records than logbook records for several species (Figure 4.8). Shortfin Mako Sharks (*Isurus oxyrinchus*) were in the observer record but not in the logbook records, whereas mako spp. (*Isurus* spp.) were present in the logbooks, but not in the observer records, suggesting that observers were able to identify to species level whereas logbook data were more often recorded to genus in 2012 (Figure 4.8). Blacktip Reef Sharks (*Carcharhinus melanopterus*) were present in the longline datasets for both logbook and observer records, meaning that some longline sets likely occurred close to reef habitats (Figure 4.8 (#15)).

In the operational level purse seine observer data, catch was dominated by Silky Sharks at >98% of total catch, with the second most frequently reported species, Oceanic Whitetip, reported at 0.05% of catch (Figure 4.9, Table 4.2). No patterns or changes in species composition were identified that coincided with the implementation of the shark sanctuary and its ban on trace wire and shark lines. Observer records from the purse seine data recorded several Basking Sharks that were not recorded by observers in the longline dataset, which may result from low observer coverage on longlines or gear susceptibility (Figure 4.9, Table 4.2).

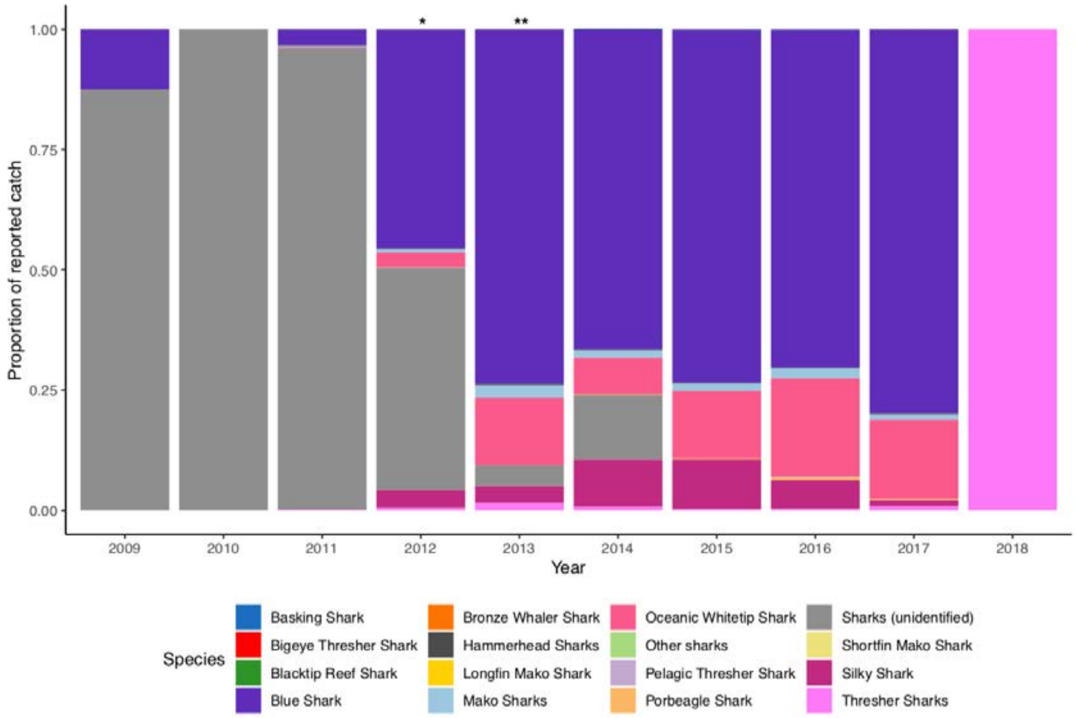

Figure 4.6: Proportion of the top 15 species of sharks plus “other sharks”, which includes all species outside of the top 15, reported from longline logbook records by species (2009-2018). * Indicates year sanctuary was declared (2012). ** Indicates year sanctuary was implemented on all vessels (2013).

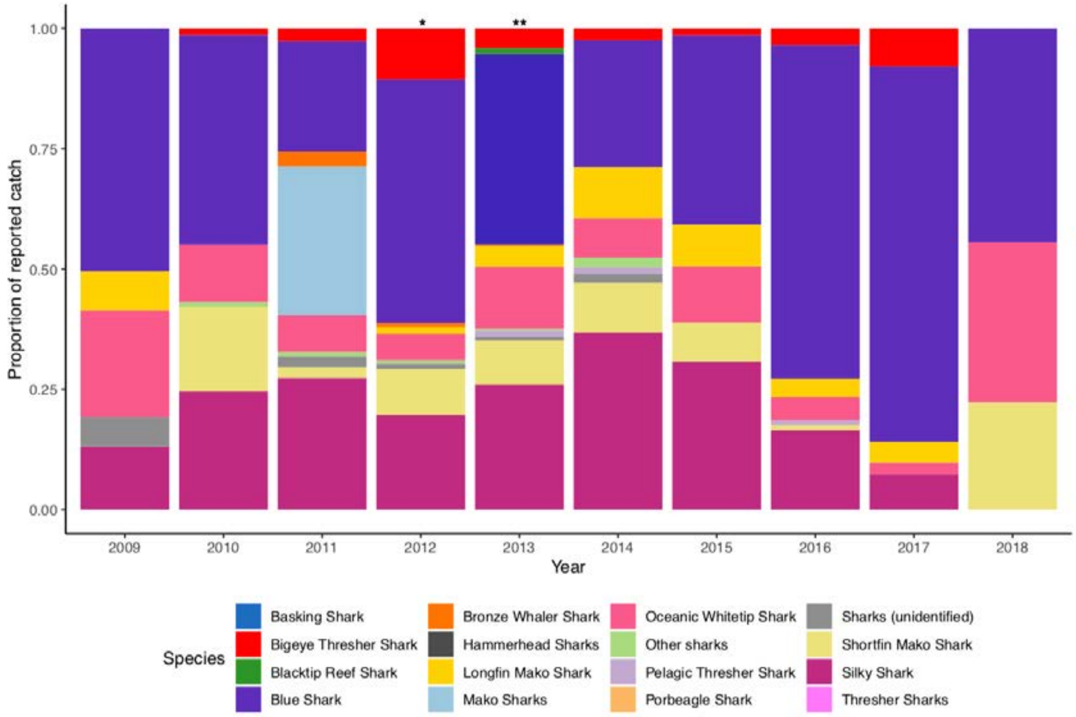

Figure 4.7: Proportion of the top 15 species of sharks plus "other sharks", which includes all species outside of the top 15, reported from longline observer records by species (2009-2018). * Indicates year sanctuary was declared (2012). ** Indicates year sanctuary was implemented on all vessels (2013).

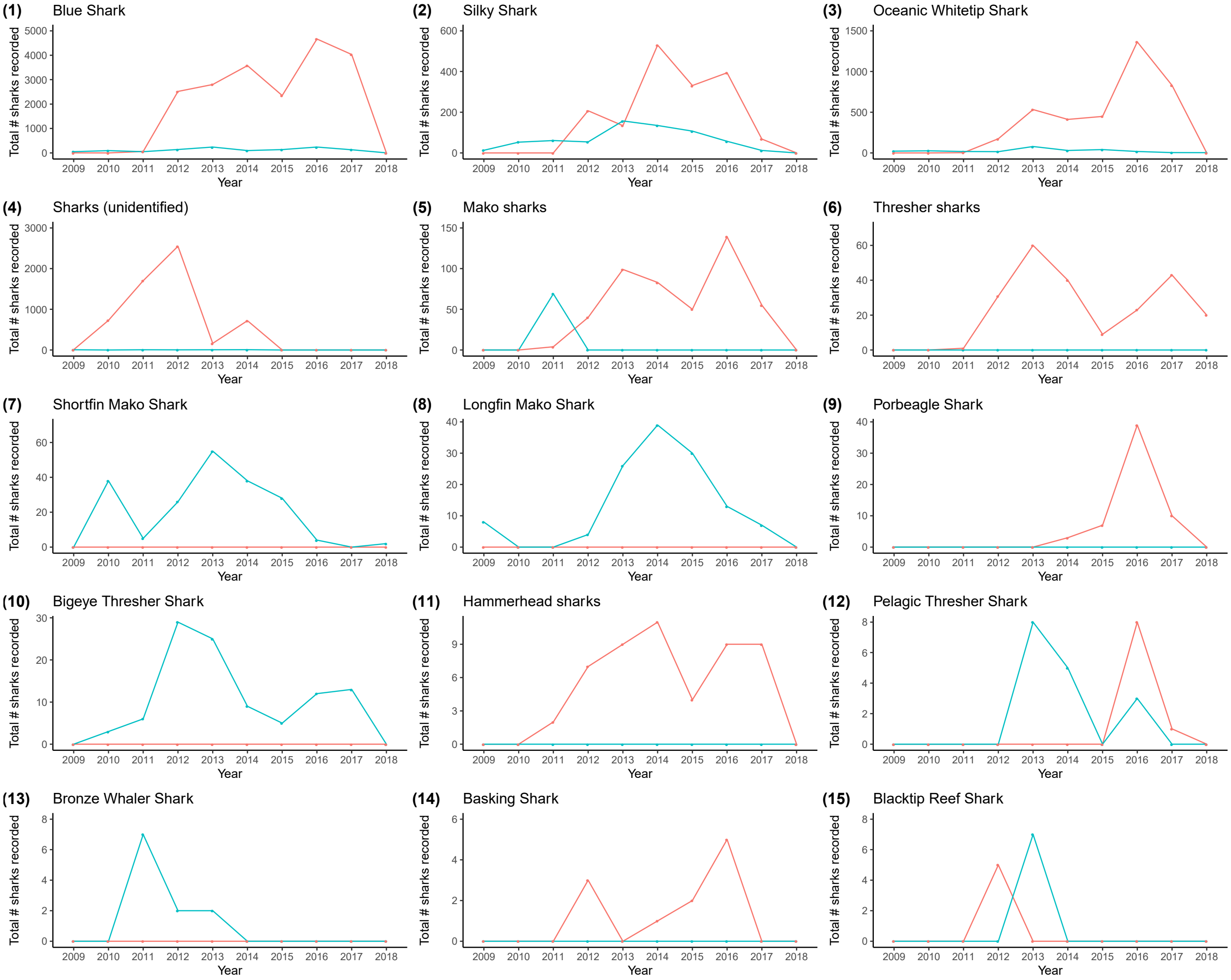

Figure 4.8: Top 15 shark species reported from longline logbook (red) and observer records (blue) by species (2009-2018). Figure includes both species and genera level plots as reported differences between logbook and observer datasets.

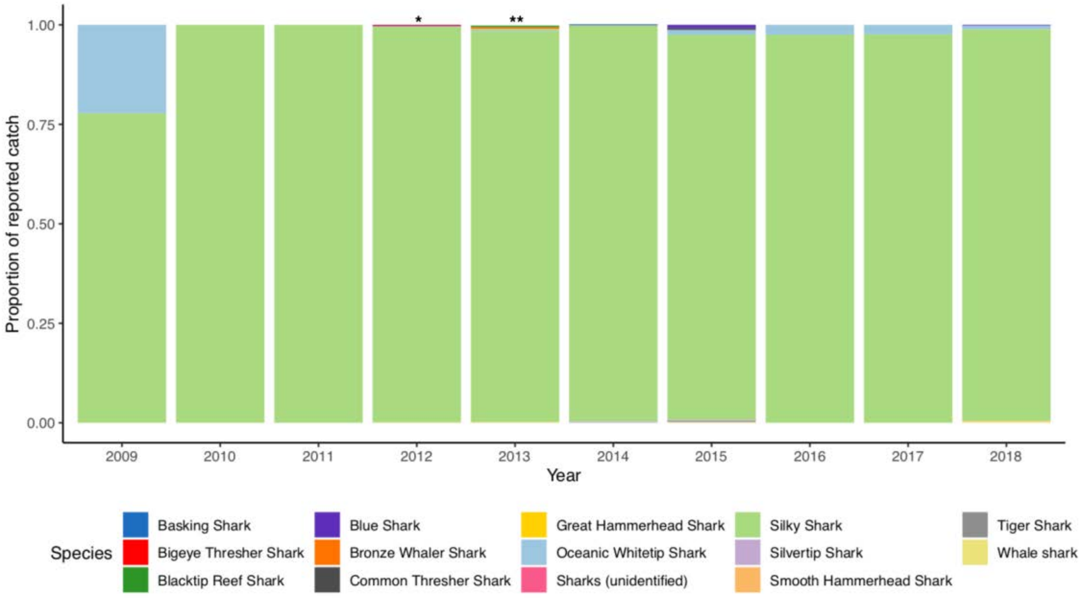

Figure 4.9: Proportion of sharks reported from purse seine observer records by species (2009-2018). * Indicates year sanctuary was declared (2012). ** Indicates year sanctuary was implemented on all vessels (2013).

4.4. DISCUSSION:

The Cook Island Shark Sanctuary was announced in December 2012, but implementation occurred throughout 2013 because annual fishing access agreements with vessels were permitted to conclude before sanctuary regulations took effect (pers. comm., MMR 2020). Analyses of catch and logbook data indicate implementation of the shark sanctuary had an effect on fisher behavior by reducing the number of sharks retained in the longline fishery. However, the scarcity of data in the purse seine fishery did not support a strong conclusion of decreased shark retention.

4.4.1. Shark Catch and Sanctuary Implementation

Shark sanctuary regulations did not ban the catching of sharks, but regulated their fates once hooked. Although it was presumed that the ban of specific gear (shark line and trace wire) mandated by the regulations might have reduced catch, shark catch did not decrease as a result of the sanctuary implementation in any of the datasets examined. Similar studies in Palau showed that switching from braided wire to monofilament as a result of shark conservation regulations reduced catch rates of pelagic sharks on longline vessels (Gilman et al. 2008, 2016b), but I did not have access to records on whether vessels complied with the braided wire and shark line bans in the Cook Islands.

The increase in catch reported in the aggregated logbook dataset as well as logbook and observer retention data that coincided with the sanctuary announcement was likely due to an increase in fishing effort during the same year. The Cook Islands Ministry of Marine Resources more than doubled fishing effort in the EEZ in 2012 as part of an exploratory longline fishery targeting Bigeye Tuna and Swordfish (MMR 2012a, 2013, 2014). While reported shark catch was roughly proportional to the number of hooks in the years prior to and following implementation of the sanctuary, shark catch was substantially higher during the exploratory fishing program (MMR 2012a, 2013, 2014). The substantial difference in longline reported shark catch might be evidence of preemptive overfishing prior to conservation policy implementation, which is similar to that shown in the Phoenix Islands Protected Area in Kiribati in the year prior to implementation of the marine reserve (McDermott et al. 2019). However, while longline aggregated and retention data showed an increase in 2012, operational-level logbook data did not. Opposite catch trends were reported by logbook and observers, which may indicate underreporting, changes in fisher behavior as a result of observers onboard, or be a result of limited observers onboard longline vessels (6% to 12.8% from 2009-2018; (MMR 2012a, 2019). Several studies highlight issues with logbook data including misreporting and underreporting; and some revealed reporting of shark data worsened immediately following retention bans, whether by the RFMO or a member nation, but that data quality increased again after several years (MMR 2013, 2014; Brouwer & Harley 2015; WCPFC 2020). Reporting issues highlight an area where RFMOs and sanctuary countries could work together to improve data, whether by piloting best practice data collection programs, and reiterating and building upon RFMO data collection guidelines. Additionally, sanctuary countries could hinge fishing licenses upon adequate data reports from previous fishing years.

In the purse seine observer data, catch of sharks did not reflect fishing effort, which more than tripled from 2009-2018 (Ponia 2016). However, compared to longline fishing, purse seine reports showed limited shark catch and low species richness. Studies have shown that purse seine sets associated with fish aggregating devices (FAD) catch substantially higher numbers of sharks (Rice & Harley 2013; Hutchinson et al. 2019b; Bonnin et al. 2021). Because the Cook Islands purse seine fishery relies on FADs, I might have expected higher shark catch reports, particularly with such high observer coverage. However, studies have also suggested that several observers are required onboard purse seine vessels to accurately record catch at various stages of vessel activity (Hutchinson et al. 2019a). In the absence of additional observers, electronic monitoring could ensure all sharks and other bycatch are accurately recorded.

Better data reporting is required in both the longline and purse seine fishery to determine breadth of the impacts of the shark sanctuary implementation on fisher behavior. Shark catch per unit effort before and after sanctuary announcement and implementation in both the purse seine and longline fisheries warrants further investigation. Particularly in the longline fishery, further investigation is required to determine whether preemptive fishing occurred or whether factors shown to reduce hooking and capture stress, such as fishing depth, soak times, and bait type (Gilman & Lundin 2008; Gilman et al. 2016b) can be improved for improved shark conservation inside sanctuaries.

4.4.2. Shark Retention and Sanctuary Implementation

Data from logbooks and observers demonstrated that the implementation of the Cook Islands shark sanctuary resulted in substantially decreased retention of sharks by longline vessels, but scarcity of sharks reported by observers on purse seine vessels did not support strong conclusion on reduced retention. Although several studies have shown that banning retention is a useful step in reducing mortality of sharks (Tolotti et al. 2015b; Gilman et al. 2016a), there is still some mortality as a result of capture stress, hook location, net entanglement and other factors (Bromhead et al. 2012; Gallagher et al. 2014; Hutchinson et al. 2015; Musyl & Gilman 2019). In conjunction with banning retention and possession of shark parts, the sanctuary legislation calls for swift release of animals in a manner that maximizes survival, but I do not know the capture-related (or post-release) mortality level inside the sanctuary, or the release condition of individuals (MMR 2012b). Assuming similar post-release survival documented for oceanic sharks in other regions (Gilman & Lundin 2008; Musyl et al. 2011; Hutchinson et al. 2015; Musyl & Gilman 2018), the sanctuary is likely benefiting sharks released in good condition. In addition to spatial protection, sanctuaries would benefit from further operational-level policy amendments that targeted gear, soak times, depth, bait type and other measures that have been enacted by RFMOs for other bycatch species to reduce stress and mortality.

Despite the reported reductions in retention in all datasets, there were discrepancies in shark retention levels reported between observers and logbooks. Observers reported substantially lower levels of shark retention than logbooks, the difference likely due to the low levels of observer coverage on vessels (6-12.8%) compared to >98% logbook coverage (MMR 2019) and that fisher behavior may change as a result of observers onboard (Hutchinson et al. 2015; WCPFC 2017). Reporting discrepancies between observer and logbook records, particularly for bycatch species like sharks, have been documented widely in fisheries management (Clarke et al. 2011b, 2015; Brouwer & Harley 2015; WCPFC 2016b, 2020). RFMOs have made progress on increasing the volume and quantity of data in capacity-limited countries (Clarke et al. 2015; WCPFC 2020), but sanctuary countries could benefit from increased observer coverage and electronic monitoring on vessels to improve data availability and promote compliance with sanctuary and other fisheries regulations (Tolotti et al. 2015b; Queiroz et al. 2019; Wang et al. 2021).

4.4.3. Species Composition and Reporting and Sanctuary Implementation

Implementation of the Sanctuary did not result in species-level changes such as switching from recording one species to another, nor did species composition change. Blue Sharks dominated analysed longline catches and Silky Sharks dominated purse seine catches, which is consistent with other commercial fisheries reports (Simpfendorfer et al. 2002; Gilman et al. 2008; Clarke et al. 2014; Rice et al. 2014; Lucena Frédou et al. 2015; Hutchinson et al. 2019a; Bonnin et al. 2021). Observers were better at identifying species than crew reports in logbooks, but neither was perfect, given lumped species reporting. Inaccurate species identification could account for some of the minor species reported, or those reported outside of their normal ranges, such as Basking Sharks. While specific species-level changes as a result of sanctuary implementation were not identified, an increase in the number of species reported was found (and fewer species recorded in the combined "shark" category) in the years following sanctuary implementation in the operational-level dataset. A gradual increase in species-level reporting was found in the aggregated dataset from 1998 onward.

The WCPFC and member countries adopted new log sheets in 2013 to record additional information about species of special interest, including sharks, that resulted in better species-level data (MMR 2013, 2014; WCPFC 2016b). Despite the new log sheets, the Cook Islands Ministry of Marine Resources reported a reduction in species-specific shark reporting following sanctuary implementation (MMR 2014). However, in the raw operational-level data species-specific shark records increased after sanctuary implementation. The changes in reporting were likely due to the change in log sheets rather than the sanctuary implementation. Several reports of misreporting or underreporting have been attributed to sanctuary regulations or retention bans by RFMOs (MMR 2013; Brouwer & Harley 2015; Clarke et al. 2015). While these issues were apparent, studies have shown that poor data and misreporting exist in non-sanctuary countries and for species not banned from retention in longline and purse seine fisheries (WCPFC 2016b, 2020; Hutchinson et al. 2019a; Wang et al. 2021). Bycatch and species-level reporting remains a pervasive problem in fisheries management, which requires continued improvement in sanctuary and non-sanctuary countries (WCPFC 2020).

4.5. CONCLUSION

The implementation of the Cook Islands Shark Sanctuary resulted in a change in fisher behavior by reducing shark retention in the longline fishery, but data were too scarce in the purse seine fishery to strongly support reduced shark retention. While retention was reduced in the longline fishery, shark catch was not in either fishery, which likely resulted in some ongoing shark mortality. Reduction of shark-fishery interactions is necessary to increase effectiveness of sanctuaries in reducing shark mortality. Scarcity of data and discrepancies between logbook and observer data warrant further investigation with regard to species reporting and compliance with regulations. Adoption of electronic monitoring and reporting could provide a solution for this issue. In addition, alignment of sanctuary and RFMO policy to decrease retention of sharks could increase protection for sharks by implementing clear operational-level guidelines on gear-and fisher-specific bycatch mitigation techniques, including handling and release guidance, and temporal and spatial protections. Sanctuary countries have shown political will for protecting sharks making them good candidates for policy reform that includes pioneering management approaches. While the effectiveness of shark sanctuaries has been debated, this work provides clear evidence that they can lead to changes in fisher behavior. However, data limitations for bycatch species such as sharks remain a pervasive issue that precludes analyses of the effectiveness of conservation and management policies. Further work is needed to understand mortality rates and accurately define the benefits to shark populations.

Chapter 5:

Movement ecology of pelagic sharks tagged within a shark sanctuary

ABSTRACT:

Fisheries have threatened the majority of oceanic shark species with extinction. As a mechanism to protect shark species, sanctuaries were enacted by several nations to ban commercial fishing vessels from retaining these species throughout a nation's exclusive economic zone (EEZ). However, the wide-ranging movements of pelagic species means they might move quickly beyond the sanctuary border into unprotected waters. The dispersal ability of species raises questions about whether sanctuaries can be effective in affording protection to wide-ranging, oceanic sharks. This chapter examined whether sanctuaries are effective in the conservation of wide-ranging sharks by elucidating their movement patterns relative to sanctuary boundaries and commercial fishing effort, using the Cook Islands Shark Sanctuary as a case study. It further evaluated sharks' risk of capture by fisheries based on swimming depth and the amount of fishing occurring in the Sanctuary that overlapped with shark movements. Sixteen satellite tags were deployed inside the Cook Islands EEZ on the three most commonly caught sharks in Cook Islands industrial fisheries: Blue Sharks (*Prionace glauca*), Oceanic Whitetip Sharks (*Carcharhinus longimanus*), and Silky Sharks (*Carcharhinus falciformis*). Results indicate that the Sanctuary is beneficial for Oceanic Whitetip and Silky Sharks because a greater proportion of their movements were within the Sanctuary boundaries. Blue Sharks likely received minimal benefit because of the extent of their movements primarily occurred outside of the Sanctuary, however, all sharks received benefit from neighboring shark sanctuaries that created a contiguous sanctuary. Despite the perceived benefits to sharks, the susceptibility to fisheries capture was substantively higher (>98%) than reported in recent studies suggesting there was almost no refuge from fishing inside the Sanctuary. Oceanic Whitetip Sharks exhibited the greatest risk of capture by industrial fisheries. These combined results suggest sanctuaries likely provide benefit to wide-ranging species whose movements are primarily restricted to sanctuary waters. Neighboring sanctuaries provide an opportunity for greater protections, but implementing uniformity in sanctuary regulations between countries would increase benefits to sharks. However, because movements of wide-ranging sharks span high seas and non-sanctuary countries, additional conservation and management tools need to be employed to protect these sharks.

5.1. INTRODUCTION

Pelagic sharks experienced a 77% decline in population in 50 years as a result of overlap with industrial fisheries, where they are targeted and captured as bycatch (Dulvy et al. 2014; Pacoureau et al. 2021). The rapid downward trajectory of many pelagic shark species, including Silky (*Carcharhinus falciformis*), Oceanic Whitetip (*Carcharhinus longimanus*), Shortfin Mako (*Isurus oxyrinchus*) and Whale Sharks (*Rhincodon typus*) has triggered conservation and management responses at global, regional, and national levels. Despite the number of management measures aimed at reducing pelagic shark interaction and mortality from fisheries, these measures are not meeting the conservation needs of pelagic sharks globally (Lawson & Fordham 2019; Pacoureau et al. 2021). Therefore, more effective approaches are needed to reduce the mortality of pelagic sharks. These may include fisheries-specific, spatial management (e.g. MPAs) and trade interventions (Bräutigam et al. 2015; Clarke 2015; Davidson et al. 2016; Dent & Clarke 2015; Ferraro & Pressey 2015). Without effective measures in place pelagic shark populations will continue to decline.

Shark sanctuaries are national-scale spatial management zones where the targeting and retention of shark (and sometimes ray) parts are banned from industrial vessels (Ward-Paige 2017). Importantly, sanctuaries do not ban fishing that targets species other than sharks, rather they change the fate of sharks once incidentally captured by industrial vessels that target more lucrative species such as tuna and swordfish (Clarke 2011; Campana 2016). Sanctuaries have been criticized for inconsistencies in size, protection levels, and for exempting artisanal fishers who primarily interact with shark and ray species on reefs (Davidson 2012; Cramp et al. 2018). Despite these exemptions, recent studies show that countries with sanctuaries had significantly higher abundances of reef sharks and rays, with the central Pacific Ocean holding highest abundances (MacNeil et al. 2020, Cramp Chapter 1). However, reef species have limited movements relative to the size of sanctuaries (Dwyer et al. 2020) improving chances of positive outcomes. In contrast, pelagic sharks are known to traverse large distances potentially crossing multiple jurisdictions, potentially weakening the benefit of sanctuaries because they can quickly move outside of sanctuary boundaries where they may be retained (Fowler 2014; Dulvy et al. 2017).

While spatial protections can benefit pelagic species that exhibit strong site fidelity (Howey-Jordan et al. 2013; Young & Carlson 2020), analysis of global pelagic shark movements showed that nearly one quarter (24%) of the mean monthly space use by pelagic sharks overlapped with longline fisheries (Queiroz et al. 2019). Understanding the spatial ecology of pelagic sharks will therefore help predict the benefits of sanctuaries to pelagic species. Measuring effectiveness of spatial protections on highly migratory sharks requires a variety of studies including examination of catch rates, enforcement and compliance of fishing vessels, movement ecology of sharks with respect to sanctuary boundaries and vessel activities, and post release survival information once sharks are released from vessels. Telemetry can provide data on shark behavior including migrations, and thermal and depth preferences (Stevens et al. 2010). Data from satellite tagged sharks have been used to identify movement between jurisdictions including sanctuary waters (Howey-Jordan et al. 2013; Byrne et al. 2017; Bradley et al. 2018; Francis et al. 2019), seasonal migrations and species-specific movement patterns (Block et al. 2011), and susceptibility to capture by industrial fishing vessels (Queiroz et al. 2019). However, no study has combined these factors within a shark sanctuary to investigate effectiveness in reducing mortality of pelagic sharks that interact with industrial fisheries.

In this chapter, I examine the movements of three pelagic shark species released within the Cook Islands Shark Sanctuary. Enacted in 2012 by regulation under the Marine Resources Act (2005), the Sanctuary spans the country's exclusive economic zone (EEZ) and extends to all elasmobranchs (sharks and rays). Regulations also ban the use of trace wire (reinforced fishing line that is difficult for sharks to bite through), and the import, export, sale, trade, possession, transshipment, barter and trade of all parts of elasmobranchs. Any elasmobranch incidentally captured must be released dead or alive, in a manner that affords the animal the greatest opportunity for survival. Fines range from $100,000 to $250,000 NZD, with each fin or piece of elasmobranch constituting a separate offence (MMR 2012b). Within the Sanctuary, as part of the Marae Moana Act (Marae Moana Act 2017), additional spatial protection measures include 50 nm industrial fisheries exclusion zones around each of the 15 islands.

The aim of this study was to examine the movement ecology of pelagic sharks caught by industrial longline and purse seine fisheries to determine the benefits derived from an individual shark sanctuary. The goals were to: (1) deploy pop-up satellite archival tags on pelagic sharks in the Cook Islands EEZ; (2) investigate shark movement relative to spatial boundaries and estimate the proportion of time sharks spent in fished and unfished areas, including the Sanctuary, the 50 nm commercial fisheries exclusion zone, neighboring jurisdictions, and areas beyond national jurisdiction; (3) determine susceptibility to fisheries based on depth and the amount of fishing occurring in the Sanctuary that overlaps with shark movements; and (4) discuss the level of protection an individual sanctuary affords pelagic sharks based on their movement ecology.

5.2. METHODS:

5.2.1 Ethics Statement:

All research was carried out under the James Cook University Animal Ethics Permit #A2310 and Cook Islands Government Research Permit #06-16.

5.2.2 Study Area:

The Cook Islands are comprised of 15 islands spanning 1.997 million km^2 of the South Pacific Ocean located between 156 and 167 degrees west longitude and 8 and 23 degrees south latitude. Bordering countries include French Polynesia to the East, Niue and American Samoa to the West, Tokelau to the Northwest, and Kiribati to the Northwest and Northeast. High seas border the Cook Islands to the East and South. French Polynesia, Kiribati and Niue have sanctuary legislation extending protection to some sharks throughout their EEZs (Figure 5.1). All satellite tags were deployed within 150 km of Rarotonga, a volcanic southern island, from 30 July 2018 to 7 May 2019 (Table 5.1; Figure 5.1). Spatial data delineating the Cook Islands 50 nm commercial fishing exclusion zones (around each island) used in this study were provided by the National Hydrography Division of the Ministry of Infrastructure, Cook Islands Government.

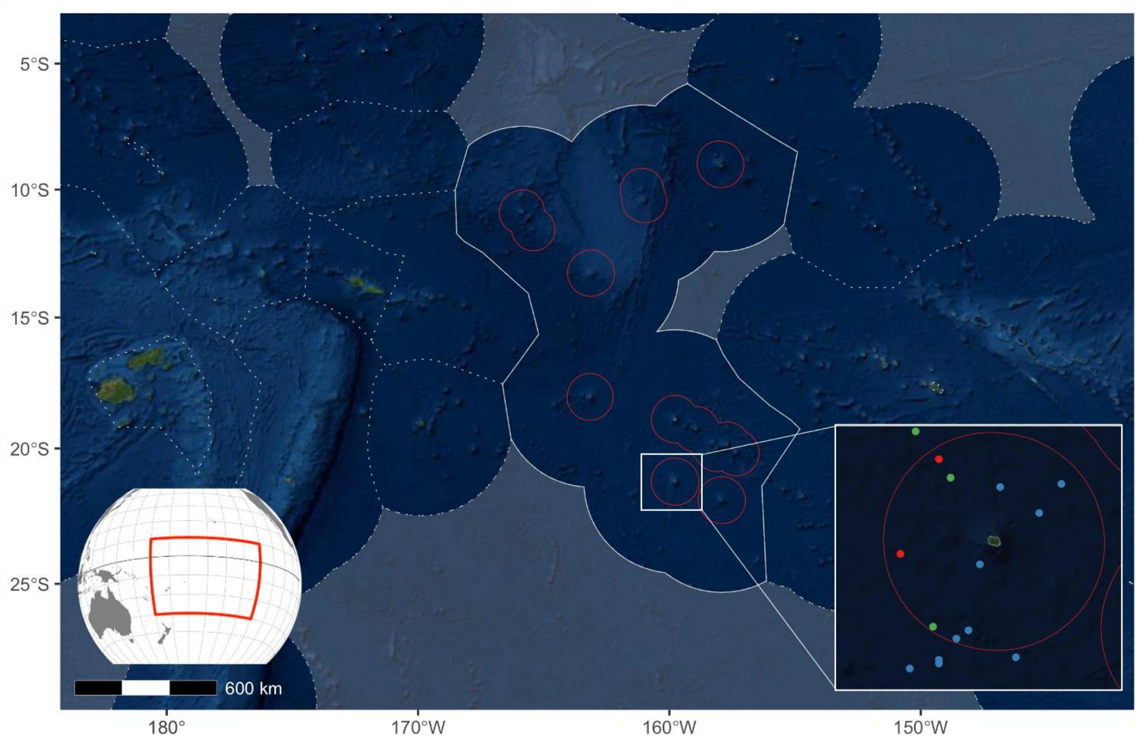

Figure 5.1: The study area. The Cook Islands Exclusive Economic Zone (white outline), and 50 nm limits around islands (red outlines). Surrounding EEZs indicated in broken white outlines, with high seas waters represented by greyed out areas. The white box indicates Rarotonga, Cook Islands. The expanded white box indicates tag deployment locations around Rarotonga, Cook Islands. The red circle delineates the 50 nm industrial fisheries exclusion zone around the island. Point color indicates species tagged including Blue Shark (n = 2, red points), Oceanic Whitetip Shark (n = 11, blue points) and Silky Shark (n = 3, green points).

5.2.3 Shark Capture, Handling, and Tagging:

Trained crew deployed sixteen shark tags from research and industrial longline fishing vessels. In partnership with local fishers, sharks were captured from recreational vessels using two methods: single hook and line, and short surface longlines that were deployed at various times of day and night. Research fishing was conducted at fish aggregating devices (FADs) that were anchored in 300 m and 1200 m of water. The vessel was tied to the FAD and then sharks were drawn to the boat by intermittent chumming with pilchards (*Sardinops* spp.) and a bait crate containing tuna heads (*Thunnus* spp.) or available scraps from local fishers. Once sharks were sighted, the single hook method was deployed similar to hand line deployment described by Howey-Jordan et al. (2013). Mustad circle hooks (16/0) were baited with *Thunnus* spp. where possible. Other bait included *Sardinops* spp., *Coryphaena hippurus, Acanthocybium solandri* and *Elagatis bipinnulata.*

Research longline fishing from recreational vessels was conducted after sunset. Longlines were deployed at 15 m depth and consisted of 500 m nylon main line (600-lb) with branch lines (2 m long) placed every 20 m that consisted of coated 7x7 steel cable and a baited 16/0 Mustad circle hook. Surface buoys were marked with glow sticks and attached to the main line every 50 m. One end of the longline was attached to the vessel, which was attached to the FAD; the other end of the line was free floating, marked by a large buoy. The line was checked for sharks every hour for the duration of the fishing effort and any missing baits were replaced. Once hooked, sharks were secured in water on the side of the vessel using a tail rope and head rope that was placed behind the jaw and in front of the gills. The shark was inverted to induce tonic immobility (Kessel & Hussey 2015). Sharks were identified, sexed, measured, and a small genetic sample was taken. All sharks were fitted with a dorsal ROTO-tag (Y-Tex Sheepstar, CCK Outfitters, Fort Worth, TX, USA). Healthy pelagic sharks of suitable size were fitted with a satellite tag (miniPAT with titanium anchor, Wildlife Computers Inc., Redmond, Washington, USA). Satellite tags were deployed on Blue Sharks (*Prionace glauca*, n = 2), Oceanic Whitetip Sharks (*Carcharhinus longimanus*, n = 11), and Silky Sharks (*Carcharhinus falciformis*, n = 3). An incision was made by clean scalpel in the skin and musculature at the base of the dorsal fin. The titanium anchor was inserted into the incision site and set into the muscle for tag retention. All fishing gear was removed from sharks before release. In the event of a swallowed hook, the steel leader was cut as close to the hook as possible.

Sharks were captured during normal commercial fishing operations onboard a Cook Islands flagged longline vessel using pelagic longline gear with nylon leaders and 16/0 circle hooks. Sharks of appropriate size (>120 cm) and condition were brought onboard during gear retrieval, identified, sexed and fitted with satellite tags. Prior to release, fishing gear was cut as close to the hook as possible. Sharks retained hooks, but were released carefully, dorsal fin up, through the fish door on the side of the vessel.

5.2.4 Satellite Tag Details:

Tags were programmed to activate when they were 5 m underwater and to collect temperature, depth and light level data for geolocation at five-second intervals. At pre-programmed times ranging 180-365 days (or after premature tag detachment), a corrodible pin released the tags. Once tags broke the surface of the water, time series data were transmitted to the Argos satellite system. Depth and temperature data were binned into daily histograms containing 12 bins (Appendix 4 Table A4.1). Tags were set to auto-release if constant depth at or below 1400 m was measured for three consecutive days, which indicated shark mortality.

5.2.5 Data pre-processing:

The tag manufacturer's proprietary Geolocation Processing Estimator 3 (GPE3) state space model was used to generate 12-hourly location estimates using sea surface temperature, bathymetry and twilight observations (Hutchinson et al. 2019b; Curnick et al. 2020). GPE3 uses a Hidden Markov Model with 0.25° x 0.25° spacing to generate two maximum likelihood positions per day. GPE3 processing was run at various animal speeds (0.5, 1, 1.5, 3 and 5 ms^{-1}) to find the optimum for each species. The speed filter parameter that produced the highest quality mean GPE3 observation score across all individuals was used to produce the most likely track (1.5 ms^{-1} selected for all species; Appendix 4 Figure A4.1). The model domain was selected as marine only to omit land-based observations. To assist position estimation, the model was constrained using known deployment and endpoint GPS positions, known bathymetry (Amante & Eakins 2009), probabilities of observed and referenced sea surface temperature (NOAA High Resolution SST data provided by NOAA/OAR/ESRL PSD, Boulder, Colorado, USA at http://www.esrl.noaa.gov/psd/), as well as observed and theoretical twilight times for each location. The location estimates were interpolated into a 0.025° x 0.025° grid and smoothed with a cubic spline. All subsequent analyses and data visualizations were conducted within the R statistical environment (R Core Team, 2021).

5.2.6 Horizontal movement analysis:

The ocean waters surrounding the Cook Islands EEZ and neighboring countries were labeled as five spatial management categories for the analyses: 1) within the 50 nm commercial fisheries exclusion zone limit; 2) outside the 50 nm limit, but within the Cook Islands EEZ; 3) within neighboring EEZs with shark protections; and, 4) within EEZs without shark protections, or 5) in the high seas. Waters adjacent to the Cook Islands EEZ were labeled either “protected”, “unprotected” or “high seas” based on the presence of national shark sanctuary regulations or legislation. Adjacent waters were labeled “protected” if they had sanctuary legislation that banned retention of sharks and/or rays during the time of the tag deployments. These included Niue, French Polynesia and Kiribati. In addition to sanctuary regulations, the Cook Islands implemented the Western and Central Pacific Fisheries Commission species-specific retention bans for Oceanic Whitetip Sharks (introduced 2011) and Silky Sharks (introduced 2013). While these regulations complement the Sanctuary, I did not consider EEZs that implemented the WCPFC regulations as sanctuaries or spatial protection zones in this study.

The maximum likelihood location estimates from GPE3 processing were used to quantify horizontal activity space and movement patterns in relation to spatial management zones across the study area. Euclidian distances were calculated between each estimated position and the closest point on the boundary of both the 50 nm limit and Cook Islands EEZ boundary. These distances were used to assess the time elapsed for animals to move from their tag location (protected waters) into adjacent regions, which included waters that were protected, unprotected, or high seas, with varying levels of fishing. Single factor ANOVAs were used to test whether mean depths reported by tags were different between species and protection zones. A post-hoc Tukey’s test was used to determine which species or protection zones were significantly different from each other. Welch’s t-tests for independent samples were conducted to compare horizontal distances and depths traveled by male and female Oceanic Whitetip Sharks.

Activity space for individuals, where sufficient positions were available, was quantified using a fixed Kernel Utilization Distribution analysis (KUD) using the ‘adehabitatHR’ package (Calenge 2006, 2015). A bivariate normal kernel using an *ad hoc* smoothing parameter was used to estimate utilization distributions of each individual (Kie 2013). Areas within the 50% KUD (core activity space) and 95% KUD (activity space extent) contour were estimated for each individual to quantify activity space used by individuals across the period of the track. The proportions of activity space of individuals overlapping the different protection zones were quantified by calculating area of KUD (core and extent of activity space) in km^2 that overlapped with: the 50nm commercial fishing exclusion zone, the Cook Islands EEZ, adjacent "protected" EEZs with sanctuaries (French Polynesia, Kiribati, Niue), adjacent "unprotected" EEZs that do not have sanctuaries (American Samoa, Tokelau), EEZs that are not adjacent but overlapped with animal movement, and the high seas. The proportion of activity space within each zone was calculated by dividing the area (km^2) of activity space within each zone by the total activity space area (km^2) for each individual. The mean proportions of time in each zone per species were calculated in the same way.

5.2.7 Depth and temperature data:

The satellite tags used to track individual horizontal movements also collected depth and temperature measurements that were summarized into bins once daily. Depth data were summarized into twelve bins (Appendix 4 Table A4.1). The percentage of time each tagged shark spent at the depths in each bin was summarized per day for the duration of the tag deployment (Appendix 4 Figure A4.2). Similarly, temperature data were summarized into twelve bins (Appendix 4 Table A4.1), with the percentage of time spent by the individual in each temperature bin summarized once per day (Appendix 4 Figure A4.3).

Daily depth and temperature logs were used to confirm when tags were shed or detached (indicated by constant depth or high temperatures at surface). Daily depth measurements were matched with the most likely positions estimated from the GPE3 processing to associate each depth summary to a relative position along the full track. This position was then used to associate each depth summary with one of five main spatial management zones described above. The depth data were also used to calculate the percentage of time individuals spent in depths at which two main fisheries operate within the wider Pacific region. The longline fishery mainly targets southern albacore tuna and bigeye tuna (operation depth range: 0 – 400 m), and the purse seine fishery mainly targets skipjack tuna (operation depth range: 0 – 120 m) (Brouwer et al. 2018).

5.2.8 Risk of spatial overlap with industrial fisheries:

Movement data collected from the three species tracked in this study were used to assess species-specific spatial overlap with the two main industrial fisheries across the Pacific region: longline fisheries and purse seine fisheries. Three components of data were processed to conduct the overlap analysis following a similar method outlined by Quieroz et al. (2019). Metrics of overlap were calculated for each of the three species and the two fishing gear types. For each month of the year, spatial overlap and risk for individually tracked sharks overlapping with monthly fishing efforts were assessed. Results were summarized into overall species-level risk metrics.

2.8.1 Industrial fishing effort: Daily fishing effort for longline and purse seine vessels was obtained from Global Fishing Watch (GFW; available from https://globalfishingwatch.org/datasets-and-code/fishing-effort/) for years 2017-2018 as the total number of fishing hours per month in 0.01° x 0.01° cells. I assumed that patterns of fishing effort were similar between years. GFW analyzes raw automatic identification system (AIS) vessel tracking data using neural network algorithms to estimate, based on vessel movement patterns, if gear was deployed from fishing vessels, and which type (e.g. drifting longline, bottom trawl, purse seine) (Kroodsma et al. 2018). Fishing effort for all types of longline fishing gear (i.e. drifting longlines, set longlines) and purse seine fishing gear were subset for the Pacific region. Total fishing effort for longline and purse seine fisheries was calculated (in hours) at a 0.5˚ x 0.5˚ spatial resolution during each calendar month of the year (Appendix 4 Figure A4.4).

2.8.2 Fishing effort spatial overlap: The spatial overlap between individual tracked sharks and fishing effort was calculated as the number of 0.5˚ x 0.5˚ cells that sharks and fishing effort co-occurred, and then standardized for the length of each shark's track. The metric of overlap was calculated as a percentage following the equation: $100(n_c/n_c)$; where n_o is the number of cells where an individual sharks' track overlapped with a cell with fishing effort, and n_c is the total number of cells occupied by the full track of the individual shark.

2.8.3 Fishing exposure index: To quantify the exposure of sharks to fishing effort in areas with high spatial overlap, a fishing exposure index (FEI) was estimated based on methods described by Quieroz et al. (2019). Briefly, the estimated positions from processed individual tracks were used to calculate the relative density of fixes within the same 0.5˚ x 0.5˚ resolution that corresponded to the spatial resolution of the fishing effort data. Relative density measures were calculated for each cell for every month of each individual shark's track. The relative densities were scaled between 0 and 1 so that monthly tracks from each individual shark contributed equally to the spatial density pattern. Overall relative densities were also summarized as mean measures across all individuals of the three species (Appendix 4 Figure A4.5). Total monthly fishing effort for longline and purse seine activities (in hours fished) were normalized between 0 and 1 to ensure relative fishing effort equally contributed in calculated overlap metrics. The FEI for each individual was then calculated within each cell for each calendar month as:

$$FEI = \frac{\sum_{i=1}^{n} f_i \, d_i}{n}$$

Where f_i is the normalized fishing effort for each month in cell i, d_i is the normalized relative density of each individual for each month in cell i, and n is the number of cells occupied by each individual shark for each month. Overall mean FEI estimates were then calculated for each species for each cell to identify regions with higher exposure to fishing effort.

5.3. RESULTS:

Sixteen pelagic sharks (Oceanic Whitetip Shark n = 11, Silky Shark n = 3, Blue Shark n = 2, Figure 5.1 b) were captured and fitted with pop-up archival transmitting satellite tags (miniPAT, Wildlife Computers Inc., Redmond, Washington, USA) (Table 5.1). Of the sixteen-tagged sharks, sufficient data were obtained from 15 individuals (2 Blue Sharks (females), 10 Oceanic Whitetip Sharks (6 males, 4 females) and 3 Silky Sharks (females) to assess horizontal and vertical movement patterns (Figure 5.2, Table 5.1). One mortality event was recorded (constant depth for 72 hours) after release from a commercial longline vessel (Tag ID 53738) and was excluded from horizontal and vertical movement models. All tags reported, resulting in 1461 days of tracking data. The time at liberty ranged 28-196 days. Individuals were tracked for a maximum duration of 196 days (Blue Shark =196 days, Oceanic Whitetip Shark = 181 days, Silky Shark = 159 days). The mean distance traveled per species was 12,193 km for Blue Sharks, 3254 km for Oceanic Whitetip Sharks, and 3626 km for Silky Sharks. The max depth bin per species was 2000 m for Blue Sharks, 800 m for Oceanic Whitetip Sharks and 800 m for Silky Sharks, with the mean depths of 154 m for Blue Sharks, 87 m for Oceanic Whitetip Sharks, and 85 m for Silky Sharks.

Table 5.1: Tag deployment and biological details for 16 pelagic sharks tagged in the Cook Islands EEZ between 2018-2019. OCS = Oceanic Whitetip Shark; SIL = Silky Shark; BSH = Blue Shark; TL = total length (cm). Vessel type represents the platform used to tag sharks. Rec = recreational vessel; LL = commercial longline vessel. *Denotes shark mortality event (constant depth recorded for 72 hours).

Tag #	Species	Sex	TL (cm)	Deploy lat	Deploy long	Pop-off lat	Pop-off long	Days at liberty	Vessel type
47622	BSH	F	253	-21.20	-159.86	-6.8392	-155.5345	143	Rec
53731	BSH	F	N/A	-21.34	-160.58	-25.3566	-177.3404	196	LL
47621	OCS	F	N/A	-21.01	-159.39	-13.1217	-151.5446	129	LL
47625	OCS	M	213	-21.424	-159.899	-19.0342	-155.8311	28	Rec
47626	OCS	M	231	-21.16	-159.81	-15.8874	-168.5397	71	Rec
47629	OCS	F	N/A	-22.22	-160.25	-8.7513	-158.262	80	LL
47632	OCS	F	N/A	-22.19	-160.25	-26.1959	-156.4066	43	LL
53698	OCS	M	N/A	-22.02	-160.1	-12.9528	-150.5434	181	LL
53699	OCS	M	N/A	-22.17	-159.59	-7.7253	-150.024	93	LL
53702	OCS	M	166	-21.25	-159.68	-16.7418	-149.6278	74	Rec
53709	OCS	F	251	-21.954	-159.996	-16.8579	-165.4661	51	LL
53727	OCS	M	N/A	-22.26	-160.50	-17.8511	-151.923	43	LL
53738*	OCS	F	220	-22.01	-159.644	-21.8784	-160.0513	0.24*	LL
47618	SIL	F	230	-21.28	-159.86	-19.6235	-166.1197	159	Rec
47620	SIL	F	252	-21.28	-159.84	-21.4042	-159.709	30	Rec
53701	SIL	F	(>200)	-21.21	-159.86	-21.9945	-156.0434	141	Rec

Table 5.2: Movement data for 16 pelagic sharks tagged within the Cook Islands EEZ between 2018-2019. OCS = Oceanic Whitetip Shark; SIL = Silky Shark; BSH = Blue Shark. Vessel type represents the platform used to tag sharks. CI EEZ = Cook Islands Exclusive Economic Zone, KUD = Kernel Utilization Distribution, Rec = recreational vessel; LL = commercial longline vessel.
* Denotes shark mortality event (constant depth recorded for 72 hours).

Tag #	Species	Sex	Days before leaving CI EEZ	Total track length (km)	Total area (km^2)	Km day^{-1}	Proportion of track in 50nm zone	Proportion of track in CI EEZ	Proportion of track outside of CI EEZ	Proportion core KUD in 50 nm	Proportion extent KUD in 50 nm	Proportion core KUD in CI EEZ	Proportion extent KUD in CI EEZ
47622	BSH	F	14.1	7856	2238800	55.0	0.05	0.29	0.71	0	0.05	0.05	0.29
53731	BSH	F	9.9	16529	1008828	84.3	0.01	0.10	0.90	0	0.01	0	0.10
47621	OCS	F	20.1	4715	1159606	36.6	0.06	0.35	0.65	0	0.06	0.08	0.35
47625	OCS	M	N/A	1342	62932	47.9	0.33	0.84	0.16	<0.001	0.33	1	0.84
47626	OCS	M	19.6	2937	901450	41.4	0.16	0.63	0.37	0.14	0.16	0.67	0.62
47629	OCS	F	17.3	2856	1396319	35.7	0.13	0.58	0.42	0.26	0.13	0.80	0.58
47632	OCS	F	5.8	2746	211866	63.9	0.02	0.13	0.87	0	0.02	0	0.13
53698	OCS	M	22.8	6843	945394	37.8	0.14	0.46	0.54	0.023	0.14	0.44	0.46
53699	OCS	M	21.6	3222	1544189	34.7	0.09	0.38	0.62	0.012	0.10	0.08	0.38
53702	OCS	M	29.4	2620	787440	35.4	0.18	0.42	0.59	0.22	0.18	0.31	0.42
53709	OCS	F	30.8	2854	338730	56.0	0.05	0.59	0.41	<0.001	0.05	0.12	0.59
53727	OCS	M	12.2	2412	244043	56.1	0.17	0.34	0.66	0	0.17	0	0.34
53738*	OCS	F	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1.0	1.0	1.0	1.0
47618	SIL	F	73.3	5629	649008	35.4	0.11	0.53	0.47	0.20	0.11	0.57	0.53
47620	SIL	F	N/A	979	15663	32.6	0.88	1	0	0.75	0.86	1	1
53701	SIL	F	67.8	4271	403367	30.3	0.15	0.58	0.42	0.28	0.15	0.62	0.58

5.3.1 Horizontal movement:

No species-specific or sex-specific movement patterns were identified in the study; however, Silky Sharks remained south of 15°S latitude; Oceanic Whitetip Sharks utilized both the southern and northern parts of the Cook Islands EEZ with the area near Penrhyn Island in the north an area of increased activity; and Blue Sharks spent the majority of their time outside of the EEZ (Table 5.2, Figure 5.2). All Silky and Blue Sharks were female, so no sex-specific differences were calculated and the mean distance traveled per day by species was 33.0 km day^{-1} and 72.1 km day^{-1}, respectively (Table 5.2). Oceanic Whitetip Sharks averaged 41.0 km day^{-1}. There was no significant difference between the daily distances traveled by male and female Oceanic Whitetip Sharks (males = 39.5 km day^{-1}, females = 43.4 km day^{-1}, $t = -0.74$, $p = 0.50$) (Table 5.2). All sharks left the 50 nm zone, but individuals from each species revisited the 50 nm zone during the study (Figure 5.3). Blue sharks spent 1-5% inside the 50 nm zones around the islands, while Oceanic Whitetip Sharks spent 2-33% and Silky Sharks 11-88% (Table 5.2, Figure 5.3). The number of days that tagged sharks remained in the Cook Islands EEZ before first departure ranged from 9.9 days to 14.1 days for Blue Sharks (mean 12.0 days), 5.8 days to 30.8 days for Oceanic Whitetip Sharks (mean 25.3 days, 1 shark did not leave the EEZ), 67.8 days to 73.3 days for Silky Sharks (mean 70.5 days, 1 shark did not leave EEZ) (Table 5.2, Figure 5.3). Some individuals from each species returned to the EEZ after first departure. The proportion of time individuals spent inside the Cook Islands EEZ ranged 10-100% (Table 5.2, Figure 5.3). Blue sharks were in the EEZ for the shortest time period before leaving, traveled the furthest and spent the least amount of time in the EEZ overall (Table 5.2, Figures 5.2, 5.3). One Oceanic Whitetip Shark (28 days at liberty) and one Silky Shark (30 days at liberty) remained in the EEZ for the duration of tag deployment (Figures 5.2, 5.3).

The core and extent of activity space for Silky Sharks showed the highest overlap with the 50 nm zone (50% KUD = 41%, 95% KUD = 38%) and Cook Islands EEZ (50% KUD = 73%, 95% KUD = 70%) (Table 5.2, Figures 5.4, 5.5). The 50% KUDs for Oceanic Whitetip Sharks that overlapped with the EEZ ranged 0-100% (mean 35%) and 13-84% (mean 47%) for the 95% KUDs. The mean proportion of overlap of Blue Sharks 95% KUDs within the Cook Islands EEZ ranged 10-29% (mean = 20%). For all three Silky Sharks, more than 50% of their 95% KUDs were within the waters of the Cook Islands EEZ and neighboring sanctuaries (Figure 5.5). The 95% KUDs for 3 of 10 Oceanic Whitetip Sharks were wholly within protected EEZs, meaning 7 of 10 sharks overlapped with high seas or unprotected EEZs. Sixty-seven percent of tagged sharks' 95% KUD overlapped with high seas areas, which represented the largest proportion of overlap (>60%) for one Blue Shark and one Oceanic Whitetip Shark. The mean proportion of the 95% KUDs that overlapped with protected EEZs for both Silky Sharks and Oceanic Whitetip Sharks was 86%, and for Blue Sharks it was 42% (Figure 5.5).

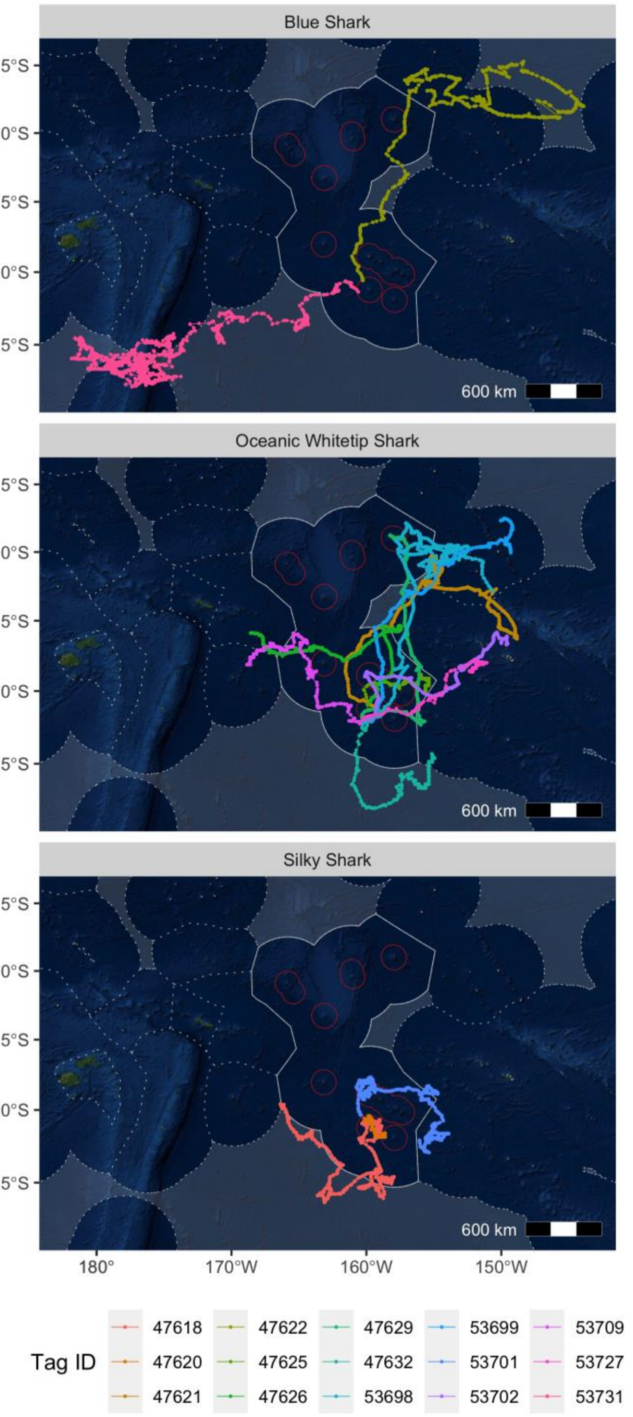

Figure 5.2: Most likely tracks of 15 individuals tagged in close proximity to the 50 nm limit (red boundaries) of Rarotonga, and within the Cook Islands EEZ (solid white boundaries). Individuals of all three species moved into EEZs of surrounding countries (broken white boundaries), and into high seas waters (greyed areas).

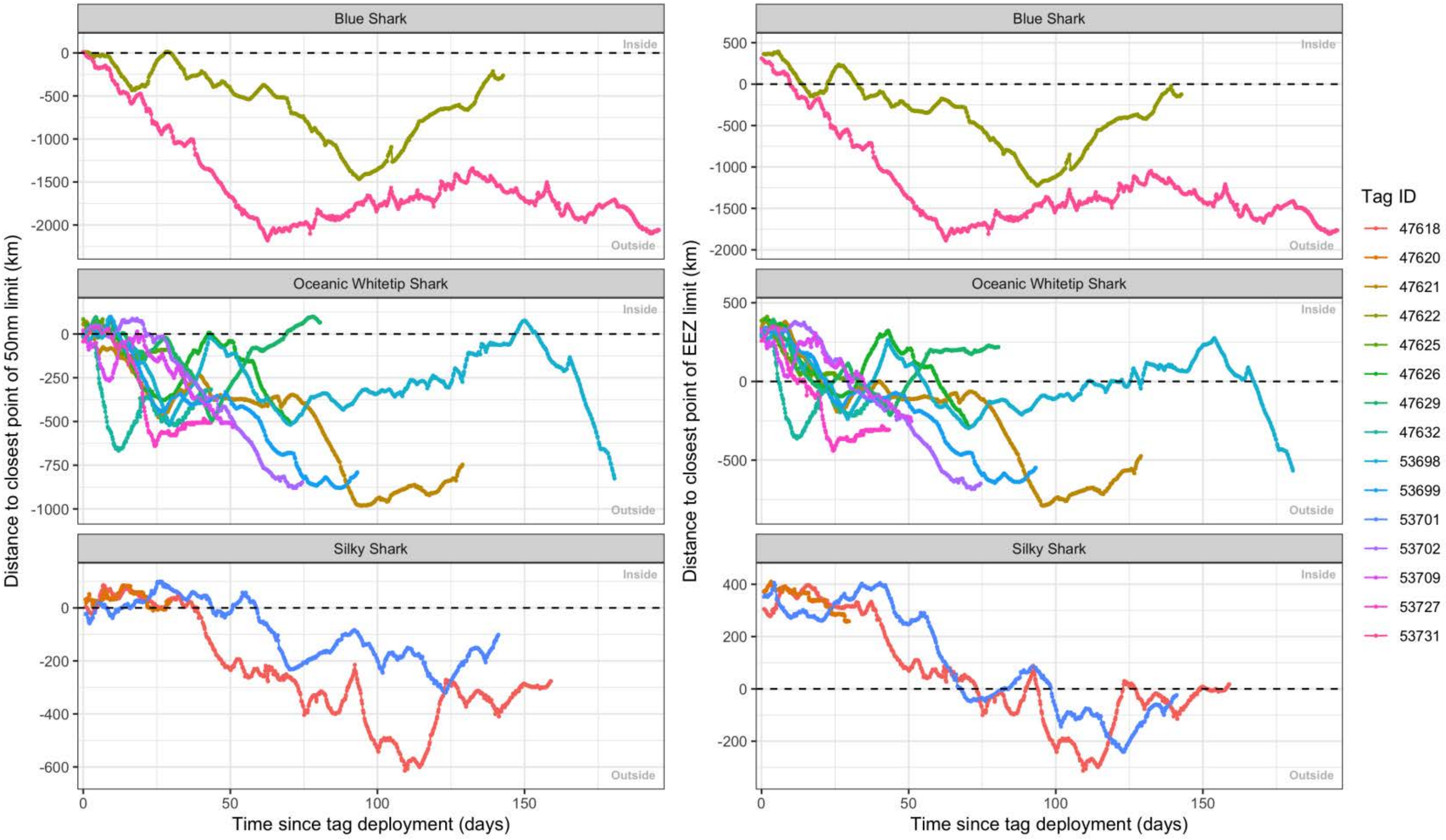

Figure 5.3: Movement of tagged Blue Sharks (top panels), Oceanic Whitetip Sharks (middle panels) and Silky Sharks (bottom panels) in relation to the 50 nm limit (left hand panels) and the Cook Islands EEZ limit (right hand panels). The dashed horizontal line indicates the boundary of the 50 nm (left panels) or EEZ limits (right panels). Distances above the dashed line indicate individuals were inside the zone, while below the line indicates individuals were tracked outside the spatial management zones.

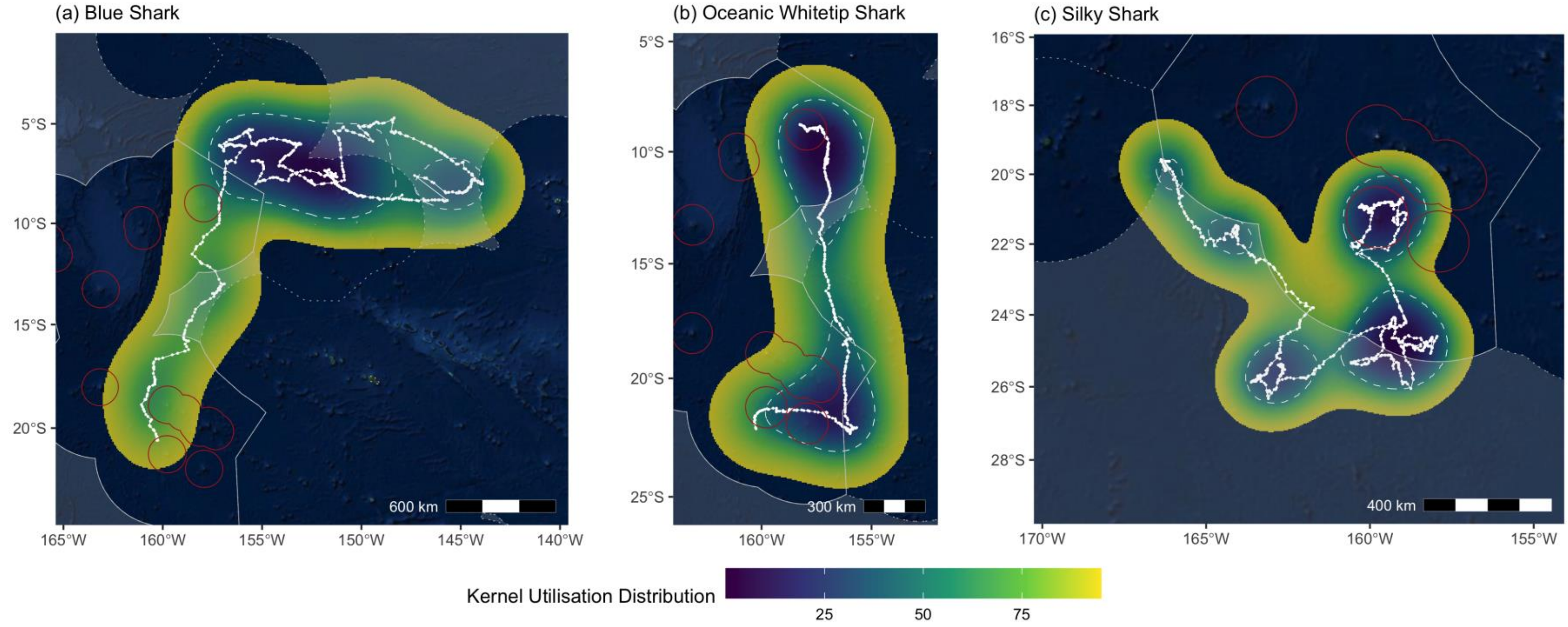

Figure 5.4: Kernel utilization distributions for 15 sharks tagged within the Cook Islands Shark Sanctuary. The dashed line indicates the core activity space (50% KUD). The yellow area indicates the extent of activity space (95% KUD). (a) Blue Sharks (b) Oceanic Whitetip Sharks (c) Silky Sharks.

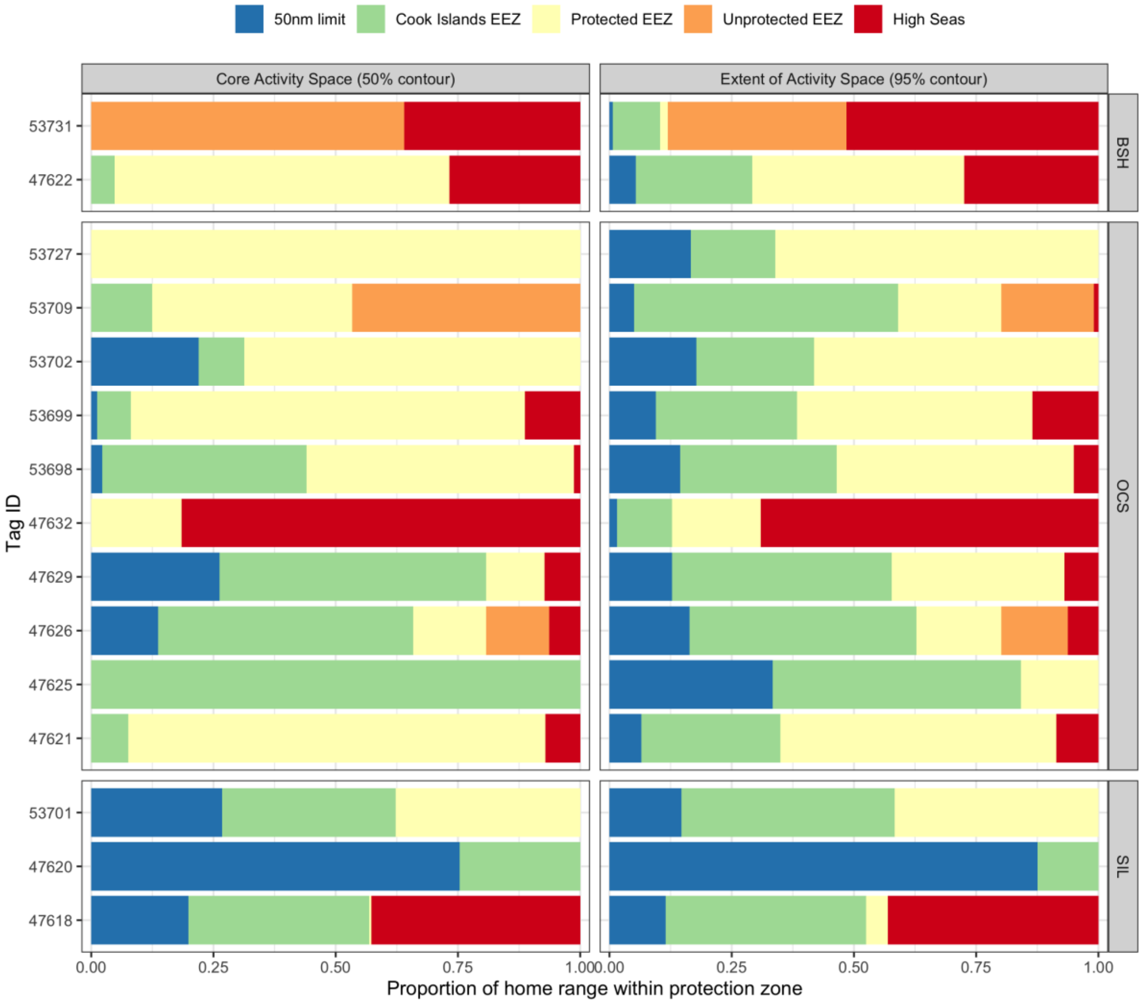

Figure 5.5: Proportions of 50% KUD (left panel) and 95% KUD (right panel) activity spaces within each protection zone. The blue and green zones are within the Cook Islands EEZ and together represent the area of the Shark Sanctuary. Yellow bars depict time spent in neighboring EEZs with sanctuary regulations and are labeled “Protected EEZ”. Unprotected EEZs are indicated in orange and high seas areas are in red.

5.3.2 Depth usage:

The maximum depth reached by Blue Sharks was in the 1000-2000 m bin; for Oceanic Whitetip and Silky Sharks it was in the 400-800 m bin. Mean depths for Blue Sharks (154 m) were nearly double the depths for Silky (85 m) and Oceanic Whitetip Sharks (87 m), with no significant difference between mean depths for male (86 m) and female (88 m) Oceanic Whitetip Sharks (t = 0.28, p = 0.79) (Table 5.3). There were significant differences in the mean depths between species (ANOVA, p <0.001). Post-hoc tests showed significant differences between Blue Sharks and Oceanic Whitetip Sharks (Tukey's, p <0.001) and between Blue Sharks and Silky Sharks (Tukey's, p <0.001), but no difference between depths occupied by Oceanic Whitetip Sharks and Silky Sharks (Tukey's, p = 0.98). The mean overlap with longline fishing depth was 98.5% for Blue Sharks, 100.0% for Oceanic Whitetip Sharks and 99.9% for Silky Sharks. The mean depth overlap with purse seine fisheries was 41.7% for Blue Sharks, 86.6% for Oceanic Whitetip Sharks, and 97.6% for Silky Sharks (Table 5.3, Figure 5.6).

Depth usage between protection zones was significantly different between species (AVOVA, df = 2, F = 22.29, p <0.001). Post-hoc tests showed differences between Oceanic Whitetip and Blue Sharks (Tukey's test, p <0.001), and between Silky and Blue Sharks (Tukey's test, p <0.001), but no significant difference between Oceanic Whitetip and Silky Sharks (Tukey's test, p = 0.979). There was also significantly different depth usage between zones for Oceanic Whitetip (ANOVA, df = 4, F = 6.476, p <0.001) and Silky Sharks (ANOVA, df = 3, F = 5.892, p = 0.001), but no significant depth usage between zones for Blue Sharks. Post hoc tests between zones for Oceanic Whitetip Sharks showed significant differences in depth usage between the Cook Islands EEZ and the 50 nm limit zones (Tukey's test, p <0.001), between the high seas zone and the 50 nm limit zone (Tukey's test, p = 0.03), and between protected EEZs and the 50 nm limit (Tukey's test, p = 0.003). The significant differences in depth usage between zones for Silky Sharks were between the high seas zone and the 50 nm limit zone (Tukey's test, p = 0.003), the high seas zone and the Cook Islands EEZ (Tukey's test, p = 0.004), and between protected EEZs and high seas zone (Tukey's test, p = 0.005).

Depth overlap with longline fisheries inside the 50 nm zone, where longline fishing was banned, was >98% for all species, >95% in the Cook Islands EEZ, >90% in protected EEZs, and >90% in unprotected waters, including EEZs without sanctuaries and high seas areas (Figure 5.6). For Oceanic Whitetip and Silky Sharks, depth overlap inside each protection zone was >98% for both longline and purse seine fisheries. Blue Sharks spent more time at depths reached by purse seine fisheries, but very little time at depths where longline vessels operate (Figure 5.6).

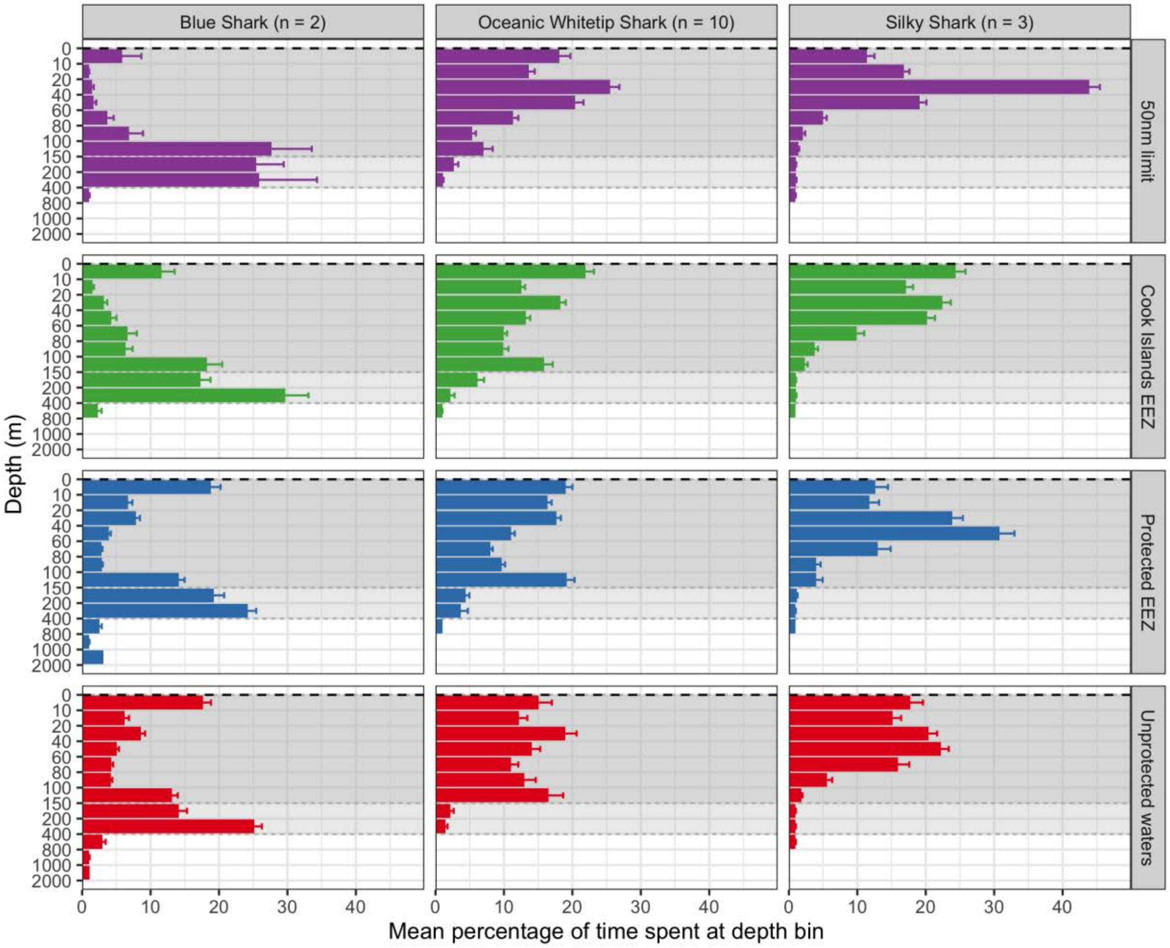

Figure 5.6: Percentage of time spent in depth bins that overlap with purse seine (dark grey) and longline (light grey) fishing depths in each of the protection zones: 50nm limit (purple), Cook Islands EEZ (green), protected EEZs (blue), and unprotected waters, which include unprotected EEZs and the high seas (red).

Table 5.3: Depth profiles of tagged sharks. BSH = Blue Sharks, OCS = Oceanic Whitetip Sharks, SIL = Silky Sharks. TL = total length, PS = purse seine fishing vessels, LL = longline fishing vessels. *Indicates mortality event.

Tag #	Species	Sex	TL (cm)	Max depth (m)	Mean depth (m)	% PS overlap	% LL overlap
47622	BSH	F	253	2000	161	23.04	99.02
53731	BSH	F	N/A	2000	140	60.32	97.97
47621	OCS	F	N/A	800	88	81.20	99.66
47625	OCS	M	213	400	93	89.01	99.97
47626	OCS	M	231	400	88	82.71	99.98
47629	OCS	F	N/A	400	82	82.80	99.98
47632	OCS	F	N/A	400	99	97.35	99.97
53698	OCS	M	N/A	800	117	57.28	99.98
53699	OCS	M	N/A	400	76	91.32	99.98
53702	OCS	M	166	400	66	98.44	99.98
53709	OCS	F	251	400	84	93.23	100.00
53727	OCS	M	N/A	400	75	92.90	99.98
53738*	OCS	F	220	N/A	N/A	N/A	N/A
47618	SIL	F	230	800	95	97.50	99.89
47620	SIL	F	252	400	80	98.49	99.98
53701	SIL	F	(>200)	800	80	96.80	99.95

5.3.3 Fisheries exposure risk:

For all species, fishing exposure to longline fishing was substantially greater than to purse seine fishing. Overlap hotspots for Blue Sharks and fishing occurred in cells outside of the Cook Islands EEZ in the eastern high seas pocket between the Cook Islands and French Polynesia, and in the high seas bordering New Zealand's Kermadec Islands (Figure 5.7 a). Exposure to longline fishing for Oceanic Whitetip Sharks was evident throughout most of the southern Cook Islands, with hotspots primarily inside of EEZs, including a stretch from the southeast border of the Cook

Islands EEZ extending to the northwest section of French Polynesia's EEZ, and on the borders between the Cook Islands, Niue and American Samoa (Figure 5.7 c). The exposure hotspots to longline fishing for Silky Sharks occurred primarily outside of EEZs in the high seas south of the Cook Islands, and inside of the 50 nm limit surrounding Rarotonga, Cook Islands (Figure 5.7 e). Purse seine exposure for Blue Sharks was limited to a few hotspots in the eastern high seas pocket and on the southern border of Tonga, as well as in the southern Cook Islands EEZ (Figure 7b). Purse seine fishing exposure hotspots for Oceanic Whitetip and Silky Sharks were on the eastern boundary of the southern Cook Islands EEZ, as well as just outside of the 50nm zone of Aitutaki, Cook Islands (Figure 5.7 d, f).

For all species, almost the entire track of the sharks overlapped with longline fishing effort in the Cook Islands EEZ, whereas the overlap with purse seine effort in the Cook Islands EEZ was around 25% (Figure 5.8). Blue Sharks had the highest spatial overlap with longline fishing in the EEZ and within the 50nm limit. However, Oceanic Whitetip Sharks and Silky Sharks experienced higher risk inside the EEZ based on time spent inside areas with high longline fishing effort, resulting in the higher fisheries exposure index (FEI). Similarly, Oceanic Whitetip Sharks were most at risk in other EEZs, whereas Silky Sharks had high spatial overlap and the highest FEI, resulting in the highest risk, on the high seas. Overlap with purse seine fishing effort was 50% or less for all species in each zone (Figure 5.8). However, Silky Sharks had the highest FEI south of the Cook Islands EEZ. Oceanic Whitetip Sharks had the highest FEI in both gears in the Cook Islands and neighboring EEZs.

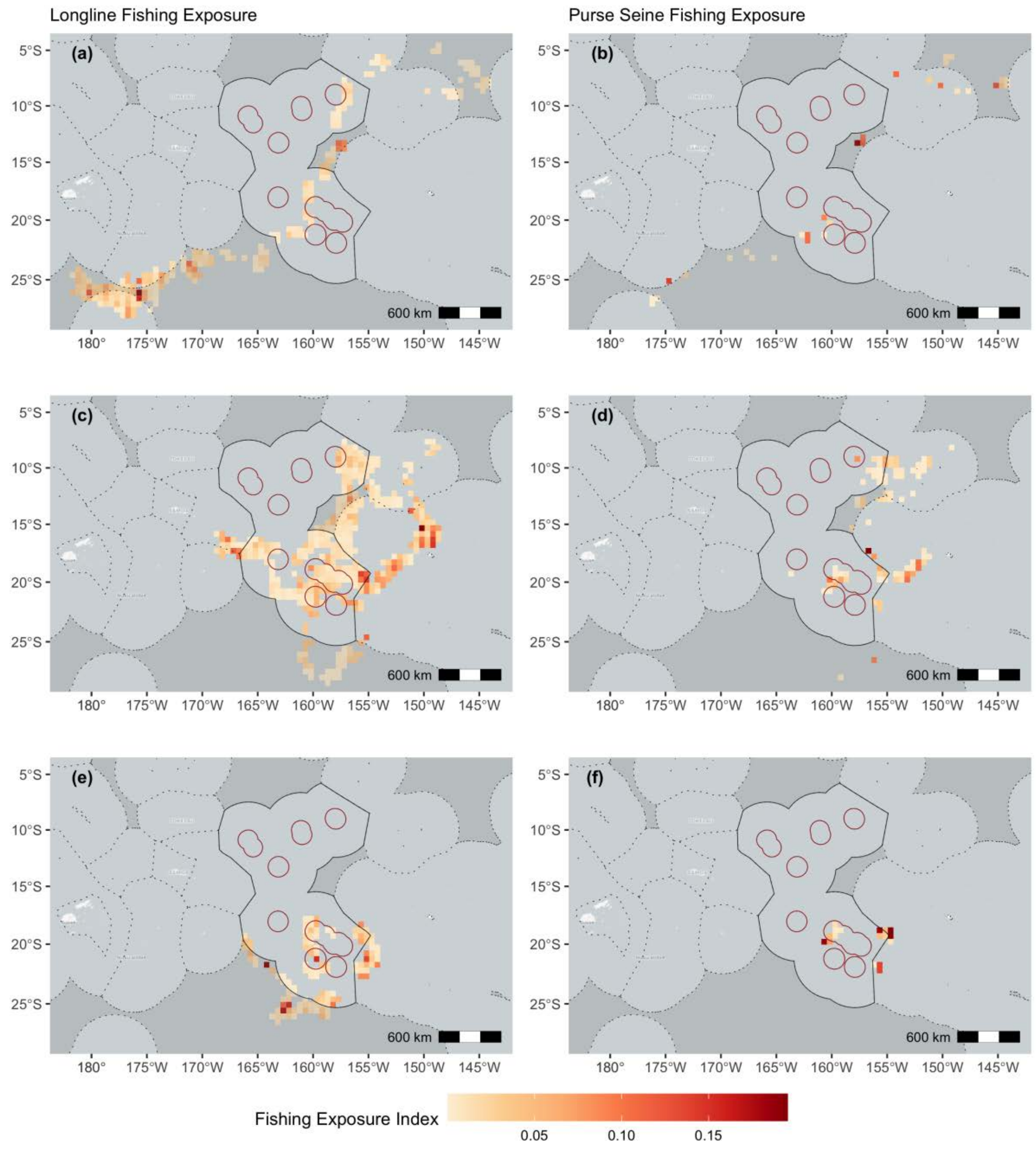

Figure 5.7: Fishing exposure index (FEI) in 0.5 x 0.5 cells for overlap with longline fishing effort (left panels) and overlap with purse seine fishing effort (right panels). Cook Islands EEZ is outlined in black, with the 50 nm zones around each island outlined in red. Other EEZs are light grey and outlined with dashes. High seas areas are dark grey. The top row (a) and (b) Blue Sharks; middle row (c) and (d) Oceanic Whitetip Sharks; and, bottom row (e) and (f) Silky Sharks.

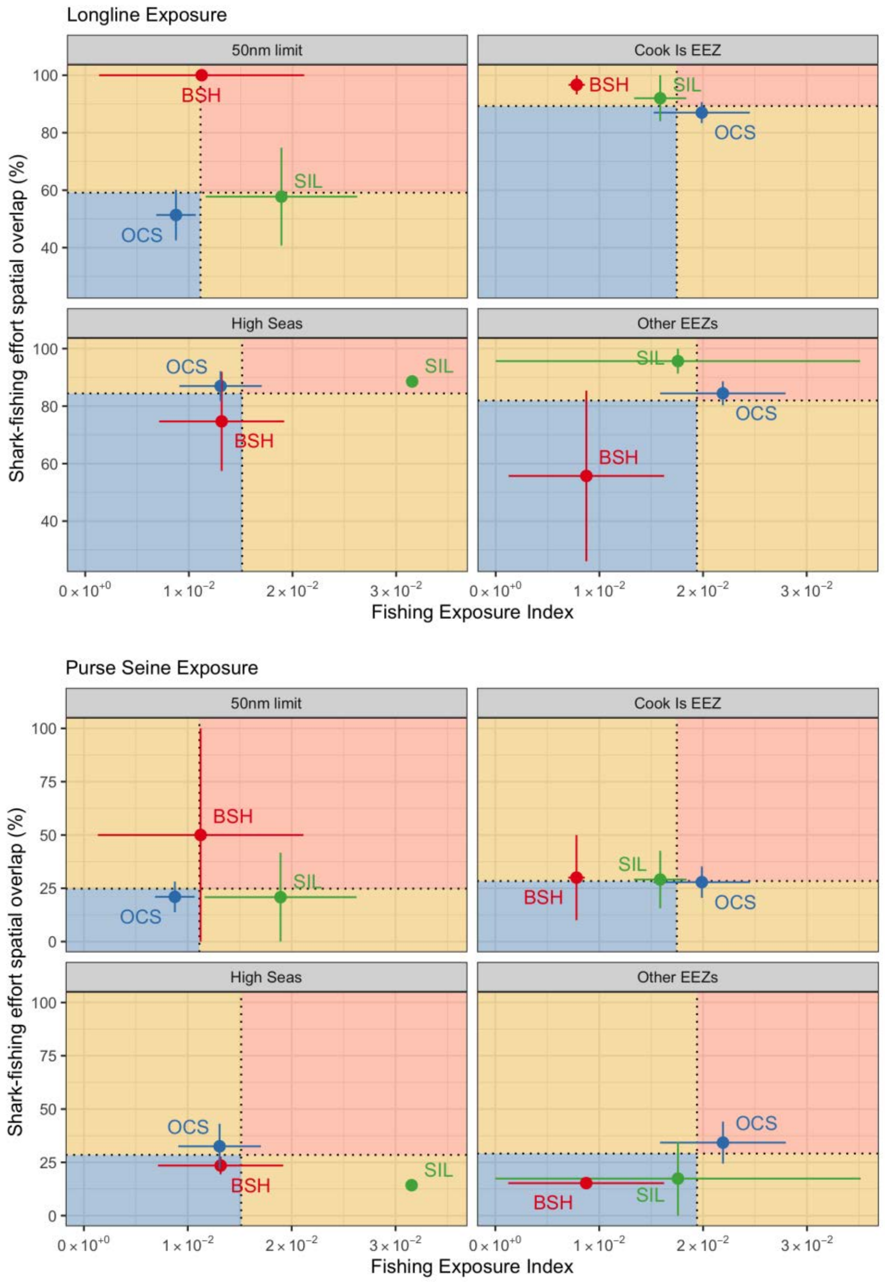

Figure 5.8: Shark-fishing effort spatial overlap and scaled fishing exposure index (FEI). The top four panels represent longline fishing exposure in each of the four zones, 50 nm limit, Cook Islands EEZ, High Seas and other EEZs. The bottom four panels represent purse seine fishing exposure in each of the same four zones. The colored boxes represent shark-fishing effort overlap and scaled FEI with respect to the overall average score across all species for both metrics. The blue quadrant identifies below average risk rating for both shark-fishing effort

overlap and scaled FEI, whereas the red region identifies above average risk for both metrics. The yellow region identifies the region where one metric is above average and the other is below, and represents a moderate risk rating.

5.4. DISCUSSION:

This research showed that three species of pelagic sharks derived different levels of benefit from the Cook Islands Shark Sanctuary and the adjacent sanctuaries. Results indicated that the Sanctuary is likely providing benefits to Oceanic Whitetip and Silky Sharks. Blue Sharks likely received minimal benefit because they quickly moved beyond the Sanctuary border, however, due to the low numbers of Blue Sharks tagged, this result should be taken with caution. All species benefitted from contiguous sanctuaries in adjacent EEZs. The movements of pelagic sharks relative to shark sanctuary boundaries have not been previously examined in the Pacific Ocean. Howey-Jordan *et al.* (2013) examined movements of Oceanic Whitetip Sharks in the Bahamas EEZ, a shark sanctuary, and found that the sharks spent 66% of their time in the Bahamas EEZ. However, effectiveness of the Bahamas Shark Sanctuary was not evaluated. Silky Shark movements were tracked in the Chagos Marine Protected Area (not a shark sanctuary), which the authors suggest provided substantial benefit to Silky Sharks based on horizontal movements (Curnick et al. 2020).

5.4.1 Horizontal movements:

The mean movement rate per day (km day^{-1}) for Oceanic Whitetip Sharks tagged in the Cook Islands was half the rate of Oceanic Whitetip Sharks tagged in the western Atlantic Ocean (Tolotti et al. 2015a). Cook Islands-tagged Oceanic Whitetip Sharks did not return to the tagging location, which was reported in Atlantic studies (Howey-Jordan et al. 2013; Tolotti et al. 2015a). Mean dispersal distances from tagging locations were similar to those tagged in the western north Atlantic (Howey-Jordan et al. 2013), with the maximum individual dispersal distances of sharks in the central Pacific Ocean and Indian Ocean over two to three times longer (Musyl et al. 2011a; Young & Carlson 2020). The track lengths of Silky Sharks tagged in the Cook Islands were similar to those of Oceanic Whitetip Sharks in the Cook Islands, but displacement distances were much smaller, indicating that Silky Sharks exhibit greater site fidelity. Studies have shown site fidelity of Silky Sharks in Cuba (Hueter et al. 2018) and the Red Sea (Clarke et al. 2011a). The presence of a network of anchored fish aggregating devices (FADs) around Rarotonga, where the sharks were tagged, could have influenced track lengths and displacement distances of Silky Sharks, which were roughly half of the maximum displacement of sharks in the central Pacific Ocean (Musyl et al. 2011a) and nearly five times smaller than sharks tagged in the Indian Ocean (Curnick et al. 2020), although the mean track length in the Cook Islands was nearly 1000 km longer. Blue Sharks traveled the furthest in this study, with maximum track distances exceeding that of both male and female Blue Sharks tagged in New Zealand by nearly 2000 km (Elliott 2020), but with displacement distances similar to Blue Sharks tagged in the central north Pacific (Musyl et al. 2011a) and northeast Atlantic Ocean (Campana et al. 2011). The differences in site fidelity and distances traveled by pelagic sharks means that local data is needed, however, a mix of management approaches are necessary to effectively protect sharks with movements that extend outside of the Cook Islands Shark Sanctuary

5.4.2 Depth usage:

Depth ranges found in this study were consistent with studies that categorized Blue Sharks as mesopelagic; and Silky and Oceanic Whitetip Sharks as epipelagic (Musyl et al. 2011a; Howey et al. 2016). However, Blue Sharks in this study spent substantially more time at depths below 400 m than sharks tagged elsewhere in the Pacific spanning both continental shelves and oceanic islands with varying bathymetry (Stevens et al. 2010; Musyl et al. 2011a). Maximum depths were similar to Blue Sharks tagged in New Zealand (Elliott 2020). The depth ranges and times at depth for Silky and Oceanic Whitetip Sharks were consistent with studies in the Atlantic, Pacific and Indian Oceans (Musyl et al. 2011a; Howey-Jordan et al. 2013; Tolotti et al. 2015a; Hueter et al. 2018; Curnick et al. 2020; Young & Carlson 2020). The significant depth differences between zones found for Oceanic Whitetip and Silky Sharks are likely explained by bathymetry constraints; the 50 nm zones have shallower water, which explained the significance of the 50 nm zones for both species. Oceanic Whitetip Sharks did not show depth significance between unprotected EEZs and the 50 nm zones, but only two of the tagged individuals spent time in unprotected EEZs, and for less than 25% of the time they were tracked. When Silky Sharks were inside the Cook Islands EEZ, they spent a large proportion of their time near the islands, where the significant differences found in depth usage were also likely due to bathymetric constraints.

5.4.3 Movement relative to sanctuary:

The study data showed that longer mean movement distances corresponded to shorter times spent in the EEZ, although this varied between individuals. The extent of movement (95% KUD) for more than half of Oceanic Whitetip and Silky Sharks revealed long-term residence inside the Cook Islands EEZ, despite movements that crossed the Sanctuary (EEZ) boundary several times, indicating that the Sanctuary would provide benefit to these sharks when released in good condition. The mean residency times for Oceanic Whitetip Sharks in the Cook Islands EEZ were lower than those of sharks tagged in the Bahamas EEZ, a shark sanctuary, despite the Cook Islands EEZ being more than three times the size of the Bahamas (Ward-Paige 2017). This result highlights differences in movement patterns between these regions. The study included more males than females (6 males, 5 females), whereas sharks tagged in the Bahamas were primarily female (10 females, 1 male) and tagged at a known aggregation site (Howey-Jordan et al. 2013). Oceanic Whitetip Sharks showed the highest variability in time that individual sharks spent in the Cook Islands EEZ ranging from 13 to 86% (0-100% in the 50nm zone). The time spent in the EEZ between male and female Oceanic Whitetip Sharks was not significantly different, meaning any sanctuary benefit applies to both sexes, which might be important for reproduction. Efforts to identify important habitat for these species should continue due to their Critically Endangered status (IUCN 2019). Silky Sharks spent the most time inside the Cook Islands EEZ, with the longest period before leaving the EEZ.

The behavior of Silky Sharks might have been influenced by the location of tag deployments, which were around coastal anchored fish aggregating devices (FADs). Several short-term satellite and acoustic telemetry studies showed that Silky Sharks exhibited site fidelity to coastal and drifting FADs (Filmalter 2015; Curnick et al. 2020), which might explain the high percentages of times the tagged Silky Sharks in this study remained inside both the EEZ and the 50 nm zones within the Sanctuary. Oceanic Whitetip and Blue Shark 95% KUDs overlap with the 50 nm zones (up to 33% and 5%, respectively) suggests that zone provides lower benefit for these species than for Silky Sharks. However, the reduced time spent by Blue and Oceanic Whitetip Sharks inside the 50 nm zone could afford disproportionate benefit to sharks due to the absence of industrial fishing effort, which is present inside the EEZ boundaries of the Shark Sanctuary.

The proportions of time spent inside of each zone may have been affected by the tagging location or because the days at liberty were too short to identify seasonality. All sharks were tagged in the southern portion of the Cook Islands EEZ, within 100 nm of islands, whereas industrial fishing activity is concentrated in the northern portion of the EEZ (MMR 2019). If sharks were tagged in each of the zones, movement patterns may have changed substantially, including overlap with fishing effort. Random walk analyses could identify some changes in movement patterns as the result of different tagging locations, but deploying tags from various locations, and also from purse seine vessels, would enhance certainty in benefits provided by the Sanctuary.

While, based on movements, the Sanctuary appeared beneficial for Oceanic Whitetip and Silky Sharks, more than half of these individuals crossed high seas. The WCPFC regulations that ban retention of Oceanic Whitetip and Silky Sharks in the Convention area extend to the high seas. However, extensive compliance failures exist with fisheries regulations on the high seas (Brouwer & Harley 2015; Campana 2016; WCPFC 2020; Wang et al. 2021). No patterns were identified that predicted high proportions of time spent in the high seas, noting that I recorded only two individuals whose greatest proportion of time was spent in the high seas and tagged few Silky and Blue Sharks. Although the majority of all sharks tagged in the Cook Islands crossed the high seas where compliance issues with conservation and management measures exist, all species benefitted substantially from contiguous sanctuaries in bordering countries, which covered over 86% of all activity space for Oceanic Whitetip and Silky Sharks and nearly half of the activity space for Blue Sharks. The shared activity space by contiguous sanctuary countries provides a unique opportunity for shared research and conservation objectives for sharks, including policy amendments to create uniformity of sanctuary regulations between countries. Likewise, because tagged sharks moved in and out of sanctuary countries and the eastern high seas pocket, a closure to fishing and transshipment, or at a minimum, shark retention, in this pocket would benefit sharks and increase effectiveness of the contiguous sanctuaries by creating a truly contiguous zone. Additional to bordering sanctuary countries, several no-take MPAs exist throughout the neighboring EEZs that were not included in this study, but might afford additional benefit to pelagic sharks where site fidelity is higher (Young & Carlson 2020). These MPAs include the Phoenix Islands Protected Area in Kiribati (Republic of Kiribati 2008) and the recently established Moana Mahu, a large no-take MPA in the eastern portion of Niue's EEZ (Government of Niue 2020).

5.4.4 Risk of capture by fisheries:

Importantly, there is still fishing-related mortality of sharks both inside of shark sanctuaries (Ward-Paige 2017) and inside of the Cook Islands 50 nm zones due to interactions with fishing. In the 50 nm zones, industrial longline and purse seine vessels are banned, meaning that shark interactions are primarily with local fishers often deploying single hook lines (pers. obs. 2018). Mortality events in the 50 nm zones from interactions with local fishing have not been quantified, but could result from conflict following a depredation event on target species (Iwane et al. 2020; pers. comm. 2020) or, as is the case in the rest of the EEZ, from capture stress, adverse impacts of retained hooks, or injuries sustained during handling and release (Cooke & Schramm 2007; Molina & Cooke 2012; Musyl & Gilman 2019). As a result of continued fishing inside the Sanctuary, the Sanctuary benefit applies only to sharks that survive capture, handling and release. Studies have shown that post-release survival for pelagic sharks is high when handled and released in good condition (Moyes et al. 2006; Hutchinson et al. 2019a; Musyl & Gilman 2019)

This study showed hotspots of shark activity that overlapped with both purse seine and longline fishing effort inside of the 50 nm zones, based on the Global Fishing Watch dataset. Fishing effort inside of the 50 nm zone is inconsistent with 2017 Marae Moana regulations that banned industrial fishing; and the fishing effort provided by Global Fishing Watch during this study contributed to increased fishing exposure risk for Blue and Silky Sharks to both gears. The presence of industrial vessels inside of the 50 nm zones might have occurred based on timing of legislation and when the data was gathered for the Global Fishing Watch dataset, which spanned the year 2017. The legislation that enacted the 50 nm zones went into force in July 2017, so it is possible that the activity shown in this study included fishing effort prior to implementation of the law. It is also possible that grid size and tag error overestimated shark overlap with fishing pressure in the 50nm zone, or that Global Fishing Watch algorithms were not 100% effective at identifying location of effort by specific gears (Musyl et al. 2011b; Queiroz et al. 2016, 2019; Kroodsma et al. 2018).

The FEI showed that the risk of capture by fisheries was much higher for longline than for purse seine fishing effort, consistent with results from the recent global study (Queiroz et al. 2019). For all species, nearly the entire horizontal tracks overlapped with longline fishing vessels in the EEZ, compared to roughly 25% with purse seining. However, the overlap of mean monthly space use for sharks and longline fishing in the Cook Islands was substantially higher (>98% for all species) than Quieroz et al. (2019) reported in Oceania (24%). There were no shark tracks from the Central South Pacific Ocean included in the global study, which might explain the discrepancy. Blue Sharks had the highest spatial overlap with longline fisheries in this study, consistent with this species being the most abundant bycatch species in the region on longline vessels (Rice et al. 2015). However, because only two Blue Sharks were tagged, the low FEI should be interpreted cautiously. Silky Sharks showed the highest risk on the high seas, but this result might also be biased by low tag numbers (n = 3) and tag deployment location near Rarotonga, since the majority of the fishing in the Cook Islands occurs near the equator and the Silky Sharks in this study remained south of this region. Further tagging of Silky Sharks in the northern Cook Islands EEZ would improve the estimate of risk from purse seine fishing in the Cook Islands. Based on their movements, Oceanic Whitetip Sharks showed the highest risk of capture by both longline and purse seine vessels inside of the EEZs.

Outside of the Cook Islands, hotspots of spatial overlap of sharks with fishing effort (risk) were primarily on country boundaries, particularly for Oceanic Whitetip and Silky Sharks, with Oceanic Whitetip Sharks showing highest risk of capture in both gears. The high overlap near boundaries is further reason for bilateral or regional conservation and management agreements, which could result in uniform regulations across contiguous sanctuaries and regulations extending to country nationals fishing on the high seas, a precedent in Article 7 of the United Nations Fish Stock Agreement (UN 1995). Because hotspots of FEI for Oceanic Whitetip Sharks and Blue Sharks also occurred in the high seas pocket adjacent to sanctuary countries, the governments would have further impetus to work together to support the conservation of threatened species, which could include closing the high seas pocket to fishing and transshipment.

In addition to horizontal overlap, nearly all depths where sharks were present overlapped with fisheries, and nearly all of the time sharks spent at those depths overlapped with longline fishing (>98% all species). While Blue Sharks spent less than half of their time at depths that overlapped with purse seine fishing, Oceanic Whitetip and Silky Sharks spent nearly all of their time at risk of capture from purse seine fisheries, meaning there was almost no refuge for these species when their activity space overlapped with the fisheries operating inside and outside of sanctuary waters. Silky Sharks did spend more time at depth on the high seas, where their risk of capture was highest; it is possible that their risk of capture by these fisheries could decrease if depth were assessed as part of fisheries exposure risk. To decrease risk of capture by limiting depth overlap in all zones and on the high seas, sanctuary and RFMO regulations could include depth restrictions specific to the target fisheries, whose depths are fairly well established (Gallagher et al. 2014; Tolotti et al. 2015b; Allain et al. 2018; Young & Carlson 2020).

5.5. CONCLUSION:

This study showed that the Cook Islands Shark Sanctuary is likely providing benefit to Oceanic Whitetip and Silky Sharks, but minimal benefit to Blue Sharks. There was almost no refuge from longline fishing for all species based on both horizontal movement and depth patterns, but sanctuaries in adjacent countries dramatically increased proportions of activity space covered by protective regulations. Despite these regulations, mortality still occurs as a result from overlap with fisheries. Therefore, future work should include maximizing protections though bilateral agreements to include uniform sanctuary regulations, working with RFMOs to adopt complementary measures on the high seas, and identifying methods to reduce shark-vessel overlap while maximizing survival of sharks caught inside sanctuaries.

Chapter 6:

General Discussion

6.1. Summary and synthesis of research findings:

The pervasive and continued population declines of many elasmobranch species, despite the range of interventions aimed at their protection, means that understanding the shortcomings of previous interventions is important for shark conservation. For example, studies have called for improvements in implementation, enforcement, and compliance of policy interventions, as well as increased protections through catch limits, gear modifications, and increased spatial refuges (Dulvy et al. 2014; Bräutigam et al. 2015; Clarke et al. 2015; Dent & Clarke 2015; Tolotti et al. 2015b; Queiroz et al. 2019; MacNeil et al. 2020; Pacoureau et al. 2021). Based on the limited capacity for elasmobranchs, understanding and implementing effective policy is critical.

This thesis explored the genesis of elasmobranch conservation and management policies, and the gaps and inconsistencies contributing to continued species declines (Chapter 2). Review indicated critical definitions were vague or missing, leaving room for political interference. Further, the lack of clarity and prescription in policies made them difficult to implement and therefore less likely to produce the intended conservation outcomes.

While improvements are needed in elasmobranch policies to halt the downward trajectory of many threatened species, results from this thesis revealed that the Cook Islands Shark Sanctuary provided benefit to elasmobranchs on several fronts. The Baited Remote Underwater Video Station analysis in Chapter 3 showed the presence of a shark sanctuary was a significant factor in higher reef shark abundance in Pacific nations, including the Cook Islands. This result indicates that sanctuaries and other closures can be highly effective for site attached or restricted movement species. In addition, in Chapter 4, analysis of fisheries data revealed a reduction in the number of elasmobranchs retained by commercial longline vessels following the implementation of the Cook Islands Shark Sanctuary, which likely resulted in a substantial mortality reduction for animals released in good condition because of high levels of post-release survival (Campana et al. 2009; Bromhead et al. 2012; Musyl & Gilman 2018). However, a scarcity of data precluded making strong conclusions about reduced retention by purse seine vessels. Data gaps and reporting discrepancies were apparent in addition to an identified need to address operational guidelines for fishing vessels interacting with elasmobranchs. Finally, through examination of movement and activity spaces of the three most frequently caught sharks in industrial fisheries that operate in the Cook Islands, movement patterns indicated the Sanctuary was likely benefiting Oceanic Whitetip and Silky Sharks. Blue Sharks were afforded minimal benefit because of their broader movements and time spent outside the Sanctuary, but this result should be interpreted with caution because of low numbers of tagged Blue Sharks. However, individual movements and time on the high seas and in unprotected waters were variable for all species. Movement data also suggest that the risk of capture for sharks tagged in the Cook Islands was substantially higher than the risk for sharks in the Oceania region based on results of Quieroz et al. (2019). While there was an increased risk of capture by fishing vessels for Oceanic Whitetip and Silky Sharks in other EEZs, the presence of contiguous sanctuaries bordering the Cook Islands benefited all three species.

6.2. Effectiveness of Cook Islands Shark Sanctuary:

Overall the Cook Islands Shark Sanctuary was effective in reducing retention and mortality of sharks. However, due to the range of species present and differences between islands (environmental and anthropogenic), measuring effectiveness was considered on a continuum, rather than as a binary "effective" or "not effective". The variables involved, in addition to ongoing fishing within and beyond the Sanctuary meant a range of factors that contributed to sanctuary effectiveness. This case study of the Cook Islands highlights the complexity of evaluating shark sanctuary efficacy since most or all of these factors will also apply to other locations.

The Cook Islands Shark Sanctuary regulations contained attributes that Ward-Paige (2018) found to be missing from other sanctuaries, (e.g. extension to all elasmobranchs, possession and transshipment bans, etc.). However, the Sanctuary included an exemption for local fishers, which contributes to undocumented mortality of elasmobranchs (both threatened and not threatened species). However, some of the specific regulations are likely to be highly effective. For example, the ban on trace wire likely had a direct, positive impact by reducing the number of sharks captured and increasing post release survival (Gilman et al. 2016b; Musyl & Gilman 2019). In addition, the Sanctuary regulations outline severe fines for infraction, an economic deterrent that is effective in reducing illegal fishing (Vince et al. 2021). However, because fishing was permitted inside of the Sanctuary, elasmobranch mortality still occurred as result of interactions with industrial fishing gear, even if animals were captured incidentally and then released. Quantifying levels of interaction with and mortality of elasmobranchs by local fishers would improve understanding of the Sanctuary effectiveness and could highlight areas for policy improvement to increase benefits to elasmobranchs. Understanding and improving post-release survival of these elasmobranchs would increase sanctuary effectiveness.

6.3. Improving sanctuary effectiveness:

There is now increasing evidence that sanctuaries benefit both reef-associated and wide-ranging elasmobranchs. Chapter 3 showed that reef shark populations in the Pacific are faring well in sanctuary nations; however, effectiveness could be increased through policy and regulatory changes for wide-ranging sharks.

Based on extensive elasmobranch movements between EEZs and the high seas (Chapter 5), the regulations in neighboring jurisdictions and the high seas are important for effective conservation of wide-ranging species. Contiguous sanctuaries were beneficial, but uniformity in regulations between neighboring sanctuaries would strengthen protections. Uniformity in regulations that closed loopholes would benefit species that cross multiple sanctuaries or jurisdictions, because vessels would be held to the same standards, regardless of location. When multiple sanctuaries exist in a region, as is the case in the major tuna RFMO area that encompasses the Cook Islands waters (WCPFC), the political will for shark protection should be used to further objectives for elasmobranch conservation and fisheries management. Formalization of sanctuary countries into a group with uniform aims and regulations could afford benefits to elasmobranch management inside of RFMOs, where the economic pressures from industrial fisheries, revenue which is an important contributor for Pacific nations (Gillett 2016), often thwarts meaningful protections (Hanich & Tsamenyi 2009).

Chapter 4 highlighted known data reporting gaps in industrial fisheries records, but sanctuary nations could trial operational-level modifications for data reporting improvements, as well as bycatch mitigation techniques that reduce mortality of elasmobranchs such as gear changes, depth restrictions, handling measures and other measures to increase survivorship post-release, therefore reducing elasmobranch mortality (Hutchinson et al. 2019a; Musyl & Gilman 2019). Spatial protections in the high seas would likely benefit all pelagic elasmobranchs, particularly if transshipment bans were in place.

Regardless of the regulatory or legislative vehicle for elasmobranch conservation and sustainable management, sanctuaries were not designed to address sustainable use of elasmobranchs that support livelihoods (Mackeracher et al. 2018; Mizrahi et al. 2019). Because sanctuaries were not designed to promote optimum utilization and sustainable use, rather they ban all retention of sharks, nations or communities with livelihood needs will have to consider fisheries interventions designed to match their policy goals such as size and catch limits, gear restrictions, or specific spatial closures of sensitive or important areas.

A key component to increasing benefits of sanctuaries for elasmobranchs is increased monitoring, since sanctuaries only benefit elasmobranchs that survive capture, handling and release. Perhaps shark sanctuaries could trial bycatch limits for threatened elasmobranchs to determine whether high stakes such as a total loss of fishing effort would encage fishers to avoid interactions with elasmobranchs (or to adhere to regulations that limit post-release elasmobranch mortality). Evaluations of bycatch limits should consider complementary measures on the high seas to ensure fishing effort was not displaced there from the Sanctuary.

In summary, there are several actions that could be applied to improve sanctuary effectiveness:

- Working neighboring sanctuaries to advocate for uniform regulations;
- Understanding of the drivers of and levels of elasmobranch mortality by fisheries exempted from sanctuary regulations, such as artisanal or non-industrial local fishing;

- Improved monitoring and reporting;
- Regular evaluations of effectiveness of Sanctuary regulations, and transparency of enforcement and compliance with regulations;
- Implementation of regulations specific to different types of elasmobranchs, such as deep water, reef-associated, or wide-ranging pelagic species, to increase benefits to each of these types of elasmobranchs.

6.4. Future directions:

Confidence in the results obtained here would be improved by additional exploration of other sanctuaries and their related policies. Detailed studies are required covering a range of aspects and targeted approaches as applied here to truly understand the dynamics and effectiveness of sanctuary policies and implementation. Movement of individuals inside and outside of sanctuary boundaries is a key determinant in effectiveness of spatial protections. Therefore increased sample sizes, inclusion of additional species and size classes of sharks, and exploration of seasonality of movements and overlap with fisheries would be beneficial. Additional telemetry studies could also elucidate corridors or habitats of importance that could aid in policy revisions for greater conservation benefit to elasmobranchs. Future work could also include random walk analyses to determine if tag deployment location would change the risk of fisheries overlap.

Further to understanding the effect of commercial fisheries inside of sanctuaries, future studies should look at expanded fisheries records with data on effort, hook type, line depth, and location to better understand the overlap with and impact of industrial fisheries on elasmobranchs inside of shark sanctuaries. These commercial fisheries studies could be coupled with research on the effectiveness of shark line and trace wire bans, ways to reduce capture and post-release mortality, handling and release measures, electronic monitoring and reporting, etc., to help determine which additional measures or combination thereof, would create the greatest benefit.

Broader surveys across a range of species would also provide valuable context for condition and status of populations within a region. Additional BRUVS deployments at more locations, at various depths, in different seasons and over consecutive years would provide more accurate abundance data. However, BRUVS sampling will not elucidate overlap with local fishers. Quantifying interaction rates and mortality from local fishers that are exempted from the Sanctuary regulations are necessary. To understand non-consumptive mortality of sharks, evaluations of human-wildlife conflict could be conducted to provide insights into fisher behavior and interactions with sharks, but also perceptions and uptake of conservation and management policy more generally (Arias et al. 2015).

In addition to better understanding species and fishers, further policy analyses could be conducted to better inform future processes. This thesis did not examine regional seas policies or the national environmental and fisheries regulations from each nation with elasmobranch conservation and management measures. The gaps and loopholes in each of these policies could highlight areas for improvement. Shark sanctuary policies could also be examined for specific loopholes that permit continued exploitation, which affords another opportunity for sanctuary countries to engage with multilateral environmental agreements, such as those of RFMOs, CITES, or CMS. These multilateral environmental agreements could acknowledge sanctuaries as a tool for elasmobranch conservation and management, and therefore use member nations' sanctuary regulations (and any associated internally or externally funded research) to advance their own conservation and management initiatives. Finally, although an adapted systematic conservation planning (SCP) approach (Pressey & Bottrill 2009) could inject rigor into the policy process, this needs to be detailed and presented to the scientific community.

Evaluating loopholes that have been utilized by vessels in the Cook Islands and other sanctuary countries during the effectiveness evaluations could strengthen sanctuary policy. In all future research endeavors aimed at increasing the effectiveness of policies for elasmobranchs, the political will of sanctuary countries should be used to gain valuable information that might advance management in slower moving management processes. The development of a Cook Islands Shark Sanctuary evaluation plan would provide opportunity to improve benefits to elasmobranchs in addition to those found by my research.

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Appendices

Appendix I: Chapter 2 Supplementary materials

Table A1.1: Table of chondrichthyans listed to species-level, by IUCN Red List threat level, and their inclusion on the policies that were examined.

			BINDING MEASURES													NON-BINDING MEASURES		
			UNCLOS	CITES		RFMOs										CMS		CMS Sharks
Species Name	**Common Name**	**Red List Status**	**Ann. I**	**App. I**	**App. II**	**CCAMLR**	**CCSBT**	**GFCM**	**IATTC**	**ICCAT**	**IOTC**	**NAFO**	**NEAFC**	**WCPFC**	**SEAFO**	**App. I**	**App. II**	**MOU Ann. I**
Carcharhinus hemiodon	Pondicherry shark	Critically Endangered	x			x[1]												
Carcharhinus longimanus	Oceanic whitetip shark	Critically Endangered	x		x	x[1]	x[2]		x	x	x			x				x
Centrophorus granulosus	Gulper shark	Critically Endangered				x[1]							x		x°			
Dipturus batis	Common skate	Critically Endangered						x										
Glaucostegus cemiculus	Blackchin guitarfish	Critically Endangered			x			x										
Glaucostegus granulatus	Sharpnose guitarfish	Critically Endangered			x													
Glaucostegus halavi	Halavi guitarfish	Critically Endangered			x													
Glaucostegus obtusus	Widenose guitarfish	Critically Endangered			x													
Glaucostegus thouin	Clubnose guitarfish	Critically Endangered			x													
Glaucostegus typus	Giant guitarfish	Critically Endangered			x													
Glyphis gangeticus	Ganges shark	Critically Endangered	x			x[1]												
Glyphis garricki	Northern river shark	Critically Endangered	x			x[1]												
Glyphis siamensis	Irawaddy river shark	Critically Endangered	x			x[1]												
Isogomphodon oxyrhynchus	Daggernose shark	Critically Endangered	x			x[1]												
Leucoraja melitensis	Maltese skate	Critically Endangered						x										
Pristis pectinata	Smalltooth sawfish	Critically Endangered		x				x								x	x	x
Pristis pristis	Largetooth sawfish	Critically Endangered		x				x								x	x	x
Pristis zijsron	Green sawfish	Critically Endangered		x												x	x	x
Rhina ancylostoma	Bowmouth guitarfish	Critically Endangered			x													

Rhynchobatus australiae	Bottlenose wedgefish	Critically Endangered			x												x	x
Rhynchobatus cooki	Clown wedgefish	Critically Endangered			x													
Rhynchobatus djiddensis	Whitespotted wedgefish	Critically Endangered			x													x
Rhynchobatus immaculatus	Taiwanese wedgefish	Critically Endangered			x													
Rhynchobatus laevis	Smoothnose wedgefish	Critically Endangered			x													x
Rhynchobatus luebberti	African wedgefish	Critically Endangered			x													
Rhynchobatus springeri	Broadnose wedgefish	Critically Endangered			x													
Rhynchorhina mauritaniensis	False shark ray	Critically Endangered			x													
Sphyrna lewini	Scalloped hammerhead	Critically Endangered	x		x	x[1]		x		x							x	x
Sphyrna mokarran	Great hammerhead	Critically Endangered	x		x	x[1]		x		x							x	x
Squatina aculeata	Sawback angelshark	Critically Endangered				x[1]		x										
Squatina oculata	Smoothback angelshark	Critically Endangered				x[1]		x										
Squatina squatina	Angelshark	Critically Endangered				x[1]		x								x	x	x
Alopias pelagicus	Pelagic thresher shark	Endangered	x		x	x[1]	x[2]				x						x	x
Anoxypristis cuspidata	Narrow sawfish	Endangered		x												x	x	x
Carcharhinus borneensis	Borneo shark	Endangered	x			x[1]												
Carcharhinus dussumieri	Whitecheek shark	Endangered	x			x[1]												
Carcharhinus leiodon	Smoothtooth blacktip shark	Endangered	x			x[1]												
Carcharhinus obscurus	Dusky shark	Endangered	x			x[1]											x	x
Cetorhinus maximus	Basking shark	Endangered	x		x	x[1]		x					x			x	x	x
Eusphyra blochii	Winghead shark	Endangered	x			x[1]				x								
Glyphis glyphis	Speartooth shark	Endangered	x			x[1]												
Isurus oxyrinchus	Shortfin mako shark	Endangered	x		x	x[1]		x		* x							x	x
Isurus paucus	Longfin mako shark	Endangered	x		x	x[1]											x	x
Lamiopsis temminckii	Broadfin shark	Endangered	x			x[1]												
Leucoraja circularis	Sandy skate	Endangered						x										
Mobula hypostoma	Atlantic devil ray	Endangered			x		x[2]		x		x					x	x	x
Mobula mobular	Giant devil ray	Endangered			x		x[2]	x	x		x					x	x	x
Mobula tarapacana	Sicklefin devil ray	Endangered			x		x[2]		x		x					x	x	x

Mobula thurstoni	Bentfin devil ray	Endangered			x		x^2		x		x					x	x	x
Pristis clavata	Dwarf sawfish	Endangered		x												x	x	x
Rhincodon typus	Whale shark	Endangered	x		x	x^1	x^2				* x			* x		x	x	x
Rhinobatos rhinobatos	Common guitarfish	Endangered						x								*x	x	x
Rostroraja alba	White skate	Endangered						x										
Alopias superciliosus	Bigeye thresher shark	Vulnerable	x		x	x^1	x^2	x		x	x						x	x
Alopias vulpinus	Common thresher shark	Vulnerable	x		x	x^1	x^2				x						x	x
Carcharhinus albimarginatus	Silvertip shark	Vulnerable	x			x^1												
Carcharhinus falciformis	Silky shark	Vulnerable	x		x	x^1	x^2		x	x				x			x	x
Carcharhinus plumbeus	Sandbar shark	Vulnerable	x			x^1												
Carcharhinus signatus	Night shark	Vulnerable	x			x^1												
Carcharhinus tjutjot	Indonesian whaler shark	Vulnerable	x			x^1												
Carcharias taurus	Sand tiger shark	Vulnerable				x^1		x										
Carcharodon carcharias	White shark	Vulnerable	x		x	x^1		x								x	x	x
Centrophorus squamosus	Leafscale gulper shark	Vulnerable				x^1							x		x$^{\circ}$			
Dalatias licha	Kitefin shark	Vulnerable				x^1							x		x$^{\circ}$			
Galeorhinus galeus	Tope shark	Vulnerable				x^1		x										
Gymnura altavela	Spiny butterfly ray	Vulnerable						x										
Lamna nasus	Porbeagle shark	Vulnerable	x		x	x^1		x					x				x	x
Mobula alfredi	Reef manta ray	Vulnerable			x		x^2		x		x					x	x	x
Mobula birostris	Giant manta ray	Vulnerable			x		x^2		x		x					x	x	x
Mobula munkiana	Pygmy devil ray	Vulnerable			x		x^2		x		x					x	x	x
Mobula rochebrunei	Lesser guinean devil ray	Vulnerable			x		x^2		x		x					x	x	x
Negaprion acutidens	Sicklefin lemon shark	Vulnerable	x			x^1												
Odontaspis ferox	Smalltooth sand tiger shark	Vulnerable				x^1		x										
Oxynotus centrina	Angular rough shark	Vulnerable				x^1		x										
Sphyrna tudes	Smalleye hammerhead	Vulnerable	x			x^1				x								
Sphyrna zygaena	Smooth hammerhead	Vulnerable	x		x	x^1		x		x								x
Squalus acanthias	Spiny dogfish	Vulnerable				x^1							x				x	x

Carcharhinus acronotus	Blacknose shark	Near Threatened	x			x[1]												
Carcharhinus amblyrhynchoides	Graceful shark	Near Threatened	x			x[1]												
Carcharhinus amblyrhynchos	Grey reef shark	Near Threatened	x			x[1]												
Carcharhinus brachyurus	Copper shark	Near Threatened	x			x[1]												
Carcharhinus brevipinna	Spinner shark	Near Threatened	x			x[1]												
Carcharhinus leucas	Bull shark	Near Threatened	x			x[1]												
Carcharhinus limbatus	Blacktip shark	Near Threatened	x			x[1]												
Carcharhinus macloti	Hardnose shark	Near Threatened	x			x[1]												
Carcharhinus melanopterus	Blacktip reef shark	Near Threatened	x			x[1]												
Carcharhinus perezi	Caribbean reef shark	Near Threatened	x			x[1]												
Carcharhinus sealei	Blackspot shark	Near Threatened	x			x[1]												
Carcharhinus sorrah	Spottail shark	Near Threatened	x			x[1]												
Centroscymnus coelolepis	Portuguese dogfish	Near Threatened				x[1]							x		x°			
Chimaera monstrosa	Rabbitfish	Near Threatened											x					
Dipturus nidarosiensis	Norwegian skate	Near Threatened											x					
Galeocerdo cuvier	Tiger shark	Near Threatened	x			x[1]												
Hexanchus griseus	Bluntnose sixgill shark	Near Threatened	x			x[1]							x		x°			
Hydrolagus mirabilis	Large-eyed rabbitfish	Near Threatened											x					
Mobula eregoodootenkee	Longhorn pygmy devil ray	Near Threatened			x		x[2]		x		x					x	x	x
Mobula japanica	Spinetail devil ray	Near Threatened			x		x[2]		x		x					x	x	x
Negaprion brevirostris	Lemon shark	Near Threatened	x			x[1]												
Prionace glauca	Blue shark	Near Threatened	x			x[1]											x	
Rhynchobatus palpebratus	Eyebrow wedgefish	Near Threatened			x													
Scoliodon laticaudus	Spadenose shark	Near Threatened	x			x[1]												
Somniosus microcephalus	Greenland shark	Near Threatened				x[1]						x	x		x°			
Sphyrna corona	Scalloped bonnethead	Near Threatened	x			x[1]				x								
Triaenodon obesus	Whitetip reef shark	Near Threatened	x			x[1]												
Amblyraja hyperborea	Arctic skate	Least Concern											x					
Apristurus albisoma	White-bodied catshark	Least Concern				x[1]							x		x°			

Apristurus aphyodes	White ghost catshark	Least Concern				x[1]							x		x°			
Apristurus melanoasper	Fleshynose catshark	Least Concern				x[1]							x		x°			
Apristurus pinguis	Bulldog catshark	Least Concern				x[1]							x		x°			
Apristurus platyrhynchus	Flatnose catshark	Least Concern				x[1]							x		x°			
Carcharhinus coatesi	Australian blackspot shark	Least Concern	x			x[1]												
Carcharhinus fitzroyensis	Creek whaler	Least Concern	x			x[1]												
Carcharhinus galapagensis	Galapagos shark	Least Concern	x			x[1]												
Carcharhinus isodon	Finetooth shark	Least Concern	x			x[1]												
Carcharhinus tilstoni	Australian blacktip shark	Least Concern	x			x[1]												
Centroscyllium fabricii	Black dogfish	Least Concern				x[1]							x		x°			
Centroselachus crepidater	Longnose velvet dogfish	Least Concern				x[1]							x		x°			
Chlamydoselachus anguineus	Frilled shark	Least Concern				x[1]							x		x°			
Deania calcea	Birdbeak dogfish	Least Concern				x[1]							x		x°			
Etmopterus spinax	Velvet belly lanternshark	Least Concern				x[1]							x		x°			
Galeus melastomus	Blackmouth catshark	Least Concern				x[1]							x		x°			
Galeus murinus	Mouse catshark	Least Concern				x[1]							x		x°			
Lamna ditropis	Salmon shark	Least Concern	x			x[1]												
Loxodon macrorhinus	Sliteye shark	Least Concern	x			x[1]												
Rajella fyllae	Round skate	Least Concern											x					
Rhinochimaera atlantica	Atlantic longnose chimaera	Least Concern											x					
Rhizoprionodon acutus	Milk shark	Least Concern	x			x[1]												
Rhizoprionodon oligolinx	Grey sharpnose shark	Least Concern	x			x[1]												
Rhizoprionodon porosus	Caribbean sharpnose shark	Least Concern	x			x[1]												
Rhizoprionodon taylori	Australian sharpnose shark	Least Concern	x			x[1]												
Rhizoprionodon terraenovae	Atlantic sharpnose shark	Least Concern	x			x[1]												
Sphyrna tiburo	Bonnethead shark	Least Concern	x			x[1]												
Apristurus fedorovi	Fedorov's catshark	Data Deficient				x[1]							x		x°			
Apristurus gibbosus	Humpback catshark	Data Deficient				x[1]							x		x°			
Apristurus herklotsi	Longfin catshark	Data Deficient				x[1]							x		x°			

Apristurus internatus	Shortnose demon catshark	Data Deficient				x^1							x		x°			
Apristurus investigatoris	Broadnose catshark	Data Deficient				x^1							x		x°			
Apristurus laurussonii	Icelandic catshark	Data Deficient				x^1							x		x°			
Apristurus macrorhynchus	Flathead catshark	Data Deficient				x^1							x		x°			
Apristurus macrostomus	Broadmouth catshark	Data Deficient				x^1							x		x°			
Apristurus micropterygeus	Smalldorsal catshark	Data Deficient				x^1							x		x°			
Apristurus parvipinnis	Smallfin catshark	Data Deficient				x^1							x		x°			
Apristurus profundorum	Deepwater catshark	Data Deficient				x^1							x		x°			
Apristurus stenseni	Panama ghost catshark	Data Deficient				x^1							x		x°			
Carcharhinus altimus	Bignose shark	Data Deficient	x			x^1												
Carcharhinus amboinensis	Pigeye shark	Data Deficient	x			x^1												
Carcharhinus cautus	Nervous shark	Data Deficient	x			x^1												
Carcharhinus porosus	Smalltail shark	Data Deficient	x			x^1												
Etmopterus princeps	Great lanternshark	Data Deficient				x^1							x		x°			
Mobula kuhlii	Shortfin devil ray	Data Deficient			x		x^2		x		x					x	x	x
Nasolamia velox	Whitenose shark	Data Deficient	x			x^1												
Oxynotus paradoxus	Sailfin rough shark	Data Deficient				x^1							x		x°			
Rhizoprionodon lalandii	Brazilian sharpnose shark	Data Deficient	x			x^1												
Rhizoprionodon longurio	Pacific sharpnose shark	Data Deficient	x			x^1												
Scymnodon ringens	Knifetooth dogfish	Data Deficient				x^1							x		x°			
Sphyrna gilberti	Carolina hammerhead shark	Data Deficient	x			x^1				x								
Sphyrna media	Scoophead shark	Data Deficient	x			x^1				x								

x^1 CCAMLR bans targeting of all sharks, but does not give any species names. We did not include rays, skates, guitarfish, sawfish or chimaeras in the CCAMLR ban. x^2 ban is in force dependent upon which overlapping RFMO Convention area (IOTC, ICCAT or WCPFC) the vessel licensed to CCSBT is fishing within. x° SEAFO bans all directed deepwater shark fisheries, but does not give any species names. We did not include rays, skates, guitarfish, sawfish or chimaeras in the SEAFO ban.

Text A1.1:

Were species listings on each policy consistent with the policy's stated intent and species listing criteria?

United Nations Convention on the Law of the Sea (UNCLOS): The UNCLOS Agreement did not specify listing criteria for chondrichthyan species. UNCLOS listed "Oceanic Sharks" on Annex I for Highly Migratory Species. Annex I included all sharks in the families Carcharhinidae, Sphyrnidae, Isuridae (Lamnidae), Alopiidae, plus *Hexanchus griseus, Cetorhinus maximus, Rhincodon typus*. However, the Convention text did not explain how it defined species as "Oceanic" or "Highly Migratory" or how or why these species were selected while others were not. No rays were listed on UNCLOS Annex I. At the time the UNCLOS policy was written, rays were not frequently considered part of the 'shark' conversation. While the Convention text states that the Annexes will be reviewed 15 years from the date the Convention took effect (1982), no changes to UNCLOS's "Oceanic Sharks" species list have been made since its inception.

Convention for the Conservation of Migratory Species of Wild Animals (CMS): The criteria for adding species to CMS are more clearly defined than for UNCLOS. For a species to be listed on CMS Appendices, it must be migratory, which the CMS Text defined as an entire population or a geographically separate part of the population of any species that "cyclically and predictably" crosses one or more national jurisdictions. Secondly, a species must have an unfavorable "conservation status." The CMS definition for "conservation status" does not dictate usage of IUCN Red List categories (which have rigorous assessment criteria) or any quantitative assessment of conservation status or risk. It was based on a list of four criteria in Article I, paragraph 1, subparagraph (c) of the Convention text. If even one of those criteria is not met, the conservation status is considered "unfavorable." The term "endangered" in CMS is a generic term without explicit definition, but is interpreted as species with elevated extinction risk in the specific threat-level categories of the "threatened" species on the IUCN Red List Assessments. CMS's endangered migratory species are listed on CMS Appendix I whereas species on Appendix II have an unfavorable conservation status and would benefit from international cooperation.

Importantly, for a species to be added to one of the Appendices it must first be nominated for listing by a CMS party and, second, voted onto the list by the CMS membership. Twenty-one shark species that were nominated and approved by the membership were listed on Appendix I; 13 of those were assessed as Critically Endangered or Endangered by IUCN's Red Listing process (Table S.1). There were inconsistencies in species listings when compared to the CMS criteria; several species met the listing criteria but were not listed, noting that threat levels may have changed once species were listed. The White Shark was listed on CMS Appendix I, but assessed as Vulnerable by IUCN, while two of the three Critically Endangered Hammerheads and the Endangered Shortfin and Longfin Mako Sharks were listed on CMS Appendix II, inferring they are less in need of conservation than Appendix I-listed species. Similarly, the Critically Endangered Oceanic Whitetip Shark (*Carcharhinus longimanus*) and Endangered Winghead Shark (*Eusphyra blochii*) were missing from CMS Appendices while the Near Threatened Blue Shark (*Prionace glauca*) was listed on CMS Appendix II. CMS membership did not warrant any listing for two Critically Endangered Wedgefishes (*Rhynchobatus djiddensis, Rhynchobatus laevis*), but listed the Critically Endangered Bottlenose Wedgefish (*Rhynchobatus australiae*) on Appendix II. Several species were listed on both CMS Appendices I and II (Table S.1). Information on whether omitted species that met CMS listing criteria were nominated and voted down was not publicly available.

Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES): The criteria for species to be listed on CITES Appendices were well defined in Resolution Conference 9.24 (Rev. CoP17). However, like CMS, species listings first required nomination by a Party and then a vote by the Convention for listing in the Appendices. Unlike CMS, species cannot to be simultaneously listed on multiple appendices unless it was a subpopulation (e.g. national or sub-regional). For a species to be listed on Appendix I it must be threatened by international trade, but the policy did not have a quantitative determination listed, and a species must meet, or must be likely to meet, at least one of the biological criteria that were listed in Annex I. These included having small wild populations, restricted geographic range, and steep declines in population size, terms that were defined in the text (Annex 5, Resolution

Conference 9.24) with quantitative reference targets. Although quantitative targets were given as reference, some subjectivity was written into the criteria for "taxon- and case-specific biological and other factors [that] are likely to affect extinction risk." CITES Appendix II criteria were defined in Annex II of Resolution Conference 9.24 (Rev. CoP17) and intended for species that required regulation of trade to reduce chances of its eligibility for Appendix I in the future or if trade threatened proliferation of wild populations. Few species were listed in the Appendices because they were not nominated by the CMS membership, despite meeting the criteria, including species that were nominated but did not pass the vote, such as the Spiny Dogfish (*Squalus acanthias*) (Table S.1). Several Critically Endangered, Endangered or Vulnerable species, or lookalikes, that were either affected by trade were not listed in CITES Appendices (Table S.1). These included Critically Endangered wedgefishes, *Rhynchobatus australiae* and *Rhynchobatus laevis*, which are listed on Appendix II and not on Appendix I, meaning that, despite their threatened global status, trade in the species is not banned meaning either the population decline was not caused by international trade, or these species were no nominated or voted for listing in CITES. Additionally, Hammerhead Sharks *Eusphyra blochii*, *Sphyrna tudes* and *Sphyrna corona*, which are lookalikes for CITES listed species, were not listed on the Appendices.

Several species were not voted onto Appendices, including *Squatina squatina* and *Rhinobatos rhinobatos*, which are Critically Endangered and traded regionally. Once the recent listings take effect in November 2019, CITES Appendices will list 26.7% of species determined threatened (but not necessarily threatened by trade) by the IUCN Red List process (Table S.1).

Regional Fisheries Management Organizations (RFMOs): There were no criteria for species to be listed for protection (either no retention or no directed fishing) by RFMOs in any Convention text or publicly available documents. Also, there were no specific criteria outlining the process for Commission members or cooperating non-members to nominate species for assessment, which RFMOs required before any management decisions were made. Accordingly, there was no basis for comparing species' listings to criteria. In the absence of specific criteria or quantitative threat-level threshold in RFMOs, any country member of the RFMO can nominate a species to be considered as a 'vulnerable' or 'key species' in the RFMO Convention area.

Consideration of threat level as indicated by the IUCN Red Listing process was applied inconsistently in RFMOs, noting that RFMOs are not mandated to consider IUCN Red List threat levels. The term 'vulnerable' was used in the tuna RFMOs ICCAT and IOTC, but without definition or reference to the IUCN Red List threat-level category 'Vulnerable'. For a species to be listed, an RFMO considered whether species were first present in its Convention area and overlapped with the fishery. Then a selection of species would be nominated for assessment to determine whether species were overfished or if overfishing was occurring. The presence of an assessment, as described earlier, was not always necessary before enacting protective policies for 'key' or 'vulnerable' species within RFMOs.
The Western and Central Pacific Fisheries Commission (tuna RFMO), however, created a process for evaluating "key species" nominations that were submitted to the Commission for assessment. In the document titled "Process for designating WCPFC key shark species for data provision and assessment" they noted that the four-step process was qualitative and was not providing criteria for nomination. Rather, it was a method to prioritize species nominations within the limitations of data and capacity of the Commission (Clarke and Harley 2010, WCPFC 2010a and 2010b).

Despite the lack of listing criteria, all RFMOs are required to uphold the precautionary approach outlined by the UN Fish Stocks Agreement, meaning that the absence of data is not a reason for halting conservation and management action. In several cases, conservation and management decisions were made in the absence of stock assessments, These included IATTC's no retention policy for Mobulids (Resolution C-15-04) and Oceanic Whitetip Sharks (Resolution C-11-10), GFCM's no retention policies for all chondrichthyans listed on Annex II of the Barcelona Convention's Specially Protected Areas and Biological Diversity (SPA/BD) Protocol (Recommendation GFCM/36/2012/3), and CCAMLR's ban on the targeting of 'sharks' (CCAMLR CM32-18 (2006)). I also found that protection was lacking for several Critically Endangered and Endangered species that overlapped with RFMO jurisdictions with potential to interact with the fisheries (Table S.1). Similarly, decisions to ban species retention within RFMOs were inconsistent. ICCAT's Recommendations detailing retention bans on Hammerhead Sharks noted rationale due to "sustainability concerns", yet similar sustainability concerns for Shortfin Mako (*Isurus oxyrinchus*) sharks did not warrant a retention ban. Further, despite

ICCAT's 2009 Report of the Standing Committee on Research and Statistics [66] that stated that there was "a non-negligible probability that the North Atlantic Shortfin Mako stock could be below the biomass that could support MSY" and then a decade later the 2019 Recommendation that stated that the stock was overfished and that overfishing was occurring, ICCAT members did not ban retention of Shortfin Mako Shark.

Text A1.2:

Was level of protection afforded by the policies consistent across interventions?

Although all RFMOs are bodies of the Food and Agriculture Organization, amongst the tuna RFMOs, protective policies aimed at managing chondrichthyans differed by name, prohibited activities and whether or not they were binding. Retention bans for the Oceanic Whitetip Shark were by a binding 'Conservation and Management Measure' in WCPFC, by a binding 'Resolution' in IOTC and IATTC, and by a binding 'Recommendation' in ICCAT. The WCPFC defined 'Conservation and Management Measures' as binding and 'Resolutions' as non-binding (Table S.2a-c). The WCPFC did not have 'Recommendations', but ICCAT's binding protective policies were 'Recommendations'. Conversely, the tuna RFMO IOTC used the broad term 'Conservation and Management Measures' to adopt specific regulation in the form of either 'Resolutions' (binding) or 'Recommendations' (non-binding), which contrasted with both the terminology and nature of both WCPFC and ICCAT, its bordering tuna RFMOs. However, IOTC's binding 'Resolutions' and non-binding 'Recommendations' mirrored the use of the terminology in the tuna RFMO IATTC. Similar inconsistencies existed within the non-tuna RFMOs. GFCM's 'Recommendations' were binding; CCAMLR did not have 'Recommendations' but binding 'Conservation Measures' and non-binding 'Resolutions'. The names of the policies and their definitions varied, causing inconsistencies for the nations fishing in more than one RFMO.

Amongst the RFMOs, in addition to the names of the policies themselves, levels of protection across policies varied between RFMOs and within individual RFMOs for different species. For example, *Lamna nasus* (Porbeagle Shark) received policy "protection" in five RFMOs (Table S.1). CCAMLR banned directed fishing (of all shark species) and required swift release of any hooked shark. CCSBT required adoption of regulations of its overlapping RFMO, ICCAT. ICCAT required release of live Porbeagles and had a data reporting mandate, but allowed dead sharks to be landed. NEAFC banned directed fishing and required swift releases of hooked Porbeagle Sharks, and also had a data reporting mandate. GFCM had the strongest protections for Porbeagles. It banned retention, transshipment, storing onboard, landing, and sale of the shark, whole or in part, and also required swift release and mandated data reporting. GFCM's overlapping RFMO, ICCAT, had the weakest protections for Porbeagles; it neither banned targeted fishing nor retention, but directed vessels to release live Porbeagles and to report data. IATTC, WCPFC and IOTC were the only RFMOs that banned retention of species in one gear type, but not another where the species was also incidentally caught. In WCPFC and IOTC, Whale Sharks (*Rhincodon typus*) were banned from retention on purse seine vessels, but not on longline vessels (Table S.2a). IATTC did not list Whale Sharks as no retention species. In the tuna RFMO IOTC, both *Alopias superciliosus* (Bigeye Thresher Shark), and *Carcharhinus longimanus* (Oceanic Whitetip Shark) are no retention species but the policy detail differed between the two species, with stronger policy protections for Bigeye Thresher Sharks. For Oceanic Whitetip Sharks, IOTC did not ban the sale of shark parts, nor did they mandate data reporting as they did for the Thresher Sharks, although the policy "encourages" data collection (Table S.1, S.2a). Additionally, IOTC permitted no exemptions for recreational or artisanal fishers to retain Bigeye Thresher Sharks, however it permitted exemptions for landing Oceanic Whitetip Sharks for recreational fishers that were fishing for consumption within their own EEZ (Table S.1, S.2a). India was also permitted an exemption by IOTC from the no retention policy for Oceanic Whitetip Sharks. ICCAT, however, permitted no exemptions for landing the Oceanic Whitetip, which was a no retention species in their policy. Conversely, it permitted an exemption for small-scale Mexican coastal fishers to retain Bigeye Thresher Sharks, highlighting the inconsistencies in species protections within "no retention" policies within a single RFMO.

IATTC, WCPFC and IOTC were the only RFMOs that banned retention of species in one gear type, but not another where the species was also incidentally caught. Silky Sharks (*Carcharhinus falciformis*) were banned from retention by IATTC on purse seine vessels, but retention that comprised up to 20% of the total catch was permitted on longline vessels. In WCPFC and IOTC, Whale Sharks (*Rhincodon typus*) were banned from retention on purse seine vessels, but not on longline vessels. IATTC did not list Whale Sharks as no retention species. WCPFC banned retention of Silky Sharks on both longline and purse seine vessels, but IOTC did not list Silky Sharks as no retention species.

Table A1.2: Species-Specific Protections for Chondrichthyans in RFMOs (a) Policy protections for species listed in 4 RFMOs. (b) Policy protections for species listed in 3 RFMOs. (c) Policy protections for species listed in 2 RFMOs**.**

(a) Policy protections for species listed in 4 RFMOs

Policy protections in 4 RFMOs

Species	RFMO	Policy Name	Policy Type	Bans Retention	Bans directed fishing	Bans Transshipment	Bans Storing Onboard	Bans landing	Bans sale	Specifies whole or in part of shark	Bans beheading and skinning	Bans Trade	Release unharmed and alive	Ban on fishing in pupping area	Data Reporting Mandate	Exemptions
A. superciliosus																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	CCSBT	Resolution ERS (2018)	Resolution	x*		x*	x*	x*	x*	x*			x*		x*	Dependent upon which RFMO vessel is fishing within (ICCAT rules in ICCAT, IOTC rules in IOTC)
	ICCAT	Rec. 09-07	Recommendation	x		x	x	x	x	x			x		x	Mexican small-scale coastal fishery with catch of <110 fish are exempt
	IOTC	Res. 12/09	Resolution	x		x	x	x	x	x			x		x	Research exemption upon approval on dead sharks.
M. mobular																
	CCSBT	Resolution ERS (2018)	Resolution	x	x	x	x	x	x	x		x	x		x	Subsistence fishers exempted that shall not be selling or offering for sale any part of mobulids

	GFCM	Recommendation GFCM/36/2012/3	Recommendation	x		x	x	x	x				x		x	
	IATTC	Resolution C-15-04	Resolution	x		x	x	x	x			x	x		x	Developing CPCs small-scale (<1.99 net tonnage) fisheries for domestic consumption are exempt Rays unintentionally frozen during purse seine operation must be surrendered to governmental authorities aat point of landing. They may not be sold or bartered (*this is no trade clause), but may be donated for purposes of domestic human consumption
	IOTC	Resolution 19/03	Resolution	x	x	x	x	x	x	x		x	x		x	Subsistence fishers exempted that shall not be selling or offering for sale any part of mobulids
R. typus																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	CCSBT	Resolution ERS (2018)	Resolution	x*	x*								x*		x*	n/a

	IOTC	Res. 13/05	Resolution	x°	x°								x°		x°	°Bans retention and directed fishing by purse seine vessels.
	WCPFC	CMM2012-04	CMM	x°	x°								x°		x°	°Bans retention and directed fishing by purse seine vessels.
S. lewini																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	CCSBT	Resolution ERS (2018)	Resolution	x*		x*	x*	x*	x*	x*					x*	n/a
	GFCM	Recommendation GFCM/36/2012/3	Recommendation	x		x	x	x	x				x		x	n/a
	ICCAT	Rec. 10-08	Recommendation	x		x	x	x	x	x					x	All *Sphyrnidae* except *Sphyrna tiburo*. If caught by developing coastal CPCs for local consumption, they are exempted, provided they submit Task I, if possible Task II data. They should not try to increase their catch of hammerheads. CPCs to take measures to ensure *Sphyrnidae* do no enter into trade.
S. microcephalus																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a

	NAFO	Conservation and Enforcement Measures (2019)	CEM	x°	x	x°				x°					x	°Retention and transshipment bans apply only to shark fins fully detached from carcass
	NEAFC	Recommendation 10:2017	Recommendation	x											x	From 01 Jan 2017 - 31 Dec 2019
	SEAFO	Recommendation 1/2008	Recommendation		x											From 2008 until further notice
S. mokarran																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	CCSBT	Resolution ERS (2018)	Resolution	x*		x*	x*	x*	x*	x*					x*	n/a
	GFCM	Recommendation GFCM/36/2012/3	Recommendation	x		x	x	x	x				x		x	n/a
	ICCAT	Rec. 10-08	Recommendation	x		x	x	x	x	x					x	Same as S. lewini
S. zygaena																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	CCSBT	Resolution ERS (2018)		x*		x*	x*	x*	x*	x*					x*	n/a
	GFCM	Recommendation GFCM/36/2012/3	Recommendation	x		x	x	x	x				x		x	n/a
	ICCAT	Rec. 10-08	Recommendation	x		x	x	x	x	x					x	Same as *S. lewini.*

x* means ban is in force dependent upon which overlapping RFMO Convention area (IOTC, ICCAT or WCPFC) the vessel is fishing within.

(b) Policy protections for species listed in 3 RFMOs

Policy protections in 3 RFMOs

Species	RFMO	Policy Name	Policy Type	Bans Retention	Bans Directed Fishing	Bans Transshipment	Bans Storing Onboard	Bans landing	Bans sale	Specifies whole or in part of shark	Bans beheading and skinning	Bans Trade	Release unharmed and alive	Ban on fishing in pupping area	Data Reporting Mandate	Exemptions
A. albisoma																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	NEAFC	Recommendation 10:2017	Recommendation		x										x	From 01 Jan 2017 - 31 Dec 2019
	SEAFO	Recommendation 1/2008	Recommendation		x											From 2008 until further notice
A. aphyodes																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	NEAFC	Recommendation 10:2017	Recommendation		x										x	From 01 Jan 2017 - 31 Dec 2019
	SEAFO	Recommendation 1/2008	Recommendation		x											From 2008 until further notice
A. fedorovi																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	NEAFC	Recommendation 10:2017	Recommendation		x										x	From 01 Jan 2017 - 31 Dec 2019
	SEAFO	Recommendation 1/2008	Recommendation		x											From 2008 until further notice

A. gibbosus																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	NEAFC	Recommendation 10:2017	Recommendation		x										x	From 01 Jan 2017 - 31 Dec 2019
	SEAFO	Recommendation 1/2008	Recommendation		x											From 2008 until further notice
A. herklotsi																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	NEAFC	Recommendation 10:2017	Recommendation		x										x	From 01 Jan 2017 - 31 Dec 2019
	SEAFO	Recommendation 1/2008	Recommendation		x											From 2008 until further notice
A. internatus																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	NEAFC	Recommendation 10:2017	Recommendation		x										x	From 01 Jan 2017 - 31 Dec 2019
	SEAFO	Recommendation 1/2008	Recommendation		x											From 2008 until further notice
A. investigatoris																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	NEAFC	Recommendation 10:2017	Recommendation		x										x	From 01 Jan 2017 - 31 Dec 2019
	SEAFO	Recommendation 1/2008	Recommendation		x											From 2008 until further notice
A. laurussonii																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	NEAFC	Recommendation 10:2017	Recommendation		x										x	From 01 Jan 2017 - 31 Dec 2019
	SEAFO	Recommendation 1/2008	Recommendation		x											From 2008 until further notice
A. macrorhynchus																

	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	NEAFC	Recommendation 10:2017	Recommendation		x										x	From 01 Jan 2017 - 31 Dec 2019
	SEAFO	Recommendation 1/2008	Recommendation		x											From 2008 until further notice
A. macrostomus																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	NEAFC	Recommendation 10:2017	Recommendation		x										x	From 01 Jan 2017 - 31 Dec 2019
	SEAFO	Recommendation 1/2008	Recommendation		x											From 2008 until further notice
A. melanoasper																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	NEAFC	Recommendation 10:2017	Recommendation		x										x	From 01 Jan 2017 - 31 Dec 2019
	SEAFO	Recommendation 1/2008	Recommendation		x											From 2008 until further notice
A. micropterygeus																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	NEAFC	Recommendation 10:2017	Recommendation		x										x	From 01 Jan 2017 - 31 Dec 2019
	SEAFO	Recommendation 1/2008	Recommendation		x											From 2008 until further notice
A. parvipinnis																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	NEAFC	Recommendation 10:2017	Recommendation		x										x	From 01 Jan 2017 - 31 Dec 2019
	SEAFO	Recommendation 1/2008	Recommendation		x											From 2008 until further notice
A. pinguis																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a

	NEAFC	Recommendation 10:2017	Recommendation		x										x	From 01 Jan 2017 - 31 Dec 2019
	SEAFO	Recommendation 1/2008	Recommendation		x											From 2008 until further notice
A. platyrhynchus																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	NEAFC	Recommendation 10:2017	Recommendation		x										x	From 01 Jan 2017 - 31 Dec 2019
	SEAFO	Recommendation 1/2008	Recommendation		x											From 2008 until further notice
A. profundorum																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	NEAFC	Recommendation 10:2017	Recommendation		x										x	From 01 Jan 2017 - 31 Dec 2019
	SEAFO	Recommendation 1/2008	Recommendation		x											From 2008 until further notice
A. stenseni																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	NEAFC	Recommendation 10:2017	Recommendation		x										x	From 01 Jan 2017 - 31 Dec 2019
	SEAFO	Recommendation 1/2008	Recommendation		x											From 2008 until further notice
A. pelagicus																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	CCSBT	Resolution ERS (2018)	Resolution	x*		x*	x*	x*	x*	x*			x*		x*	n/a
	IOTC	Res. 12/09	Resolution	x		x	x	x	x	x			x		x	Research exemption upon approval on dead sharks.
A.vulpinus																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a

	CCSBT	Resolution ERS (2018)	Resolution	x*		x*	x*	x*	x*	x*			x*		x*	n/a
	IOTC	Res. 12/09	Resolution	x		x	x	x	x	x			x		x	Research exemption upon approval on dead sharks.
C. maximus																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	GFCM	Recommendation GFCM/36/2012/3	Recommendation	x		x	x	x	x				x		x	
	NEAFC	Recommendation 08:2016	Recommendation		x											From 01 Jan 2016- 31 Dec 2019 (data collection urged, but not mandated)
I. oxyrinchus																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	GFCM	Recommendation GFCM/36/2012/3	Recommendation	x		x	x	x	x				x		x	
	ICCAT	17/08	Recommendation	x									x		x	North Atlantic Shortfin Mako only; vessels allowed to catch, retain on board, transship or land if: (1) vessel >12m + must have EMS and qualified observer onboard +shortfin mako must be dead when brought alongside vessel. (2) vessel <12m: shortfin mako must be dead when brought alongside vessel (3) if shortfin mako is dead + observer is onboard + if it doesn't exceed quota. (4) if shortfin mako is dead or alive + domestic laws require fork lengths

																≥180cm (males), ≥210cm (females). (5) if domestic law requires dead/dying sharks to be landed, but fisherman will not profit.
M. alfredi																
	CCSBT	Resolution ERS (2018)	Resolution	x	x	x	x	x	x	x		x	x		x	Subsistence fishers exempted that shall not be selling or offering for sale any part of mobulids

	IATTC	Resolution C-15-04	Resolution	x		x	x	x	x			x	x		x	Developing CPCs small-scale (<1.99 net tonnage) fisheries for domestic consumption are exempt Rays unintentionally frozen during purse seine operation must be surrendered to governmental authorities aat point of landing. They may not be sold or bartered (*this is no trade clause), but may be donated for purposes of domestic human consumption
	IOTC	Resolution 19/03	Resolution	x	x	x	x	x	x	x		x	x		x	Subsistence fishers exempted that shall not be selling or offering for sale any part of mobulids
M. birostris																
	CCSBT	Resolution ERS (2018)	Resolution	x	x	x	x	x	x	x		x	x		x	Same as *M. alfredi*
	IATTC	Resolution C-15-04	Resolution	x		x	x	x	x			x	x		x	Same as *M. alfredi*
	IOTC	Resolution 19/03	Resolution	x	x	x	x	x	x	x		x	x		x	Same as *M. alfredi*
M. eregoodootenkee																
	CCSBT	Resolution ERS (2018)	Resolution	x	x	x	x	x	x	x		x	x		x	Same as *M. alfredi*
	IATTC	Resolution C-15-04	Resolution	x		x	x	x	x			x	x		x	Same as *M. alfredi*
	IOTC	Resolution 19/03	Resolution	x	x	x	x	x	x	x		x	x		x	Same as *M. alfredi*
M. hypostoma																
	CCSBT	Resolution ERS (2018)	Resolution	x	x	x	x	x	x	x		x	x		x	Same as *M. alfredi*
	IATTC	Resolution C-15-04	Resolution	x		x	x	x	x			x	x		x	Same as *M. alfredi*
	IOTC	Resolution 19/03	Resolution	x	x	x	x	x	x	x		x	x		x	Same as *M. alfredi*

M. japanica																
	CCSBT	Resolution ERS (2018)	Resolution	x	x	x	x	x	x	x		x	x		x	Same as *M. alfredi*
	IATTC	Resolution C-15-04	Resolution	x		x	x	x	x			x	x		x	Same as *M. alfredi*
	IOTC	Resolution 19/03	Resolution	x	x	x	x	x	x	x		x	x		x	Same as *M. alfredi*
M. kuhlii																
	CCSBT	Resolution ERS (2018)	Resolution	x	x	x	x	x	x	x		x	x		x	Same as *M. alfredi*
	IATTC	Resolution C-15-04	Resolution	x		x	x	x	x			x	x		x	Same as *M. alfredi*
	IOTC	Resolution 19/03	Resolution	x	x	x	x	x	x	x		x	x		x	Same as *M. alfredi*
M. munkiana																
	CCSBT	Resolution ERS (2018)	Resolution	x	x	x	x	x	x	x		x	x		x	Same as *M. alfredi*
	IATTC	Resolution C-15-04	Resolution	x		x	x	x	x			x	x		x	Same as *M. alfredi*
	IOTC	Resolution 19/03	Resolution	x	x	x	x	x	x	x		x	x		x	Same as *M. alfredi*
M. rochebrunei																
	CCSBT	Resolution ERS (2018)	Resolution	x	x	x	x	x	x	x		x	x		x	Same as *M. alfredi*
	IATTC	Resolution C-15-04	Resolution	x		x	x	x	x			x	x		x	Same as *M. alfredi*
	IOTC	Resolution 19/03	Resolution	x	x	x	x	x	x	x		x	x		x	Same as *M. alfredi*
M. tarapacana																
	CCSBT	Resolution ERS (2018)	Resolution	x	x	x	x	x	x	x		x	x		x	Same as *M. alfredi*
	IATTC	Resolution C-15-04	Resolution	x		x	x	x	x			x	x		x	Same as *M. alfredi*
	IOTC	Resolution 19/03	Resolution	x	x	x	x	x	x	x		x	x		x	Same as *M. alfredi*
M. thurstoni																
	CCSBT	Resolution ERS (2018)	Resolution	x	x	x	x	x	x	x		x	x		x	Same as *M. alfredi*
	IATTC	Resolution C-15-04	Resolution	x		x	x	x	x			x	x		x	Same as *M. alfredi*
	IOTC	Resolution 19/03	Resolution	x	x	x	x	x	x	x		x	x		x	Same as *M. alfredi*

(c) Policy protections for species listed in 2 RFMOs

Policy protections in 2 RFMO

Species	RFMO	Policy Name	Policy Type	Bans Retention	Bans Directed Fishing	Bans Transshipment	Bans Storing Onboard	Bans landing	Bans sale	Specifies whole or in part of shark	Bans beheading and skinning	Bans Trade	Release unharmed and alive	Ban on fishing in pupping area	Data Reporting Mandate	Exemptions
C. anguineus																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	NEAFC	Recommendation 10:2017	Recommendation		x										x	From 01 Jan 2017 - 31 Dec 2019
C. carcharias																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	GFCM	Recommendation GFCM/36/2012/3	Recommendation	x		x	x	x	x				x		x	
C. coelolepsis																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	NEAFC	Recommendation 10:2017	Recommendation		x										x	From 01 Jan 2017 - 31 Dec 2019
C. crepidater																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	NEAFC	Recommendation 10:2017	Recommendation		x										x	From 01 Jan 2017 - 31 Dec

																2019
C. fabricii																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	NEAFC	Recommendation 10:2017	Recommendation		x										x	From 01 Jan 2017 - 31 Dec 2019
C. granulosus																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	NEAFC	Recommendation 10:2017	Recommendation		x										x	From 01 Jan 2017 - 31 Dec 2019
C. squamosus																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	NEAFC	Recommendation 10:2017	Recommendation		x										x	From 01 Jan 2017 - 31 Dec 2019
C. taurus																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	GFCM	Recommendation GFCM/36/2012/3	Recommendation	x		x	x	x	x				x		x	
D. calcea																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	NEAFC	Recommendation 10:2017	Recommendation		x										x	From 01 Jan 2017 - 31 Dec 2019
D. licha																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	NEAFC	Recommendation 10:2017	Recommendation		x										x	From 01 Jan 2017 - 31 Dec 2019
E. blochii																

	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	ICCAT	Rec. 10-08	Recommendation	x		x	x	x	x	x					x	Same as *S. lewini.*
E. princeps																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	NEAFC	Recommendation 10:2017	Recommendation		x										x	From 01 Jan 2017 - 31 Dec 2019
E. spinax																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	NEAFC	Recommendation 10:2017	Recommendation		x										x	From 01 Jan 2017 - 31 Dec 2019
G. galeus																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	GFCM	Recommendation GFCM/36/2012/3	Recommendation	x		x	x	x	x				x		x	n/a
G. melastomus																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	NEAFC	Recommendation 10:2017	Recommendation		x										x	From 01 Jan 2017 - 31 Dec 2019
G. murinus																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	NEAFC	Recommendation 10:2017	Recommendation		x										x	From 01 Jan 2017 - 31 Dec 2019
H. griseus																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	NEAFC	Recommendation 10:2017	Recommendation		x										x	From 01 Jan 2017 - 31 Dec

																2019
O. centrina																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	GFCM	Recommendation GFCM/36/2012/3	Recommendation	x		x	x	x	x				x		x	n/a
O. ferox																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	GFCM	Recommendation GFCM/36/2012/3	Recommendation	x		x	x	x	x				x		x	n/a
O. paradoxus																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	NEAFC	Recommendation 10:2017	Recommendation		x										x	From 01 Jan 2017 - 31 Dec 2019
S. acanthias																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	NEAFC	Recommendation 08:2019	Recommendation	x	x								x		x	For 2019 and 2020
S. aculeata																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	GFCM	Recommendation GFCM/36/2012/3	Recommendation	x		x	x	x	x				x		x	n/a
S. corona																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a

	ICCAT	Rec. 10-08	Recommendation	x		x	x	x	x	x					x	All *Sphyrnidae* except *Sphyrna tiburo*. If caught by developing coastal CPCs for local consumption, they are exempted, provided they submit Task I, if possible Task II data. They should not try to increase their catch of hammerheads. CPCs to take measures to ensure *Sphyrnidae* do no enter into trade.
S. gilberti																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	ICCAT	Rec. 10-08	Recommendation	x		x	x	x	x	x					x	Same as *S. corona.*
S. oculata																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	GFCM	Recommendation GFCM/36/2012/3	Recommendation	x		x	x	x	x				x		x	n/a
S. media																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a

	ICCAT	Rec. 10-08	Recommendation	x		x	x	x	x	x					x	Same as *S. corona.*
S. ringens																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	NEAFC	Recommendation 10:2017	Recommendation		x										x	From 01 Jan 2017 - 31 Dec 2019
S. squatina																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	GFCM	Recommendation GFCM/36/2012/3	Recommendation	x		x	x	x	x				x		x	n/a
S. tudes																
	CCAMLR	CMM 32-18 (2006)	CMM		x								x			n/a
	ICCAT	Rec. 10-08	Recommendation	x		x	x	x	x	x					x	Same as *S. corona.*

Text A1.3:

Were species listed on binding or non-binding policies and was policy language prescriptive for what governments and fishers were bound to do?

Convention on the Conservation of Migratory Species of Wild Animals (CMS and CMS Sharks MOU): Despite language for CMS Appendix I-listed species, which stated that countries "shall prohibit take" of those species, they were not legally bound to do so, thereby limiting recourse for countries that failed to implement. For species listed on both CMS Appendix II and the CMS Sharks MOU, countries were directed to work together to design conservation plans that, when implemented, limited mortality and rebuilt species stocks. However, the non-binding policies had no legal recourse for any countries that did not implement the suggestions of CMS or the CMS Sharks MOU.

United Nations Convention on the Law of the Sea (UNCLOS): For species listed on UNCLOS Annex I of Highly Migratory Species, similar to CMS and the CMS Sharks MOU, states were directed to work together through bilateral agreements or through regional organizations to "conserve and promote optimum utilization"; and to ensure that harvested species "are not in danger of overexploitation." UNCLOS is a binding policy. It planned a review of the Convention every five years, with Annexes reviewed every 15 years. Importantly, there were no standards outlined for how states should work together, or any measures of success or penalties attached to non-compliance for UNCLOS for the species listed on Annex I.

Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES): The binding CITES Appendices I and II were clear and prescriptive on what states were bound to do. Definitions for species, specimens and trade were clear. Reporting requirements were clear and permit requirements were clear and time-bound. For species listed on Appendix I, international trade was prohibited, with exceptions. Import and export permits were required, but were to be withheld if the species were harvested illegally or "detrimental to the survival of the species", which was not quantitatively defined. For Appendix II-listed species, no import permit was required. Export permit requirements were the same for Appendix I-listed species. Parties were directed to confiscate specimens that were harvested illegally, with after-care instructions provided in the policy, and to penalize for illegal trade. However, there were no specific compliance mechanisms or penalties for non-compliance outlined on CITES. Similar to the other multilateral environment agreements, CITES required states to implement national legislation that reflected the CITES Appendix listings, with national compliance mechanisms.

Regional Fisheries Management Organizations (RFMOs): A few binding RFMO chondrichthyan-specific policies were prescriptive about gear types, banned activities, had clear definitions for vessels and species included, stipulated data reporting requirements, and were time-bound, e.g. IOTC's no retention mobulid policy (Res. 19/03), IATTC's Silky Shark policy (Res C-19-05), GFCM's no retention sharks policy (GFCM 36_2012_3). However, many lacked detail about what countries and vessels were bound to implement.

CCAMLR banned directed fishing of sharks within the Convention area, but no definition was included for which species or family constituted 'sharks', meaning it was unclear whether rays, skates or chimaeras were included under the shark fishing ban. NAFO banned directed fishing for the Greenland Shark (*Somniosus microcephalus)*, which directed countries to make "all reasonable efforts" to minimize catch and mortality of the species, but without any specific ways to ban directed fishing or to minimize mortality, whether by gear, time-area closures or safe handling release guidelines. Similarly, ICCAT's binding recommendation for Porbeagle Sharks (Rec.15-06) called for release of live animals, but had no prescriptive language or reference to any document describing how to do this in a manner that causes little harm to the animal. IOTC's Mobulid policy was the only policy to specify safe release guidelines for any listed species. WCPFC's Oceanic Whitetip (*Carcharhinus longimanus*) no retention policy (CMM 2011-04) was time-bound, but did not outline data reporting requirements, whereas ICCAT's Hammerhead Shark no retention policy (Rec. 10-08) described data reporting requirements, but was not time-bound. While resolutions existed within RFMOs and their basic texts that called on the roles of compliance committees to review implementation of the policies, no specific reference was made by any RFMO in any chondrichthyan-specific binding protective measure to define the compliance process of either the Commission or member states, or describe the process and any associated penalties for non-compliance.

Appendix 2: Chapter 3 Supplementary materials

Table A2.1: Ranges of oceanographic variables per reef. GBR = Great Barrier Reef

Reef	Site	Location	Min annual SST	Mean min month SST	Mean annual Chl-a	Mean month Chl-a
Tutuila North	Tutuila Island	American Samoa	28.49454	28.92459	162.5665	162.0708
Tutuila North	Tutuila Island	American Samoa	28.49454	28.92459	162.5665	162.0708
Rib Reef	Central GBR	Australia-Pacific	26.3672	26.19982	504.9978	509.0939
Helix Reef	Central GBR	Australia-Pacific	26.31099	28.42792	475.1298	407.6745
Knife Reef	Central GBR	Australia-Pacific	26.47281	28.36673	28.36673	332.717
Chicken Reef	Central GBR	Australia-Pacific	26.41798	28.73283	379.0812	321.0434
Balls Pyramid	Lord Howe Island	Australia-Pacific	20.78104	22.22849	499.454	380.352
Balls Pyramid South	Lord Howe Island	Australia-Pacific	20.78104	22.22849	499.454	380.352
Lord Howe Island	Lord Howe Island	Australia-Pacific	20.89688	22.29782	492.1559	375.291
Lord Howe Island South East	Lord Howe Island	Australia-Pacific	20.89688	22.29782	492.1559	375.291
13-124	Northern GBR 1	Australia-Pacific	26.26264	26.78516	816.4566	697.3419
Corbett Reef	Northern GBR 1	Australia-Pacific	26.25665	26.78516	722.6382	620.2949
Lagoon Reef	Northern GBR 2	Australia-Pacific	26.49478	26.71808	536.8868	507.6137
Mantis Reef	Northern GBR 2	Australia-Pacific	26.50494	26.71808	452.4279	423.8224
Orpheus Green Zone	Orpheus Island	Australia-Pacific	25.74231	26.86508	952.477	1083.077

Orpheus Yellow Zone	Orpheus Island	Australia-Pacific	25.74231	26.86508	952.477	1083.077
Heron/Wistari Reef Green Zone	Southern GBR	Australia-Pacific	23.83919	24.60887	689.445	637.0575
Heron/Wistari Reef Yellow Zone	Southern GBR	Australia-Pacific	23.83919	24.60887	689.445	637.0575
Aitutaki	Aitutaki	Cook Islands	27.07801	27.24298	106.3067	105.8534
North Lagoon	Penrhyn	Cook Islands	28.73567	29.05104	211.7362	186.009
Omoka	Penrhyn	Cook Islands	28.73567	29.05104	211.7362	186.009
Rarotonga	Rarotonga	Cook Islands	25.77023	28.09131	112.6468	75.11054
Chuuk Barrier Reef	Chuuk	Federated States of Micronesia	29.49622	29.58366	143.273	140.1684
Chuuk Lagoon	Chuuk	Federated States of Micronesia	29.49622	29.58366	143.273	140.1684
Ant Atoll	Pohnpei	Federated States of Micronesia	29.48032	29.4087	148.8513	151.0676
Pohnpei West	Pohnpei	Federated States of Micronesia	29.43612	29.39716	143.1784	143.8427
Kiobo	Kubulau	Fiji	27.24912	25.45447	457.8064	426.9865
Kiobo Tabu	Kubulau	Fiji	26.90340	26.02908	463.2588	455.3086
Navatu	Kubulau	Fiji	27.24912	25.45447	457.8064	426.9865
Namena	Kubulau	Fiji	27.01405	26.7908	517.7197	540.1329
Namuri Reserve	Kubulau	Fiji	26.90340	26.4037	26.4037	408.0827
Namena Open	Kubulau	Fiji	27.01405	26.7908	517.7197	540.1329

Namuri and Nasau	Kubulau	Fiji	27.01405	26.7908	517.7197	540.1329
Nasue Reserve	Kubulau	Fiji	27.01405	26.7908	517.7197	540.1329
Fiji East	Ovalau	Fiji	26.85489	26.37393	413.176	376.9536
Sybil Rock and Lighthouse	Savusavu	Fiji	27.12113	26.95679	527.7648	585.3739
Amanu 1	Amanu	French Polynesia	27.24462	26.42047	111.6626	122.4479
Apataki1	Apataki	French Polynesia	27.92911	28.31025	159.2588	144.5082
Mangareva 1	Mangareva	French Polynesia	24.88366	23.52565	104.6193	103.1677
Mangareva 2	Mangareva	French Polynesia	24.88366	23.52565	104.6193	103.1677
Maupiti1	Maupiti	French Polynesia	28.14217	28.14217	131.0016	131.0016
Maupiti2	Maupiti	French Polynesia	28.14217	28.14217	131.0016	131.0016
Moorea1	Moorea	French Polynesia	27.52572	27.52572	159.2662	159.2662
Moorea2	Moorea	French Polynesia	27.52572	27.52572	159.2662	159.2662
Moorea3	Moorea	French Polynesia	27.61278	27.99	170.2348	172.197
Nuku Hiva 1	Nuka Hiva	French Polynesia	27.98968	27.10663	350.1772	369.9424
Nuku Hiva 2	Nuka Hiva	French Polynesia	27.98968	27.10663	350.1772	369.9424
Raiatea1	Raiatea	French Polynesia	27.82519	28.19146	143.8709	148.8391
Raiatea2	Raiatea	French Polynesia	27.82519	28.19146	143.8709	148.8391

Rangiroa1	Rangiroa	French Polynesia	27.98461	28.34333	136.3548	113.5276
Rangiroa2	Rangiroa	French Polynesia	27.98461	28.34333	136.3548	113.5276
Rurutu 2	Rurutu	French Polynesia	25.35143	23.65887	135.0929	159.9004
Tahiti1	Tahiti	French Polynesia	27.42751	27.42751	156.1975	156.1975
Tahiti2	Tahiti	French Polynesia	27.37865	27.37865	157.5937	157.5937
Tahiti3	Tahiti	French Polynesia	27.53659	27.87634	166.5193	167.0102
Takapoto1	Takapoto	French Polynesia	28.13489	28.54299	137.8128	111.5446
Takaroa 1	Takaroa	French Polynesia	28.13258	28.55220	142.1463	114.4072
Takaroa 2	Takaroa	French Polynesia	28.13258	27.40431	142.1463	182.0999
Tetiaroa1	Tetiaroa	French Polynesia	27.7628	28.10463	160.1512	159.8494
Tetiaroa2	Tetiaroa	French Polynesia	27.7628	28.10463	160.1512	159.8494
Tikehau 1	Tikehau	French Polynesia	28.05828	28.44533	146.4081	126.7031
Tubuai1	Tubuai	French Polynesia	24.95344	25.68981	143.0676	128.9418
Tubuai2	Tubuai	French Polynesia	24.88846	25.64333	142.552	127.8987
Uapou 1	Uapou	French Polynesia	28.05578	27.19788	367.5088	388.8511
Uapou 2	Uapou	French Polynesia	28.05578	27.19788	367.5088	388.8511
Agana	Guam	Guam	28.52261	28.4831	117.9399	120.8792

Galvez Bank	Guam	Guam	28.55376	28.52044	118.1762	121.4338
Guam South	Guam	Guam	28.52261	28.4831	117.9399	120.8792
Haputo	Guam	Guam	28.52261	28.4831	117.9399	120.8792
Pagat	Guam	Guam	28.52261	28.4831	117.9399	120.8792
Pati	Guam	Guam	28.52261	28.4831	117.9399	120.8792
Tarague	Guam	Guam	28.52261	28.4831	117.9399	120.8792
Tumon	Guam	Guam	28.52261	28.4831	117.9399	120.8792
Reef 1	Kiritimati	Kiribati	27.00375	28.16428	363.5705	338.8891
Reef 2	Kiritimati	Kiribati	27.00375	28.16428	363.5705	338.8891
Grand Astrolabe	New Caledonia	New Caledonia	26.32347	24.85861	258.0844	320.0813
Matthew Island	New Caledonia	New Caledonia	25.03363	23.9818	269.3417	319.8697
Petit Astrolabe	New Caledonia	New Caledonia	26.3012	24.80984	269.4959	331.2019
Southern Horn East	New Caledonia	New Caledonia	24.37877	23.17349	429.9163	479.9711
Walpole Island	New Caledonia	New Caledonia	25.15194	24.86618	281.2107	323.8563
Raoul Island	Kermedec North	New Zealand	21.05918	18.34193	372.5908	646.9284
Macauley Island	Kermedec South	New Zealand	20.37224	17.82281	408.6779	679.9366
Beveridge Reef	Beveridge Reef	Niue	25.88427	25.68411	138.5409	120.6864

Niue	Niue	Niue	25.88427	25.68411	138.5409	120.6864
Palau East	Koror State	Palau	29.13325	30.44968	209.2874	210.1136
Palau West	Koror State	Palau	29.13325	30.44968	209.2874	210.1136
Kayangel	Palau North	Palau	29.11717	29.93747	213.3417	210.9541
Ngaruangel	Palau North	Palau	29.12233	29.93747	216.4793	214.6113
Milne Bay Lagoon	Conflict Islands	Papua New Guinea	27.62931	26.30894	375.289	332.8353
Outer Milne Bay	Conflict Islands	Papua New Guinea	27.62931	26.30894	375.289	332.8353
Kapalaman	Kavieng	Papua New Guinea	30.06233	29.92488	252.6628	220.3839
Tsoi Islands	Kavieng	Papua New Guinea	30.06698	29.89233	260.8088	222.604
Hoskins Lagoon	Kimbe Bay	Papua New Guinea	30.04914	29.84219	314.8088	327.6487
Restoff Island	Kimbe Bay	Papua New Guinea	30.04028	29.83995	324.9298	346.7262
Aleipata	Upolu	Samoa	28.8196	27.71887	142.381	137.5761
Falealili	Upolu	Samoa	28.8196	27.71887	142.381	137.5761
Gizo Open	Gizo Area	Solomon Islands	28.62996	27.27014	352.267	401.8414
Zaira Open	Zaira Area	Solomon Islands	28.55741	27.21713	325.1987	376.9774
Zaira Protected	Zaira Area	Solomon Islands	28.56925	27.21713	335.2056	405.8698
North Minerva	Minerva Reef	Tonga	24.06681	22.35196	254.0198	320.2226

French Frigate Shoals	French Frigate Shoals	USA-Pacific	25.4893	28.21564	215.7805	151.9683
Kona Airport	Hawaii	USA-Pacific	25.48477	24.99149	199.9636	201.806
Kealakekua Bay	Hawaii	USA-Pacific	25.48477	24.99149	199.9636	201.806
Jarvis Reef	Jarvis Island	USA-Pacific	27.34814	28.02762	395.8326	360.486
Lanai South	Lanai	USA-Pacific	24.07104	23.86502	263.1526	264.9869
Litsianski Island	Litsianski Island	USA-Pacific	24.29043	25.99086	272.0454	235.0293
Maui West	Maui	USA-Pacific	24.09437	23.87215	251.5633	253.9834
Midway Atoll	Midway Atoll	USA-Pacific	23.12635	27.13672	258.5821	151.5577
Molokai	Molokai	USA-Pacific	24.05803	23.84665	255.0966	258.5356
Oahu	Oahu	USA-Pacific	24.16738	23.93618	246.861	249.7784
Pearl and Hermes Atoll	Pearl and Hermes Atoll	USA-Pacific	23.01606	25.2306	285.5587	228.6048
East Luganville	Espiritu Santo	Vanuatu	27.79508	26.57072	195.4985	168.918
Vuti	Espiritu Santo	Vanuatu	27.79508	26.57072	195.4985	168.918
Emao / Coast	Nguna	Vanuatu	27.11396	26.08241	265.8542	208.3155
Nguna / Pele	Nguna	Vanuatu	27.12995	26.07426	269.971	214.7355

Table A2.2: Variance Inflation Factor tables for (a) Total elasmobranchs (b) Species-level.

(a) Total Elasmobranchs

Total Elasmobranchs: (all variables)
Gravity + Relief+ Depth + min_month_sst + mean_month_chl + Hard Coral + Consolidated + Unconsolidated + Macroalgae+ Soft Coral

Gravity	**Relief**	**Depth**	**SST (min month)**	**Chl (mean month)**	**Hard Coral**	**Soft Coral**	**Macro-algae**	**Consolid-ated**	**Unconsol-idated**
1.033	3.299	1.139	1.277	1.433	20.370	1.822	4.195	17.910	13.155

Total Elasmobranchs: (removed consolidated and unconsolidated)
Gravity + Relief+ Depth + min_month_sst + mean_month_chl + Hard Coral + Macroalgae+ Soft Coral

Gravity	**Relief**	**Depth**	**SST (min month)**	**Chl (mean month)**	**Hard Coral**	**Soft Coral**	**Macro-algae**
1.033	1.904	1.137	1.221	1.424	1.825	1.051	1.052

(b) Species-level

Species-level: (all variables)
Gravity + Relief+ Depth + min_month_sst + mean_month_chl + Hard Coral + Consolidated + Unconsolidated + Macroalgae+ Soft Coral

Gravity	**Relief**	**Depth**	**SST (min month)**	**Chl (mean month)**	**Hard Coral**	**Soft Coral**	**Macro-algae**	**Consolid-ated**	**Unconsol-idated**
1.033	3.301	1.141	1.279	1.432	20.433	1.822	4.196	17.936	13.159

Species-level: (removed consolidated and unconsolidated)
Gravity + Relief+ Depth + min_month_sst + mean_month_chl + Hard Coral + Macroalgae+ Soft Coral

Gravity	**Relief**	**Depth**	**SST (min month)**	**Chl (mean month)**	**Hard Coral**	**Soft Coral**	**Macro-algae**
1.032	1.907	1.139	1.222	1.4242	1.828	1.051	1.052

Table A2.3: Model selection using Aikaike Information Criterion (AICc) for (A) Total elasmobranchs (B) Grey Reef Sharks (C) Blacktip Reef Sharks (D) Whitetip Reef Sharks

(A) Model selection for Total elasmobranchs (all sharks and rays). In b-e, SST = minimum monthly sea surface temperature; chl = mean monthly primary productivity; HC = hard coral habitat; MA = macroalgae habitat; SC = soft coral habitat. (a) Null model. (b) Zero inflated negative binomial model with “location” as a fixed effect. SST and chl scaled in base R. (c). Zero inflated negative binomial model with “location” as a fixed effect. SST and chl scaled in base R. “sanctuary” removed as variable. (d) Zero inflated negative binomial model with “location” as a random effect. SST and chl scaled in base R. “sanctuary” added as variable. (e) Zero inflated negative binomial model with “location” removed. SST scaled by location; chl scaled in base R. (f) Zero inflated negative binomial model with “location” removed. SST and chl scaled by location.

Model	Df	AICc
(a) Null	5	11412.13
(b) glmmTMB(abundance~location + reef type + sanctuary + scale(log(gravity)) + scale(SST) + scale(log(chl)) + scale(depth) + scale(relief) + scale(HC) + scale(MA) + scale(SC) + (1| site/reef), data=pacbruvs, family = ‘nbinom2’, ziformula = ~1)	32	10996.63
(c) glmmTMB(abundance~location + reef type + scale(log(gravity)) + scale(SST) + scale(log(chl)) + scale(depth) + scale(relief) + scale(HC) + scale(MA) + scale(SC) + (1|site/reef), data=pacbruvs, family = ‘nbinom2’, ziformula = ~1)	31	10994.60
(d) glmmTMB(abundance~ reef type + sanctuary + scale(log(gravity)) + scale(SST) + scale(log(chl)) + scale(depth) + scale(relief) + scale(HC) + scale(MA) + scale(SC) + (1|location/site/reef), data=pacbruvs, family = ‘nbinom2’, ziformula = ~1)	16	10990.49
(e) glmmTMB(abundance~ reef type + sanctuary + scale(log(gravity)) + s(SST) + scale(log(chl)) + scale(depth) + scale(relief) + scale(HC) + scale(MA) + scale(SC) + (1|site/reef), data=pacbruvs, family = ‘nbinom2’, ziformula = ~1)	**15**	**10256.05**
(f) glmmTMB(abundance~ reef type + sanctuary + scale(log(gravity)) + s(SST) + s(log(chl)) + scale(depth) + scale(relief) + scale(HC) + scale(MA) + scale(SC) + (1|site/reef), data=pacbruvs, family = ‘nbinom2’, ziformula = ~1)	16	10256.70

(B) Model selection for *Carcharhinus amblyrhynchos*. In b-g, SST = minimum monthly sea surface temperature; chl = mean monthly primary productivity; HC = hard coral habitat; MA = macroalgae habitat; SC = soft coral habitat. (a) Null model. (b) Poisson model. (b) Poisson model with SST and chl scaled in base R using scale() function. (c) Poisson model with SST and chl scaled by location. (d) Poisson model with SST and chl scaled by location, zero inflated. (e) Negative binomial model with SST and chl scaled by location. (f) Negative binomial model with SST and chl scaled by location, zero inflated.

Model	Df	AICc
(a) Null	4	6191.842
(b) glmmTMB(Abundance~reef type + sanctuary + scale(depth) + scale(log(gravity)) + scale(relief) + scale(SST) + scale(log(chl)) + scale(HC) + scale(MA) + scale(SC) + (1|site/reef), family = Poisson)	13	6241.050
(c) glmmTMB(Abundance~reef type + sanctuary + scale(depth) + scale(log(gravity)) + scale(relief) + s(SST) + s(log(chl)) + scale(HC) + scale(MA) + scale(SC) + (1|site/reef), family = Poisson)	13	5944.737
(d) glmmTMB(Abundance~reef type + sanctuary + scale(depth) + scale(log(gravity)) + scale(relief) + s(SST) + s(log(chl)) + scale(HC) + scale(MA) + scale(SC) + (1|site/reef), family = Poisson, ziformula = ~1)	14	5881.714
(e) glmmTMB(Abundance~reef type + sanctuary + scale(depth) + scale(log(gravity)) + scale(relief) + s(SST) + s(log(chl)) + scale(HC) + scale(MA) + scale(SC) + (1|site/reef), family = nbinom2)	**14**	**5685.823**
(f) Abundance~reef type + sanctuary + scale(depth) + scale(log(gravity)) + scale(relief) + s(SST) + s(log(chl)) + scale(HC) + scale(MA) + scale(SC) + (1|site/reef), family = nbinom2, ziformula = ~1	15	5687.841

(C) Model selection for *Carcharhinus melanopterus*. In b-f, SST = minimum monthly sea surface temperature; chl = mean monthly primary productivity; HC = hard coral habitat; MA = macroalgae habitat; SC = soft coral habitat. (a) Null model, Poisson. (b) Poisson model. (b) Poisson model with SST and chl scaled in base R using scale() function. (c) Poisson model with SST and chl scaled by location. (d) Poisson model with SST and chl scaled by location, zero inflated. (e) Negative binomial model with SST and chl scaled by location. (f) Negative binomial model with SST and chl scaled by location, zero inflated.

Model	Df	AICc
(a) Null	3	5157.033
(b) glmmTMB(Abundance~reef type + sanctuary + scale(depth) + scale(log(gravity)) + scale(relief) + scale(SST) + scale(log(chl)) + scale(HC) + scale(MA) + scale(SC) + (1|site/reef), family = Poisson)	13	4976.622
(c) glmmTMB(Abundance~reef type + sanctuary + scale(depth) + scale(log(gravity)) + scale(relief) + s(SST) + s(log(chl)) + scale(HC) + scale(MA) + scale(SC) + (1|site/reef), family = Poisson)	**13**	**4570.678**
(d) glmmTMB(Abundance~reef type + sanctuary + scale(depth) + scale(log(gravity) + scale(relief) + s(SST) + s(log(chl)) + scale(HC) + scale(MA) + scale(SC) + (1|site/reef), family = Poisson, ziformula = ~1 blacktip3)	14	4572.695
(e) glmmTMB(Abundance~reef type + sanctuary + scale(depth) + scale(log(gravity) + scale(relief) + s(SST) + s(log(chl)) + scale(HC) + scale(MA) + scale(SC) + (1|site/reef), family = nbinom2)	14	NA
(f) glmmTMB(Abundance~reef type + sanctuary + scale(depth) + scale(log(gravity) + scale(relief) + s(SST) + s(log(chl)) + scale(HC) + scale(MA) + scale(SC) + (1|site/reef), family = nbinom2, ziformula = ~1)	15	NA

(D) Model selection for *Triaenodon obesus*. In b-f, SST = minimum monthly sea surface temperature; chl = mean monthly primary productivity; HC = hard coral habitat; MA = macroalgae habitat; SC = soft coral habitat. (a) Null model, Poisson. (b) Poisson model. (b) Poisson model with SST and chl scaled in base R using scale() function. (c) Poisson model with SST and chl scaled by location. (d) Poisson model with SST and chl scaled by location, zero inflated. (e) Negative binomial model with SST and chl scaled by location. (f) Negative binomial model with SST and chl scaled by location, zero inflated.

Model	Df	AICc
(a) Null	3	3854.315
(b) glmmTMB(Abundance~reef type + sanctuary + scale(depth) + scale(log(gravity)) + scale(relief) + scale(SST) + scale(log(chl)) + scale(HC) + scale(MA) + scale(SC) + (1|site/reef), family = Poisson)	13	3607.914
(c) glmmTMB(Abundance~reef type + sanctuary + scale(depth) + scale(log(gravity)) + scale(relief) + s(SST) + s(log(chl)) + scale(HC) + scale(MA) + scale(SC) + (1|site/reef), family = Poisson)	**13**	**3424.910**
(d) glmmTMB(Abundance~reef type + sanctuary + scale(depth) + scale(log(gravity)) + scale(relief) + s(SST) + s(log(chl)) + scale(HC) + scale(MA) + scale(SC) + (1|site/reef), family = Poisson, ziformula = ~1)	14	3426.927
(e) glmmTMB(Abundance~reef type + sanctuary + scale(depth) + scale(log(gravity)) + scale(relief) + s(SST) + s(log(chl)) + scale(HC) + scale(MA) + scale(SC) + (1|site/reef), family = nbinom2)	14	3426.927
(f) glmmTMB(Abundance~reef type + sanctuary + scale(depth) + scale(log(gravity)) + scale(relief) + s(SST) + s(log(chl)) + scale(HC) + scale(MA) + scale(SC) + (1|site/reef), family = nbinom2, ziformula = ~1)	15	NA

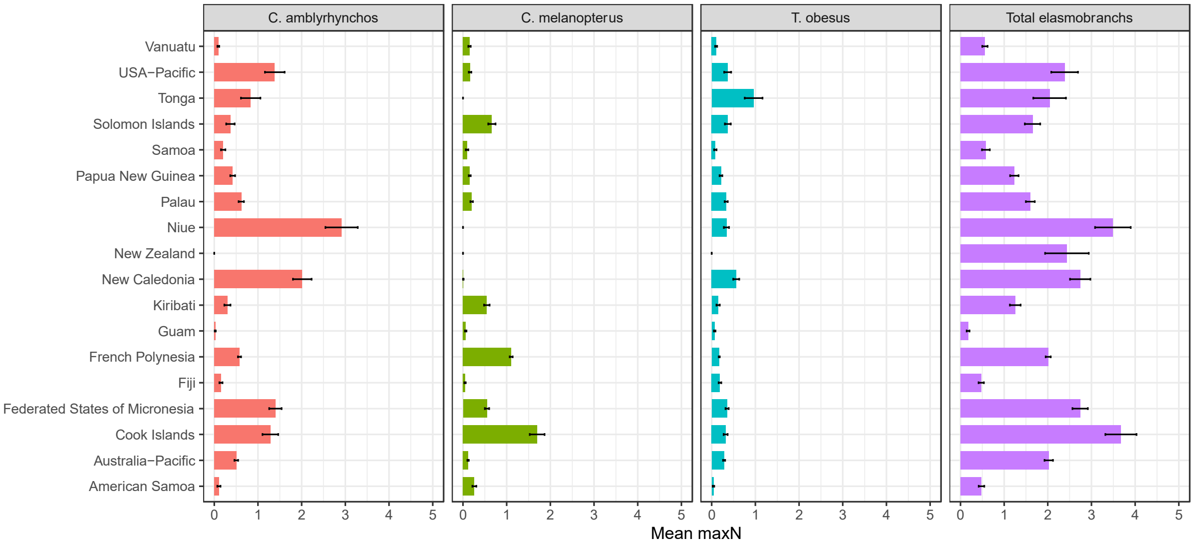


Figure A2.1: Mean (+/- SE) maxN by nation including the top three species, *Carcharhinus amblyrhynchos*, *Carcharhinus melanopterus*, *Triaenodon obesus* and Total elasmobranchs.

Appendix 3: Chapter 4 Supplementary materials

Figure A3.1: Total number of sharks recorded (individuals) by species and gear (2009-2018): (a) longline logbook; (b) longline observer, and; (c) Purse seine observer.

(a) Total sharks (individuals) recorded in longline logbooks.

Species	Total # sharks recorded
Blue Shark	23654
Sharks (Unidentified)	5870
Oceanic Whitetip Shark	5608
Silky Shark	1852
Mako Sharks	565
Thresher Sharks	247
Porbeagle Shark	112
Hammerhead Sharks	73
Basking shark	11
Pelagic Thresher Shark	11
Blacktip Reef Shark	5
Mackerel Sharks Porbeagle	1

(b) Total sharks (individuals) recorded by longline observers.

Species	Total # sharks recorded
Blue Shark	1179
Silky Shark	649
Oceanic Whitetip Shark	253
Shortfin Mako Shark	196
Longfin Mako Shark	127
Bigeye Thresher Shark	102
Sharks (Unidentified)	26
Pelagic Thresher Shark	16
Bronze Whaler Shark	11
Blacktip Reef shark	7
Mako Sharks	3
Sandbar Shark	3
Bignose Shark	2
Blacktip Shark	2
Great White Shark	2
Grey Reef Shark	2
Silvertip Shark	2
Velvet Dogfish	2

(c) Total sharks (individuals) recorded by purse seine observers.

Species	Total # sharks recorded
Silky Shark	5524
Oceanic Whitetip Shark	61
Blue Shark	8
Whale Shark	5
Silvertip Shark	5
Pelagic Thresher Shark	3
Tiger Shark	2
Bronze Whaler Shark	2
Blacktip Reef Shark	2
Bigeye Thresher Shark	2
Smooth Hammerhead Shark	1
Great Hammerhead Shark	1
Basking Shark	1
Sharks (Unidentified)	0

Appendix 4: Chapter 5 Supplementary materials

Table A4.1: Summarised daily depth and temperature data collected and transmitted by satellite tags were within 12 bins.

Depth bins (m)	Temperature bins (˚C)
0 – 10	< 10
10 – 20	10 – 12
20 – 40	12 – 14
40 – 60	14 – 16
60 – 80	16 – 18
80 – 100	18 – 20
100 – 150	20 – 22
150 – 200	22 – 24
200 – 400	24 – 26
400 – 800	26 – 28
800 – 1000	28 – 30
1000 – 2000	> 30

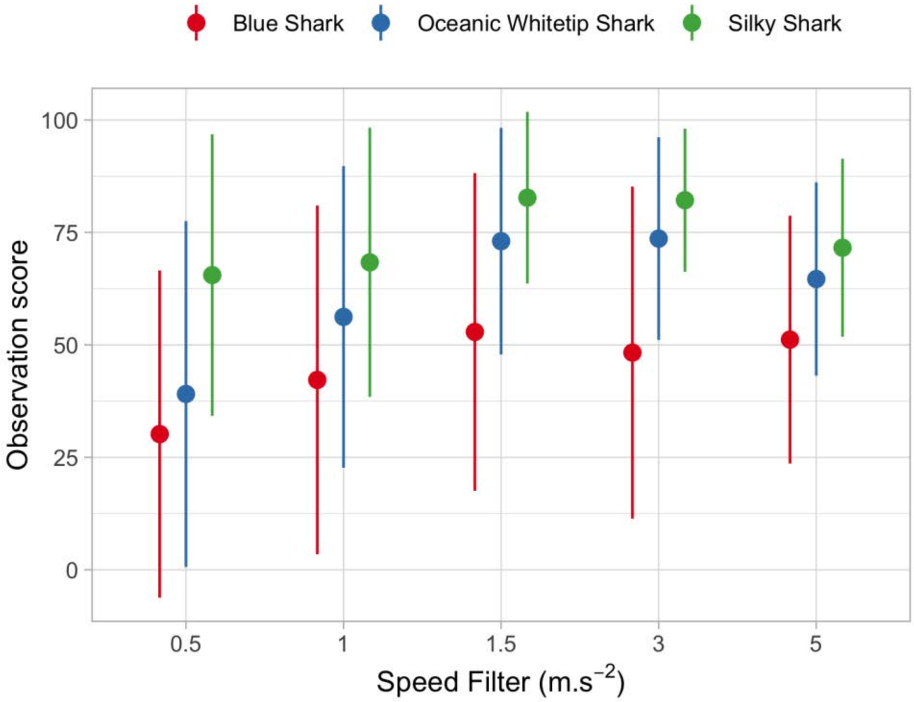


Figure A4.1: Effect of speed filter selection on observation quality score used to assess optimal specifications for track estimation using the GPE3 algorithm.

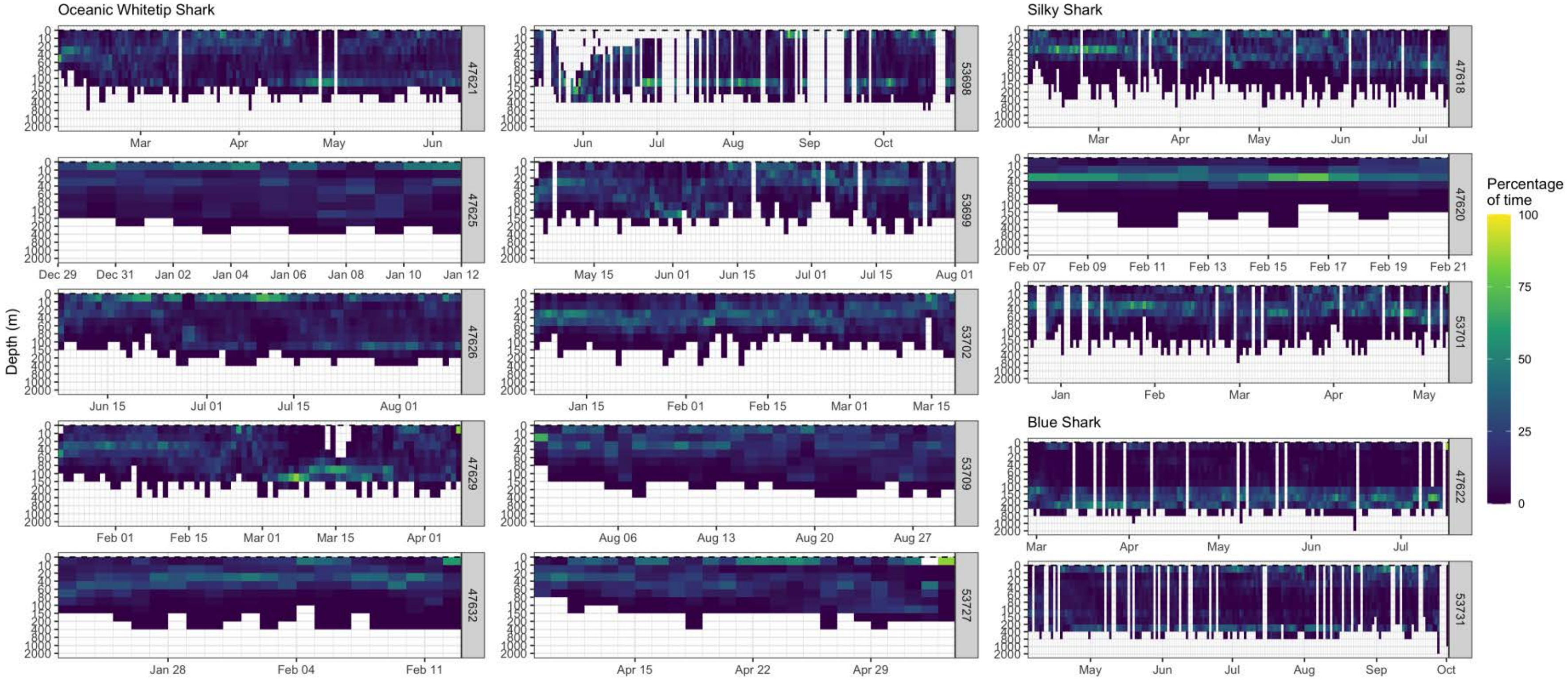


Figure A4.2: Depth profiles (binned) for individual tagged sharks.

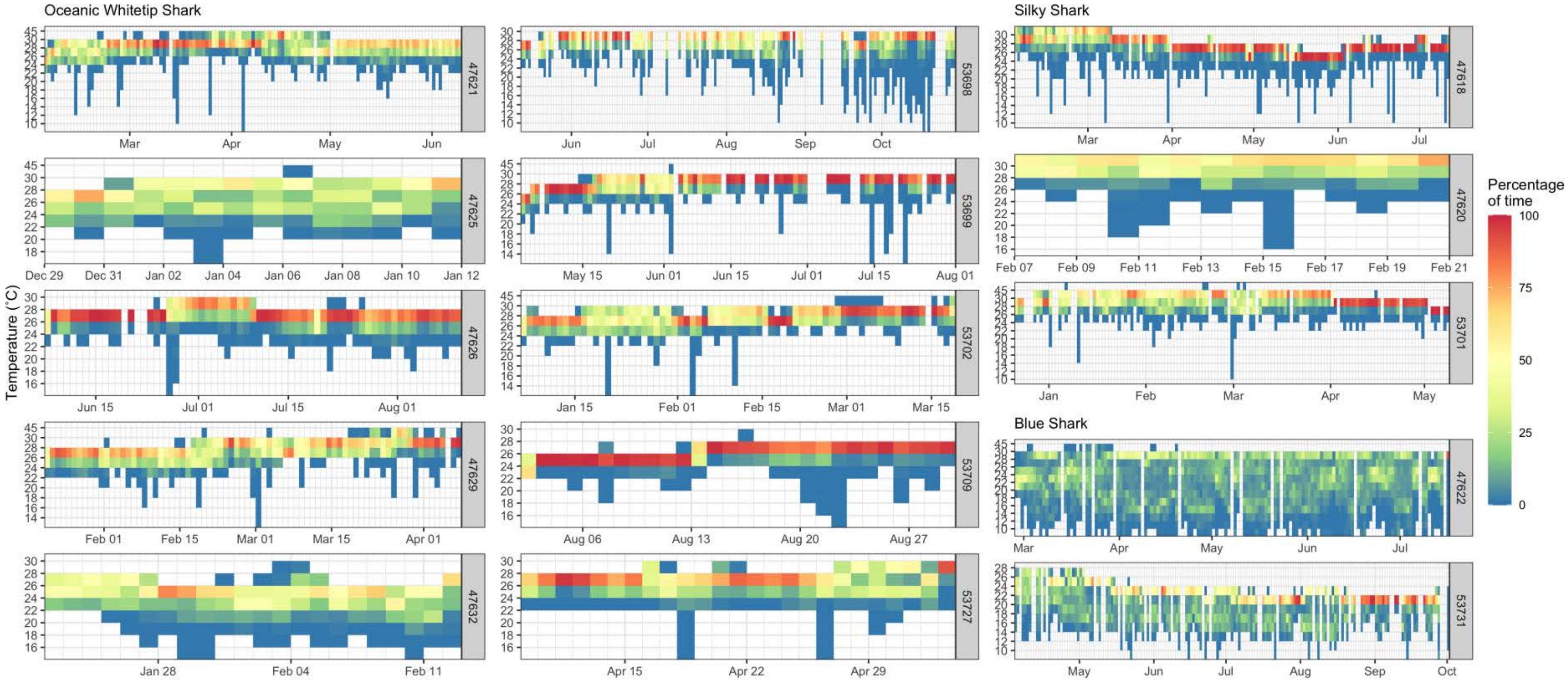


Figure A4.3: Temperature profiles (binned) for individual tagged sharks.

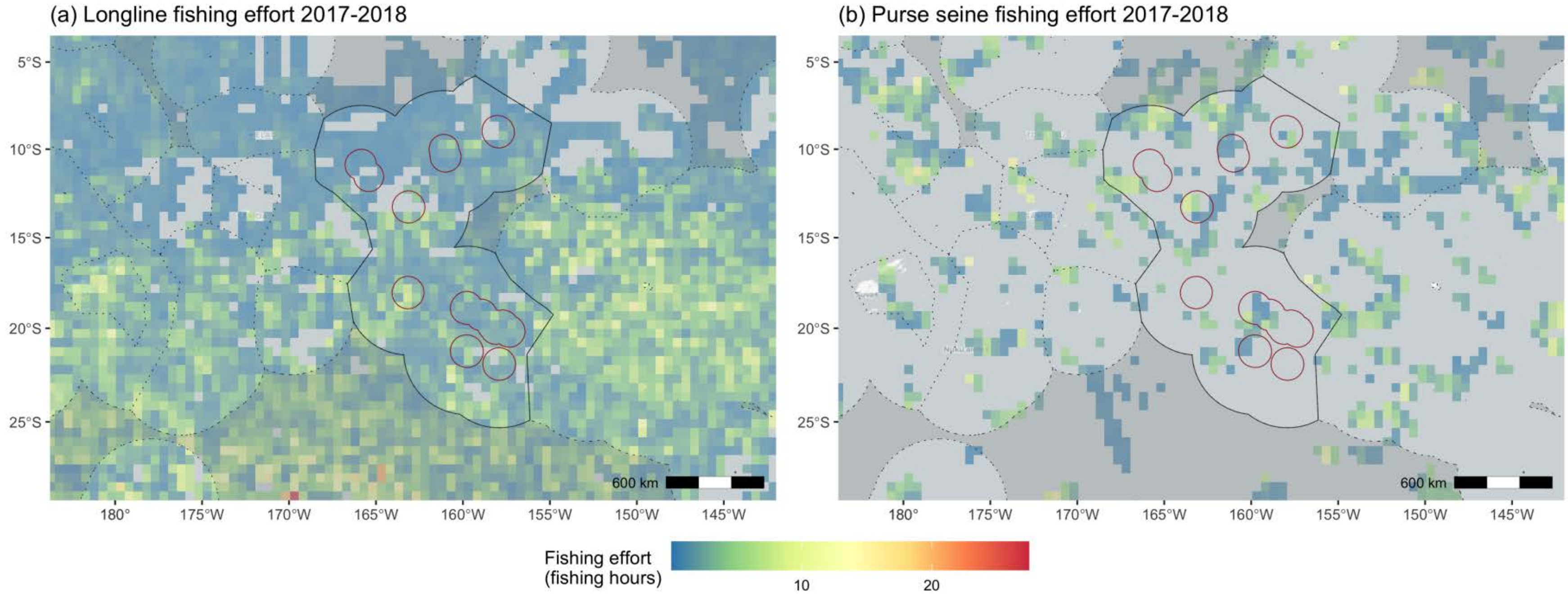
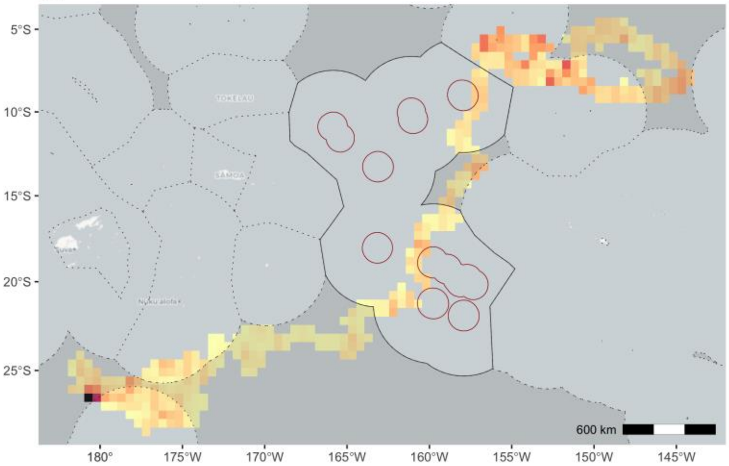
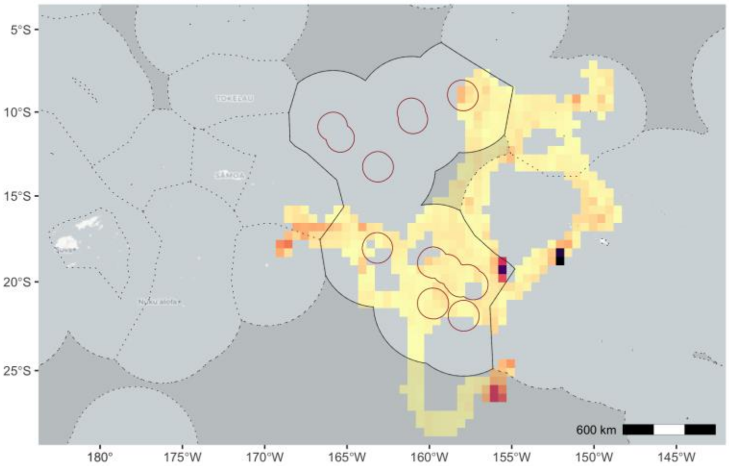


Figure A4.4: Fishing effort (hours) in 0.5˚ x 0.5˚ cells using Global Fishing Watch data in the study area. Black border indicates Cook Islands EEZ. Red circles indicate 50 nm zones around each island in the Cook Islands. Dashed lines indicate neighboring EEZs. High seas areas are shaded in grey. a) Longline fishing effort 2017-2018. b) Purse seine fishing effort 2017-2018.

(a) Blue Shark



(b) Oceanic Whitetip Shark



(c) Silky Shark

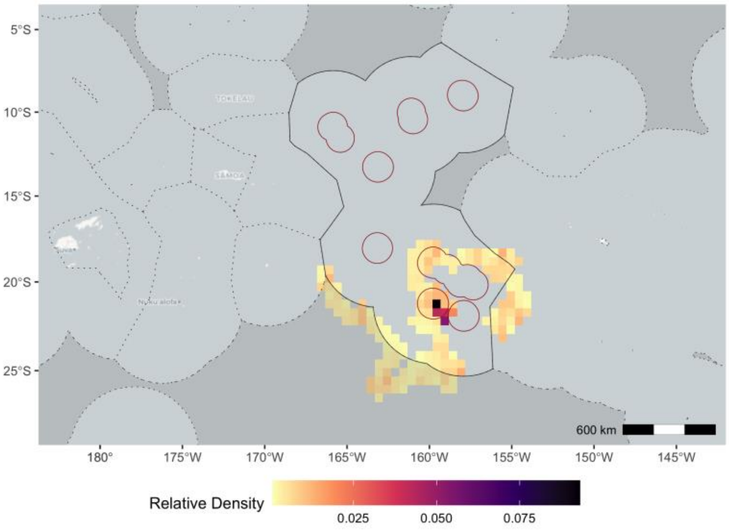


Figure A4.5: Spatial overlap of shark movements and fishing effort that co-occurred in 0.5˚ x 0.5˚ cells. a) Blue Sharks. b) Oceanic Whitetip Sharks. c) Silky Sharks.