Socio-ecological indicators for sustainable management of global marine biodiversity conservation using sharks as a model species

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Submitted for the degree of Doctor of Philosophy

November 2021

Abstract

Global biodiversity is disappearing at an unprecedented rate; sharks are currently among the most threatened vertebrate groups with widespread overexploitation leaving 31% of all species at risk of extinction. Since 2009, 17 coastal nations have adopted a precautionary approach banning all commercial shark fishing. However, evaluating effectiveness of these 'shark sanctuaries' is impeded by a lack of robust data. Evidence-based conservation urgently requires data against which socio-ecological change can be measured to assess efficacy of policy and management interventions. This thesis takes an interdisciplinary approach to advance understanding of the complexities of shark conservation within one of the world's principal shark sanctuaries - the Maldives. Historical abundance trends derived from fisher Local Ecological Knowledge (LEK, 87 interviews) showed substantial declines in shark population abundance (>65%) and distribution (>60%) between 1970-2019. Validation of contemporary spatial LEK using Baited Remote Underwater Videos (BRUVs, 50 hours of footage) highlighted the potential of LEK to provide fine-scale distribution data for shark populations in data poor regions. Analysis of BRUVs (464 hours of footage) and citizen science data (2,024 dives) over a 5-year period (2016-2020) revealed historical population declines have now been halted and suggests species abundances are stable following sanctuary implementation. However, positive correlations between prey and reef shark abundance raises uncertainty over the long-term efficacy of sanctuaries, which still permit exploitation of prey species. Interviews with fishers (n = 103) identified correlations between fisher characteristics, perceptions, and support for the Maldives shark sanctuary. Findings identified several management actions that could increase support: increasing stakeholder participation and representation (voice to capture local knowledge); mitigation of the costs associated with fisher-shark interactions and increasing transparency in management decision making. The potential severity and inequity in livelihood costs associated with shark sanctuaries was also highlighted revealing that small-scale reef fishers were disproportionally impacted compared to pelagic tuna fishers. This thesis highlights the importance of integrating human and ecological dimensions into shark conservation to tailor measures more likely to be effective in specific contexts and suggests that low support for sanctuary regulations, fisher-shark conflict and overexploitation of reef resources, could hinder long-term population recovery. Findings outline rapid, cost-effective approaches towards generating priority data to provide a basis for evidence-based management that will help define future efforts to enhance shark conservation in the context of achieving the UN Sustainable Development Goal (SDG) 14.

Acknowledgements

Over the past three years and throughout my PhD, I have received substantial support and assistance from many people, without whom this project would not have been possible. I would like to start by thanking my supervisor's Dr Steve Newman, Prof. Selina Stead, Prof. Mark Whittingham and Dr Richard Francksen who have provided guidance and feedback throughout. I have always looked forward to our meetings and chats whether that be in person or via zoom. Specifically, I would like to thank Steve and Selina for creating the initial research questions and finding the time and energy to help obtain funding. Mark and Richard for the unique terrestrial perspective and insight which always made for interesting discussion.

Newcastle University's Institute for Sustainability funded the PhD and I am grateful for being given the amazing opportunity to carry out this project. This thesis was the result of a collaborative research project between Newcastle University, Banyan Tree Marine Lab and Banyan Tree Global Foundation, without whom this project would not have been possible. I am also grateful to the Maldives Ministry of Fisheries and Agriculture for granting research permits which allowed this work to proceed.

Fieldwork has been a highlight of my PhD thanks to the brilliant team in the Maldives including Ali Nasheed, Mohamed Arzan, Nikk Mohamed, Hassan Nishan, Samantha Gallimore, Charlie Everitt, Nick Hardman and Naff Asim. I am also grateful to the rest of the Angsana and Banyan Tree staff for their support and assistance during my many months in the field.

I have been very lucky to have considerable support from friends both within my field and outside of it. I thank Megan Self, Jemma Black, Emma Brownbridge, Carolina D'Angelo and Nadia Alsagoff for always listening and trying to understand my work. I am also grateful for my peers who provided invaluable chats to discuss research ideas and statistics including Christina Skinner, Max Kelly, Georgina Hunt, Ellen Barrowclift and Mike Zhu and for the many laughs we shared in our office. I thank my mam for always supporting my dream to become a marine biologist and my brother Ryan and his partner Jordan for listening to me practise my many presentations. I also thank my great aunt and uncle Jill and Derek for their support throughout.

Declaration

Data collected to document fisher spatial LEK using participatory mapping exercises (Chapter 2) built on a preliminary study conducted by Jack Marley in 2016 for his MSc thesis.

Annual collection of Baited Remote Underwater Videos (BRUVs) reported in Chapter 3 was a collaborative effort. Specifically, Kirsty Ballard collected and analysed BRUVs as part of her MSc project in 2016 and Dr Christina Skinner in 2017 during her PhD: Elucidating coral reef predator trophodynamics across an oceanic atoll, Newcastle University PhD thesis. All other BRUVs were collected and analysed by Danielle Robinson.

In Chapter 4, flow rate models were provided by Rasheed Shuaib and Yves Plancherel from Imperial College London.

Chapter 6 is currently in review at Conservation letters: Robinson, D., Newman, S.P., Whittingham, M.J., Francksen, R.M., Adam, M.S., and Stead, S.M. (2022) Fisher-shark interactions: a loss of support for the Maldives shark sanctuary from reef fishers whose livelihoods are affected by shark depredation.

All other work was done by Danielle Robinson with support and guidance from my supervisors.

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List of acronyms

AIC	Akaike Information Criterion
BRUVs	Baited Remote Underwater Videos
CBD	Convention on Biological Diversity
DF	Degrees of Freedom
EDF	Estimated Degrees of Freedom
EEZ	Exclusive Economic Zone
FAD	Fish Aggregation Device
GAM	Generalised Additive Model
GIS	Geographic Information's System
GLM	Generalised Linear Model
GLMM	Generalised Linear Mixed Model
GDP	Gross Domestic Product
HL	Handline
HWC	Human-Wildlife Conflict
ICCAT	International Commission for the Conservation of Atlantic Tunas
IUCN	International Union for the Conservation of Nature
IPOA	International Plan of Action
LDA	Latent Dirichlet Allocation
LEK	Local Ecological Knowledge
LPI	Living Planet Index
MoFA	Ministry of Fisheries and Agriculture
MPA	Marine Protected Area
NPOA	National Plan of Action
PA	Protected Area
PL	Pole-and-line
RMFOs	Regional Fisheries Management Organisations
SDGs	Sustainable Development Goals
SBS	Shifting Baseline Syndrome
SEM	Structural Equation Model
SSFs	Small Scale Fisheries
ToFA	Time of First Arrival
USA	United States of America
UNCLOS	United Nations Convention on the Law of the Sea
VIF	Variance Inflation Factor
WWF	World Wildlife Fund

Thesis overview

The following section represents a broad overview of this thesis including background and rationale for the project. A detailed review of the literature is presented in Chapter 1.

Background and rationale

Human impacts on natural ecosystems are significant and indisputable. The pressures of overexploitation, habitat loss, pollution and climate change are intensifying (Geldmann *et al.*, 2014; Maxwell *et al.*, 2016; Raven and Wagner, 2021) and biodiversity is disappearing at an unprecedented rate (Kindsvater *et al.*, 2018; IPBES, 2019). Globally more than 26,000 species are threatened with extinction, equating to 27% of assessed species (IUCN, 2021), and data from the 2020 Living Planet Index (LPI) shows an average 68% decline in monitored populations (20,811 populations of 4,392 species) between 1970 and 2016 (WWF, 2020). Reversing biodiversity declines is not only important from an intrinsic perspective on the value of species persistence, but also broadly for the provision of key ecosystem services upon which humanity relies (Williams *et al.*, 2021) and is central to the United Nations 2030 agenda (UN, 2015). Continued loss of biodiversity threatens to undermine the achievement of most of the United Nations Sustainable Development Goals (SDGs) including poverty alleviation and food and security (WWF, 2020).

Extinction threat to living genera is strongly associated with body size (Payne *et al.*, 2016) with elevated threats to large-bodied species, particularly predator populations. Over the past few decades, predator populations have been depleted throughout the worlds ecosystems due to a combination of anthropogenic stressors such as habitat degradation and overexploitation (Maxwell *et al.*, 2016; Roff *et al.*, 2018). Predatory fish biomass is estimated to have declined by two-thirds over the last 100 years (Christensen *et al.*, 2014), while declines of large mammalian carnivores is a major environmental concern (Estes *et al.*, 2011). Occupying the highest position in food webs, predators exert significant influence on the structure and function of associated ecosystems (Tickler *et al.*, 2017). Studies of predator prey interaction have shown that the removal of apex predators results in cascading changes in both animal and plant community composition (Beschta and Ripple, 2010; Levi and Wilmers, 2012). These trophic cascades have been documented in all of the world’s major biomes from the tropics to the poles in terrestrial and marine systems (Estes *et al.*, 2011).

In marine environments sharks are important predators, they connect food webs, habitats and ecosystems greatly influencing energy transfer at large spatial scales (Dulvy *et al.*, 2017). However, sharks are one of the world's most threatened species groups with 32.1% (167/ 536) of shark species at risk of extinction (Dulvy *et al.*, 2014; Dulvy *et al.*, 2021). Their k-selected life history traits and vulnerability to capture make them highly susceptible to overfishing and substantial population declines have been reported globally (Dulvy *et al.*, 2008; Roff *et al.*, 2018; Pacoureau *et al.*, 2021). The threat of overfishing is disproportionately high for populations in tropical and subtropical waters and risks loss of key ecosystem functions and services upon which millions of coastal communities are highly dependent (Dulvy *et al.*, 2021).

There is an urgent need for improved fisheries management to reduce the large-scale exploitation of shark populations (Gallagher and Hammerschlag, 2011; Dulvy *et al.*, 2014; Jaiteh *et al.*, 2016; Dulvy *et al.*, 2021). However, management efforts to improve the sustainability of shark fisheries in the tropics, remain hindered by a lack of biological data and species-specific landing statistics to assess population trends (Clarke *et al.*, 2018). In the absence of such data, 17 coastal nations have adopted the precautionary approach instigating vast shark fishing bans within their Exclusive Economic Zones (EEZ). These 'shark sanctuaries' typically prohibit the possession, sale or trade of shark parts, with some limited exceptions for artisanal catch (Ward-Paige, 2017). The vast majority (88%) of shark sanctuary area is in the tropical Pacific, covering a total of 13,742,401 km^2 including the Republic of Palau, the Marshall Islands, French Polynesia, the Cook Islands, New Caledonia, and the Federated States of Micronesia. The Caribbean has the second largest sanctuary area including Honduras, the Bahamas and the British Virgin Islands, covering 951,807 km^2. The Indian Ocean has one shark sanctuary in the Republic of Maldives (hereafter the Maldives), covering a total of 916,011 km^2 (Pew, 2018).

Combined shark sanctuaries now cover >3% of the ocean (Ward-Paige, 2017), however, the efficacy of this approach has been widely criticised (Davidson, 2012; Chapman *et al.*, 2021) and impacts on shark biodiversity and associated livelihoods remains unclear (Mizrahi *et al.*, 2019). Notwithstanding recent global assessments of relative shark abundance (MacNeil *et al.*, 2020) and decline (Ward-Paige and Worm, 2017) within protected and unprotected regions, both of which show that shark sanctuaries could be a valuable conservation tool for sharks, there is an urgent need to evaluate shark sanctuary impact at local levels (MacKeracher *et al.*, 2018). Well defined goals are considered crucial for conservation success (Techera, 2019), yet sanctuary regulations for all 17 countries lack detail regarding program goals and guidelines for evaluation (Ward-Paige, 2017). Higher resolution data on shark abundance, habitat requirements and spatial distribution is needed to direct priority conservation needs and enhance the benefits of both existing and future shark conservation (Espinoza *et al.*, 2014; Acuña-Marrero *et al.*, 2018). However, many developing coastal nations, where the majority of shark sanctuaries have been enacted, lack the financial and technical capacity for science and monitoring (Exeter *et al.*, 2021). Novel and cost-effective approaches to monitor shark populations are therefore required (Espinoza *et al.*, 2020). Evaluations of sanctuary efficacy also require an understanding of historical population trajectories, however this is challenging in the absence of baseline data (Ward-Paige, 2017). Triangulation of data from a range of sources, including fishers Local Ecological Knowledge (LEK) (Almojil, 2021; Leduc *et al.*, 2021), citizen science (Vianna *et al.*, 2014; Ward-Paige *et al.*, 2018; Giovos *et al.*, 2019) and non-invasive scientific surveys (Rizzari *et al.*, 2014a; Murray *et al.*, 2019) could be a valuable approach to build a comprehensive understanding of both contemporary and past populations in data depauperate regions.

While ecological indicators (abundance, distribution etc.), are mainly used to determine effectiveness of a fishery management measure such as blanket-bans, successful implementation relies on understanding fisher perceptions and behaviour to influence positive compliance of rules (Peterson and Stead, 2011). Understanding the perceptions of those directly impacted by conservation policies is also important for the long-term sustainability of conservation efforts (Bennett, 2016) and can provide insights to guide future planning by identifying lessons learnt. However, socio-economic factors are rarely incorporated into shark conservation strategies (Booth *et al.*, 2019) and understanding of the complex human dimensions of shark sanctuaries remains limited (MacKeracher *et al.*, 2018; Collins *et al.*, 2020b).

The Maldives

The Maldives archipelago is located to the south-west of the Indian subcontinent and ranges over approximately 1000 km from north to south and 150 km from east to west (Rasheed *et al.*, 2021a). Twenty-six geographic atolls form the archipelago (Stevens and Froman, 2019) each ranging in size from a few kilometres to tens of kilometres. Lying within an exclusive economic zone (EEZ) of 916,000 km^2 the atolls encompass more than 1200 islands and thousands of individual reefs. The country is almost entirely dependent on marine resources with more than 99% of its area covered by ocean and is widely recognised as a marine ecological hotspot (Stevens and Froman, 2019). Forming part of the world's most extensive atoll formation and the seventh largest reef system in the world, the Maldives contains over 3% of the world's coral reefs (Stevens and Froman, 2019) and is home to 40 species of shark (Ali and Sinan, 2015).

Seventy-one percent of the Maldives population rely on the ocean for their primary source of income (Dixon, 2021). Fisheries and tourism, both fundamentally dependent on the health of marine resources, are the country's main economic sectors accounting for 35% of GDP and almost all foreign exchange earnings (WorldBank, 2021). While the relative importance of the fisheries sector has declined since the late 1970s, due to the rapid growth of tourism, its role in Maldivian economy remains significant. The fisheries sector employs 20% of the population with about 22,000 individuals involved in fishing activities full-time (MEE, 2016). Comparatively, tourism employs ~59% of the population (155,600 jobs) and accounts for 30% of gross domestic product (GDP) (Stevens and Froman, 2019).

Shark fishing in the Maldives

Shark fishing was carried out in the Maldives for centuries if not millennia, but was historically of relatively little importance (Anderson and Ahmed, 1993). Traditionally, sharks were sourced for oil to paint Maldivian fishing boats (dhoni), with fisheries primarily targeting tiger sharks (Sinan *et al.*, 2011). In the 1970s, widespread motorisation of fishing vessels and trade developments led to the diversification of the shark fishery and the emphasis shifted from shark liver oil to shark fin for export (Anderson and Ahmed, 1993). Demand for high-value shark liver oil greatly increased in the 1980s, when Japanese buyers visited the Maldives looking for supplies. A small multi-hook handline fishery soon developed targeting deepwater gulper sharks (*Centrophorus* spp.) to meet demand (Sinan *et al.*, 2011). By the late 1980s, there were three main shark fisheries: 1) a gulper shark fishery which peaked in 1982-84 and effectively collapsed due to overfishing in the early 1990s, 2) a reef shark fishery using gillnets, handline and longline and 3) a pelagic shark fishery which used longline and handline. Fins and meat from both the reef and pelagic shark fisheries were produced for export (Anderson and Ahmed, 1993).

Shark fisheries management

Since 1981 the Ministry of Fisheries and Agriculture (MoFA) has introduced various shark fishery management measures (Table 1). These measures were implemented in response to concerns about over-exploitation of shark stocks and to address conflicts between the shark fishery and other stakeholder groups (Ali and Sinan, 2014). A major conflict of interest which influenced early management decisions was conflict between oceanic shark fishers and the tuna fishery. Fishers noted close relationships between tuna schools and sharks, particularly silky sharks and most believe that harvesting of sharks has a large negative impact on tuna availability (Anderson and Ahmed, 1993). The second conflict was between shark fishers and the tourism sector. In 1992 it was estimated that divers spent US$2.3 million to dive/ snorkel with sharks in the Maldives; in contrast export of shark products was valued at US$0.7 million in the same year (Anderson and Ahmed, 1993). The economic importance of shark dive tourism was of key importance in the introduction of increasingly strict and wide-ranging restrictions on shark fishing, leading up to the Maldives becoming the world's second nation to implement a complete ban in 2010 (Sinan *et al.*, 2011).

Table 1. Timeline of developments in shark fisheries management in the Maldives. Adapted from (Sinan *et al.*, 2011).

Date	Measure	Policy document
10 Nov 1981	Shark fishing prohibited during daytime in tuna fishing areas.	Ministry of Fisheries Iu'laan 48/81/34/MF
19 May 1992	Shark fishing with livebait prohibited in vicinity of tuna schools while other vessels are present and fishing for tunas.	Ministry of Fisheries and Agriculture Iu'laan 16/92/29FA.A1
05 Jun 1995	Declaration of first Marine Protected Areas (15 dive sites, nine of which were well-known for their reef sharks).	Ministry of Planning, Human Resources and Environment Iu'laan E/95/32
24 Jun 1995	Ban on fishing for whale sharks.	MOFA Iu'laan FA-A1/29/95/39
08 Oct 1996	Ban on taking sharks or any type of fishing that might be detrimental to pole and line tuna fishing within 3 miles radius of any Fish Aggregation Device (FAD).	MOFA Iu'laan FAA1/29/96/39
28 Nov 1996	Longlining banned in vicinity of seamount between Hadhdhunmathi and Huvadhoo Atolls.	MOFA Iu'laan FA-A1/29/96/43
10 Dec 1997	Longlining banned in vicinity of seamount south of Addu Atoll.	MOFA Iu'laan FA-A1/29/96/54
8 Sep 1998	10-year moratorium on shark fishing within 12 nautical miles of seven (tourism zone) atolls.	MOFA Iu'laan FA-A1/29/98/39
1 Mar 2009	Ban on shark fishing within 12 nautical miles of any atoll.	MOFA Iu'laan FAD/29/2009/20
11 Mar 2010	Ban on shark fishing throughout Maldives from 15th March 2010.	MOFA Iu'laan 30-D2/29/2010/32
21 Jul 2011	Ban on capture, keeping, trade or harming sharks.	Ministry of Housing and Environment Iu'laan138/1/2011/42

Of the seventeen countries which have declared their EEZ shark sanctuaries, the Maldives had the highest shark catch per square kilometre between 1950 and 2010 and the third highest total shark catch (Pauly and Zeller 2015). A key difference between shark sanctuary policies is that exemptions to a total ban on all shark fishing are in effect in five countries allowing small-scale and artisanal catch (Palau, Marshall Islands, British Virgin Islands, Kiribati, Samoa). Like many other island nations in the tropics, the current status of shark populations in the Maldives in unclear. Moreover, the lack of biological and ecological data, unreliable (or virtually non-existent) landings data and limited understanding of the social acceptability of the shark sanctuary impedes evaluation of this conservation approach. In 2015 the Maldives adopted a National Plan of Action for the conservation and management of sharks (NPOA-sharks) following guidance outlined in the FAOs International Plan of Action for sharks (IPOA-sharks). The NPOA outlines 10 key objectives and actions including a need to; i) assess threats to shark populations, ii) determine and protect critical habitats and iii) carry out a socio-economic study of the impact of the ban on fishers (Ali and Sinan, 2015).

Thesis outline

Despite the proliferation of shark sanctuaries many have been implemented in the absence of, or paucity of baseline data. Similarly, evaluation of shark sanctuary efficacy is a gap in current knowledge. With many shark populations in decline there is an urgent need to implement effective management and protection measures that capture the inherent complexity of global shark fisheries. The interdisciplinary research described herein develops valuable baselines of data for shark abundance and distribution and fisher perceptions of sanctuary impact in the Maldives, providing and consolidating essential evidence for the foundation of future long-term monitoring. The findings contribute towards our understanding of the efficacy of shark sanctuaries, while also identifying future research needs and opportunities.

The overall aims of this research were to:

1) Quantify spatiotemporal patterns in shark distribution and abundance to establish a scientifically robust shark population baseline.
2) Disentangle complex relationships between shark population abundance and marine biodiversity in a changing environment to guide current and future management and policy of elasmobranchs.
3) Increase understanding of fisher perceptions of and support for the Maldives shark sanctuary.

Chapter one applied a topic modelling approach to review trends in shark conservation research between 1990 and 2020. A key term search of the literature ('shark' and 'conservation' and/ or 'management') resulted in a total of 2,261 articles pertaining to shark conservation which were quantitatively analysed to identify research themes, emerging ideas and priority gaps to facilitate sustainable long-term management of shark populations. **Chapter two** utilised fisher Local Ecological Knowledge (LEK) to assess temporal trends in shark abundance and spatial distribution. The value of LEK to provide fine-scale distribution data was assessed by validating contemporary shark "hot" and "cold" spots identified in fisher interviews with empirical abundance data from Baited Remote Underwater Videos (BRUVs). In **chapter three**, BRUVs and citizen science data were used to quantify contemporary shark populations and assess temporal trends in abundance between 2016-2020. This provided a population baseline post sanctuary implementation, against which future change can be measured to assess the long-term efficacy of the Maldives sanctuary. **Chapter four** uses a combination of Underwater Visual Census (UVC) and BRUVs to investigate the influence of abiotic and biotic drivers on the spatial variance in shark abundance using General Additive Models (GAMs). In **chapter five**, a Structural Equation Model (SEM) was constructed based on quantitative and qualitative data collected through interviews with fishers to assess the influence of fisher characteristics and perceptions on support for the Maldives shark sanctuary. **Chapter six** builds on data collected in chapter five by comparing perceptions of fisher-shark conflict across reef, pelagic handline and pelagic pole-and-line fisheries. Participatory maps were used to identify areas with high conflict potential by investigating spatial overlap between reef fishing activity and shark hotspots. In the **final** chapter, the thesis findings are reviewed and the contributions to shark conservation are discussed. Recommendations for future research and the broader implications for marine management are also suggested.

Chapter 1 Gaps and trends in shark conservation research: a topic modelling approach

1.1. Abstract

More than 31% (167/ 536 species) of the world's sharks are threatened with extinction. Despite substantial research growth and increased conservation effort, shark populations continue to decline globally. Tracking research trends and emerging ideas is urgently required to develop novel conservation approaches and achieve biodiversity targets. Here I undertake a topic modelling analysis of shark conservation literature (2,261 articles) between 1990 and 2020 to identify key topics, changes in topic popularity over time, and research gaps. Findings show that ecological research dominated the literature, with the most prevalent topics falling under the themes of genetics and biogeography. Only 9% (193/ 2261) of articles explicitly explored the human dimensions of shark conservation. Three topics – perceptions, population genetics and movement, were identified as rapidly expanding 'hot topics'. Fisher knowledge, physiology and population trends were identified as 'cold topics' with lower-than-average growth and low publication rate between 1990 and 2020. Emerging topics included conservation status, taxonomy, and abundance. Research was taxonomically and geographically biased with research effort focused on developed nations and thus misaligned with conservation risk in areas where shark populations are particularly vulnerable. Although findings suggest the shark conservation literature was generally well integrated across a broad range of topics and disciplines, key knowledge gaps remain particularly with respect to fisher knowledge and the integration of social and ecological knowledge sources. Findings suggest that greater consideration and inclusion of socioeconomic research is needed as it is the socioeconomic and governance context that ultimately determines the success or failure of conservation initiatives and management interventions.

1.2. Introduction

Following similar trends to scientific research at large, shark conservation research output has significantly increased in the last three decades (Shiffman *et al.*, 2020). The rapid expansion of the field is attributed to widespread declines in global shark populations throughout the last half a century (Roff *et al.*, 2018; MacNeil *et al.*, 2020; Pacoureau *et al.*, 2021) and greater recognition by scientists, policy makers, media and the general public that urgent action is needed to protect sharks (Lack and Sant, 2011; Shiffman and Hammerschlag, 2016b). Despite the increased volume of research, the global crisis in shark population declines is as present as ever, with 31.2% (n = 167/ 536) of all shark species threatened with extinction (Dulvy *et al.*, 2021). It is therefore timely to assess the quantity and diversity of scientific research into shark conservation and synthesize available information that can build towards achieving goals for shark population recovery.

Assessments of trends and development in shark conservation have so far been based on literature reviews which are limited by the number of publications and time periods considered (Shiffman and Hammerschlag, 2016a; Shiffman *et al.*, 2020). Existing studies are also limited in scope, focusing on specific topics including genetics (Dudgeon *et al.*, 2012; Larson *et al.*, 2017) shark bycatch (Molina and Cooke, 2012; Oliver *et al.*, 2015), and migrations (Chapman *et al.*, 2015). Most notably, previous reviews have focused on top-down approaches to map trends in shark research, with key topics of interest selected by analysts (e.g. region, habitat, species, method) and broad reviews limited (Martin, 2007; Hammerschlag *et al.*, 2011; Dudgeon *et al.*, 2012; Sans-Coma *et al.*, 2017).

Identifying topics, research directions and emerging ideas can provide insights into how a discipline is changing over time and is critical to the development of novel concepts and methods (Westgate *et al.*, 2015). Given that biodiversity conservation and management initiatives are designed and implemented on the basis of existing research, tracking research developments will have direct implications for evidence-based conservation and is therefore a critical skill for research scientists (Sutherland *et al.*, 2009; Velasco *et al.*, 2015). Moreover, identification and monitoring of trends in conservation research will enable realignment of research effort relative to changing biodiversity and human-development priorities (Di Marco *et al.*, 2017). This is particularly important to the achievement of the UN's 2030 Sustainable Development Goals (SDGs) as current biodiversity issues require an integrated and interdisciplinary application of existing knowledge to inform policy makers and advance scientific understanding (Nguyen and Vuong, 2020). However, substantial growth in scientific publications (Larsen and Ins, 2010) makes it difficult to synthesise information in a timely manner.

Topic modelling provides a novel statistical approach used to uncover and characterise abstract "topics" that occur in large bodies of literature (Syed *et al.*, 2018) based on the co-occurrence patterns of words in abstracts (Mair *et al.*, 2018). This approach provides quantitative rigor to summarising key topics and themes and allows synthesis across disparate information sources at various temporal and spatial scales (Westgate *et al.*, 2015). However, its application remains limited in conservation science.

This study undertakes a topic modelling analysis to uncover key research topics within the shark conservation literature to 1) quantify changes in topic popularity over time and 2) explore interconnections among topics to identify research gaps and areas for future research for this highly threatened group.

1.3. Methods

1.3.1. Literature search and corpus

Scopus was used to identify articles, with a search conducted using the following keywords: 'shark' and 'conservation' and/ or 'management'. Search results returned 2,378 documents categorised as research articles or reviews spanning from 1949 – 2020. The conservation and management of shark populations was limited prior to 1990 with the United Nations Convention on the Law of the Sea (UNCLOS), and the 1995 Fish Stocks Agreement considered to be the starting point for fisheries regulation at international levels (Techera, 2019). This was supported in the search results with low levels of publication (28 documents) between the years 1949 and 1989 and thus documents published before 1990 were removed from the analysis. In 1999, the International Plan of Action for the conservation and management of sharks (IPOA-sharks) was adopted by the FAO Committee on Fisheries (Lack and Sant, 2011). The IPOA-sharks is a voluntary instrument which recommends states develop National Plans of Action (NPOA) for the conservation and management of sharks. Abstracts were downloaded and imported into the program R (R Core Team, 2019) using the package bibliometrix. Articles that did not have abstracts were removed leaving 2,261 articles.

Abstracts were transformed into a corpus (defined as a collection of texts) and processed using the R package tm (Feinerer *et al.*, 2008). Search terms (Grün and Hornik, 2011), numbers written as words, digits and white space were removed (Mair *et al.*, 2018). English stop-words (see Table A1), pre-defined in the tm package (Feinerer *et al.*, 2008), terms added by publishers for copyright and punctuation were removed. 'Stemming' (reducing words to their base or root form) was used to aid identification of important words. A document term matrix was generated using the topic models package in R (Grün and Hornik, 2011).

1.3.2. Topic identification

Latent Dirichlet Allocation (LDA) was used to identify common topics reported in the literature (Blei, 2003). Latent Dirichlet Allocation models assign topics based on co-occurrence of words, so each topic can be interpreted as a meaningful combination of ideas within the corpus. The optimal number of topics, based on validation and checking if topics are well defined and separated, was set based on best performance of three indexes proposed by Griffiths and Steyvers (2004), Cao *et al.* (2009) and Arun *et al.* (2010). The optimal number of topics ranged between 90 and 120. However, the number of topics was set to 40 to capture the complexity of the corpus but ensure results could be interpreted and communicated clearly (Westgate *et al.*, 2015; Mair *et al.*, 2018). The 20 highest weighted words within each topic (Table A2) were used to name topics and then categorise them into broad themes (Westgate *et al.*, 2015).

1.3.3. Topic generality/ specificity

Some topics reflect broad themes common to many documents within the corpus while others only describe the key theme of an individual article. The distribution of topic weights within documents was used to assess topic generality versus specificity. LDA was used to calculate a matrix describing the weight of each topic within each article. For each document the topic that received the highest weight was selected. The mean weight of a topic was then calculated when it was selected and again when it was not selected. These values were plotted against each other for all topics providing a comparison of generality versus specificity (Westgate *et al.*, 2015).

1.3.4. Topic popularity

Topic popularity was assessed based on two metrics: 1) the total number of documents published on each topic during the study period (1990 – 2020); and 2) the change in the number of topics over the study period. A Generalised Linear Mixed Model (GLMM) with a Poisson distribution and log-link was fitted to the data in the lme4 package (Bates *et al.*, 2015). The response variable was the number of documents per topic per year and the explanatory variables were year and topic. Consideration of both metrics allowed the identification of 'hot topics' categorised by a large and increasing number of publications and 'cold topics' which had a small and decreasing number of publications (Westgate *et al.*, 2015).

1.3.5. Topic co-occurrence

The distribution of topic weights within documents (produced by the LDA model) was used to identify pairs of topics that co-occurred. The Bray-Curtis distance was calculated between each pair of topics and distances scaled from zero to one (Westgate *et al.*, 2015). This was then plotted as a correlation matrix. Lower metrics indicated low co-occurrence and represented topics that were typically separate in terms of their thematic content and the articles in which they appeared (Westgate *et al.*, 2015).

1.4. Results

The 20 highest weighted words per topic (see Table A2) were used to name topics and assign them to broad themes (Table 1.1). The most frequently occurring topics within the corpus fell primarily within the theme of genetics (Figure 1.1A). However, the theme biogeography included the highest number of topics including those related to global and regional distributions and finer scale habitat-use. The theme shark ecology included seven individual topics related to feeding ecology, behaviour and physiology. Three topics fell within the theme of socioeconomics, one which considered fisher knowledge, and the other perceptions linked to shark attacks and support for conservation, and the third focused on dive tourism. The theme contextual included five topics all of which had low frequency and included words that provided external context to the article, for example methodological or analytical approach. One shark species was found to have high enough prevalence in the corpus to be identified as a distinct topic: scalloped hammerhead (*Sphyrna lewini*). Great white (*Carcharodon carcharias*), tiger (*Galeocerdo cuvier*), bull (*Carcharhinus leucas*) and requiem sharks (*Carcharhinus* species) were also commonly studied (Table 1.1). The remaining themes (life history, conservation, fisheries and taxonomy) included 2-6 individual topics.

Table 1.1. Topic number, the five highest weighted words, topic name (assigned based on the 20 highest weighted words, see table A2) and theme. Top 5 words have been stemmed.

Topic	Topic (Abb)	Top 5 words (stemmed)	Theme
Carcharhinus	Carchar	speci, carcharhinus, bull, suggest, river	Biogeography
Evidence-based	E.based	data, inform, provid, avail, result	Contextual
Physiology	Phys	activ, tissu, high, concentr, muscl	Shark ecology
Bioenergetics	Bioen	chang, bodi, condit, effect, increase	Shark ecology
NPOA	NPOA	manag, develop, marin, nation, plan	Conservation
Movement	Move	movement, tag, day, pattern, individu	Biogeography
Hammerhead	HH	land, fisheri, hammerhead, speci, sphyrna	Fisheries
Reproduction	Repro	femal, size, male, matur, reproduct	Life history
Trophic role	T.role	predat, ecosystem, prey, trophic, ecolog	Shark ecology
Observation	Obs	whale, observ, aggreg, sight, year	Biogeography
Depth	Depth	speci, water, depth, small, deep	Biogeography
Life history	L.hist	estim, year, growth, age, rate	Life history
Research area	R.area	research, biolog, ecolog, societi, review	Contextual

MPA	MPA	reef, protect, marin, area, coral	Conservation
DNA barcoding	DNA.bar	speci, dna, identifi, sequenc, identif	Genetics
Ocean	Ocean	ocean, atlant, region, pacif, western	Biogeography
Species diversity	Diversity	speci, ray, chondrichthyan, diversity, group	Taxonomy
Stock assessment	Stock	fisheri, manag, exploit, stock, assess	Fisheries
Fisher knowledge	Fisher.kn	fish, local, fisher, scale, interview	Socioeconomic
Region	Region	area, water, region, coast, gulf	Biogeography
Bycatch	Bycatch	bycatch, release, net, mortal, captur	Fisheries
Genomics	Genomics	gene, vertebr, sequenc, express, protein	Genetics
Abundance	Ab	island, survey, abund, site, time	Life history
Context	Context	distribut, provid, common, use, term	Contextual
Habitat-use	Habit.use	model, spatial, habitat, distribut, use	Biogeography
Dive tourism	Tourism	tourism, dive, activ, dolphin, impact	Socioeconomic
Population trends	Pop.trend	popul, declin, increas, abund, trend	Life history
Taxonomy	Taxa	record, sea, mediterranean, collect, present	Taxonomy
Perceptions	Percep	public, support, human, toward, knowledge	Socioeconomic
Fin Trade	Trade	fin, trade, speci, product, market	Fisheries
Behaviour	Behav	anim, behaviour, natur, environ, group	Shark ecology
Juvenile habitat	Juv.hab	habitat, area, juvenil, coastal, nursery	Biogeography
Pelagic fisheries	Pel.fish	catch, fisheri, speci, longlin, tuna	Fisheries
Megafauna	M.fauna	marin, sea, turtl, impact, include	Fisheries
Data	Data	use, sampl, non, result, tiger	Contextual
Australia	Aus	white, australia, south, australian, carcharia	Biogeography
Population genetics	Pop.gen	popul, genet, structur, divers, connect	Genetics
Conservation status	Cons.st	speci, threaten, extinct, list, assess	Conservation
Identification	Indentif	indivu, use, identifi, sawfish, mark	Life history
Method	Method	approach, use, base, method, model	Contextual

The Atlantic Ocean region was the most commonly studied (n = 1346 articles) followed by the Pacific (n = 1288), Indian (n = 585) and Arctic Ocean (n = 94). Research output was dominated by the United States of America (n = 860 articles), Australia (n = 572) and the UK (n = 304). Other countries with high rates of publication included Canada (n = 262), Brazil (n = 151), South Africa (N = 114), France (n = 113), Mexico (n = 99) and Portugal (n = 93).

Research output has increased 25-fold during the last 20 years from less than 10 articles per year in the 1990s to over 250 articles in 2020 with a substantial increase in the number of articles published from 2005 (Figure 1.1B).

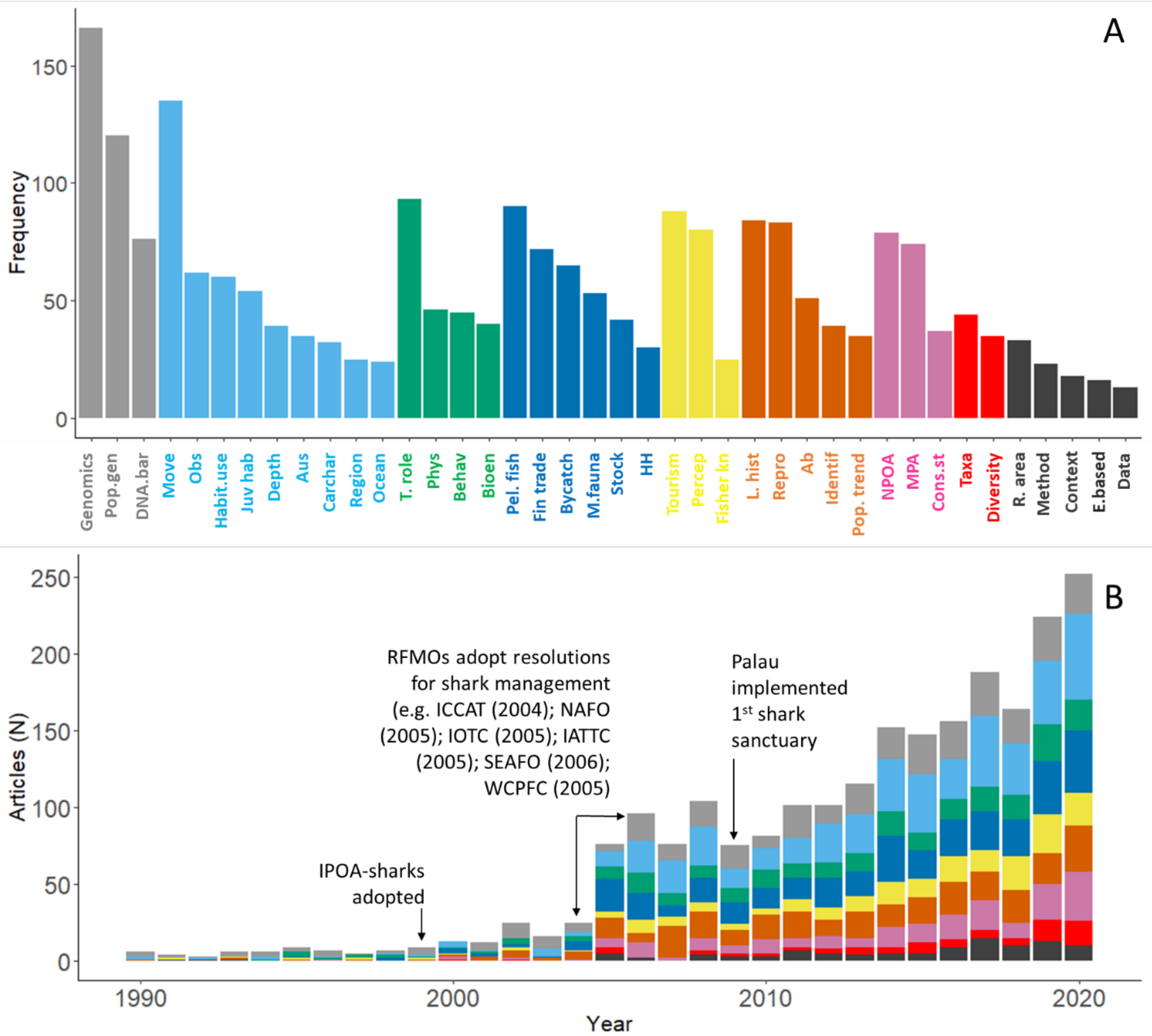

Figure 1.1. A) Topic frequency in the corpus. Each article was assigned to the topic with the highest weight. The x-axis gives the abbreviated topic name, full topic names and key words are listed in Table 1.1. B) Annual growth in research articles within each theme. Key legislation dates are presented as these may have driven some of the observed patterns, these include the International Plan of Action (IPOA) for sharks (2009), the adoption of shark fishing regulations by Regional Fisheries Management Organisations (RFMOs) in the mid-2000s and implementation of the first shark sanctuary (2009).

1.4.1. Topic generality/ specificity

Topics within the theme of genetics showed the highest specificity, particularly genomics (Figure 1.2A). The socioeconomic topics also showed relatively high specificity, with the exception of fisher knowledge. Physiology, bycatch, fin trade, plus the majority of topics within life history were also relatively specific. Conversely, topics within biogeography, taxonomy and contextual topics were general, indicating these topics were broad and often discussed in association with other topics (Figure 1.2A).

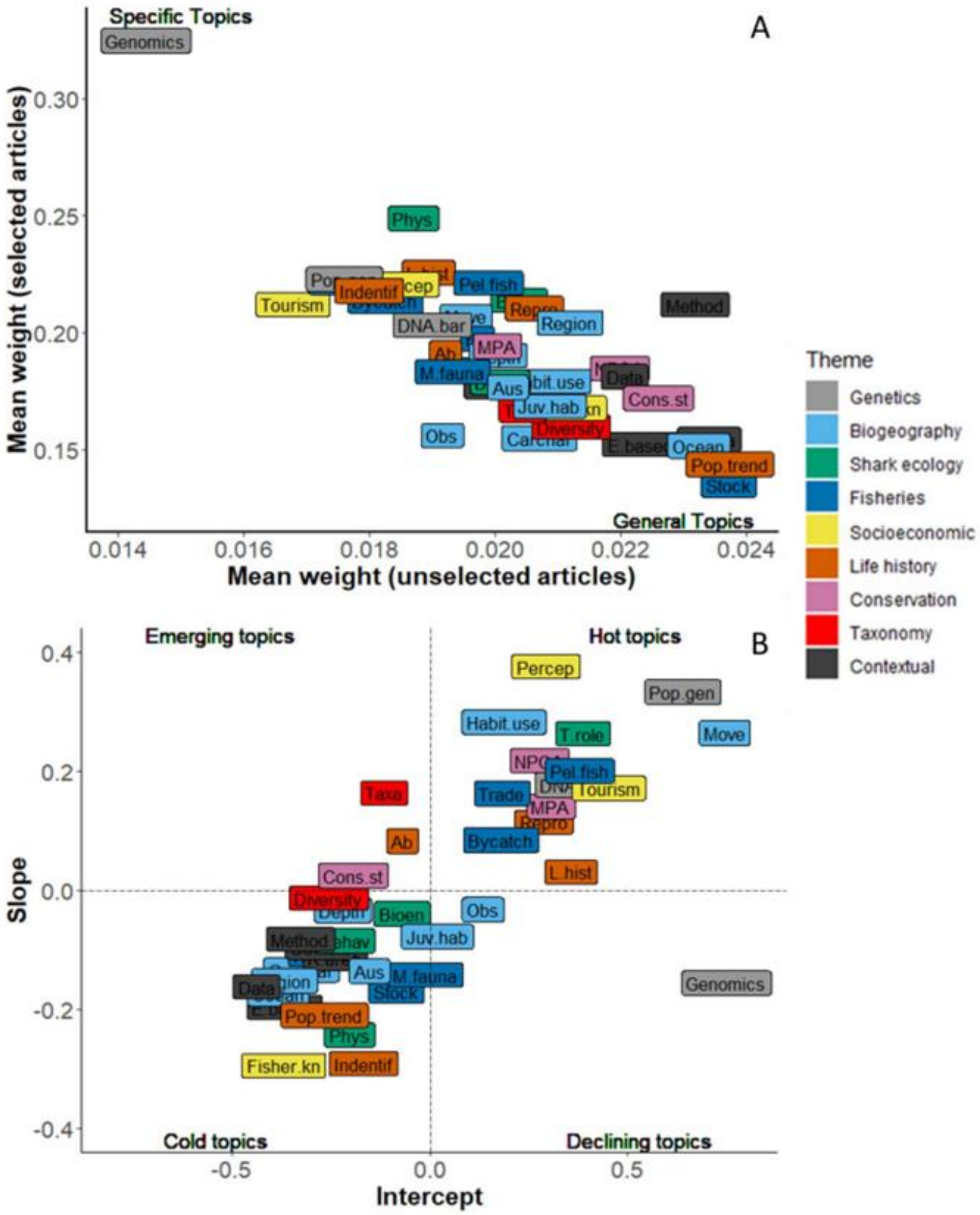

Figure 1.2. A) Topic generality/ specificity. Topic names are abbreviated with full topic names and key words listed in Table 1.1. Topics in the top left are specific (more likely to be the sole topic present within individual articles), while topics in the bottom right are general (broad and common to many articles). B) Topic popularity. A positive intercept indicates high topic frequency and negative indicates low topic frequency (x-axis). Topics which showed an increase over time have a positive slope, topics that have declined negative (y-axis). Emerging topics are categorised by low publication frequency and an increase in popularity over time; hot topics indicate high frequency and increasing popularity; cold topics are categorised by low publication frequency and a decline in popularity over time; declining topics are categorised by high publication frequency and declining popularity.

1.4.2. Topic popularity

In general, topic frequency correlated with topic popularity with the most frequent topics increasing in number and those with a lower frequency declining. Several topics clustered around a slope of zero, demonstrating relatively small changes in popularity over time (Figure 1.2B). Genomics had a large intercept, but low slope showing a high number of publications over time but declining popularity. In contrast, movement, perceptions and population genetics were rapidly expanding "hot" topics (Figure 1.2B). Several topics clustered together, with a consistently large and increasing number of publications, including NPOA, trophic role, habitat-use, dive tourism, and pelagic fisheries. Topics gaining research interest included abundance, taxonomy and conservation status. "Cold" topics categorised by a small and declining number of publications included physiology, fisher knowledge, population trends, identification and the majority of topics within themes shark ecology and contextual.

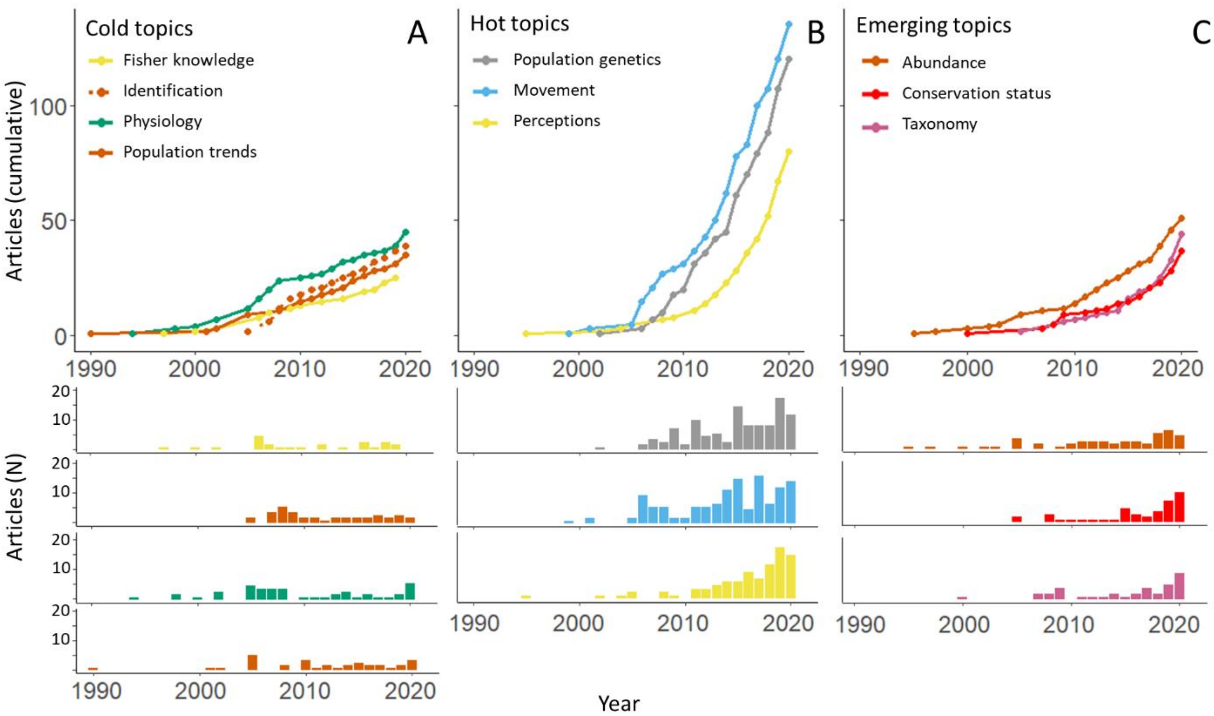

Figure 1.3.Temporal trends in cold (A), hot (B) and emerging topics (C). Line graphs represent the cumulative number of articles published between 1990 and 2020, while bar graphs show annual publication rates.

For cold topics, publication output was highest between 2005-2009 (~3.6 articles annually) then declined between 2015-2020 (~2 articles annually, Figure 1.3A). Hot topics population genetics and movement showed a rapid increase from 2007 and 2006 respectively while articles investigating perceptions showed an exponential increase from 2011 (Figure 1.3B). On average, 11.5 articles were published annually for each hot topic between 2015 and 2020. For emerging topics publication output was substantially higher between 2018 and 2020 (~6.3 articles annually) relative to previous years (~1.9 articles annually between 1990 and 2017).

1.4.3. Topic co-occurrence and research gaps

Analysis of co-occurrence between topics showed that in general topics were well integrated and commonly co-occurred both within and across themes (Figure 1.4). As expected, contextual topics showed high co-occurrence with other topics. However, topics which were highly specific (e.g. genomics) and low in frequency (e.g. fisher knowledge) showed higher separation from other topics.

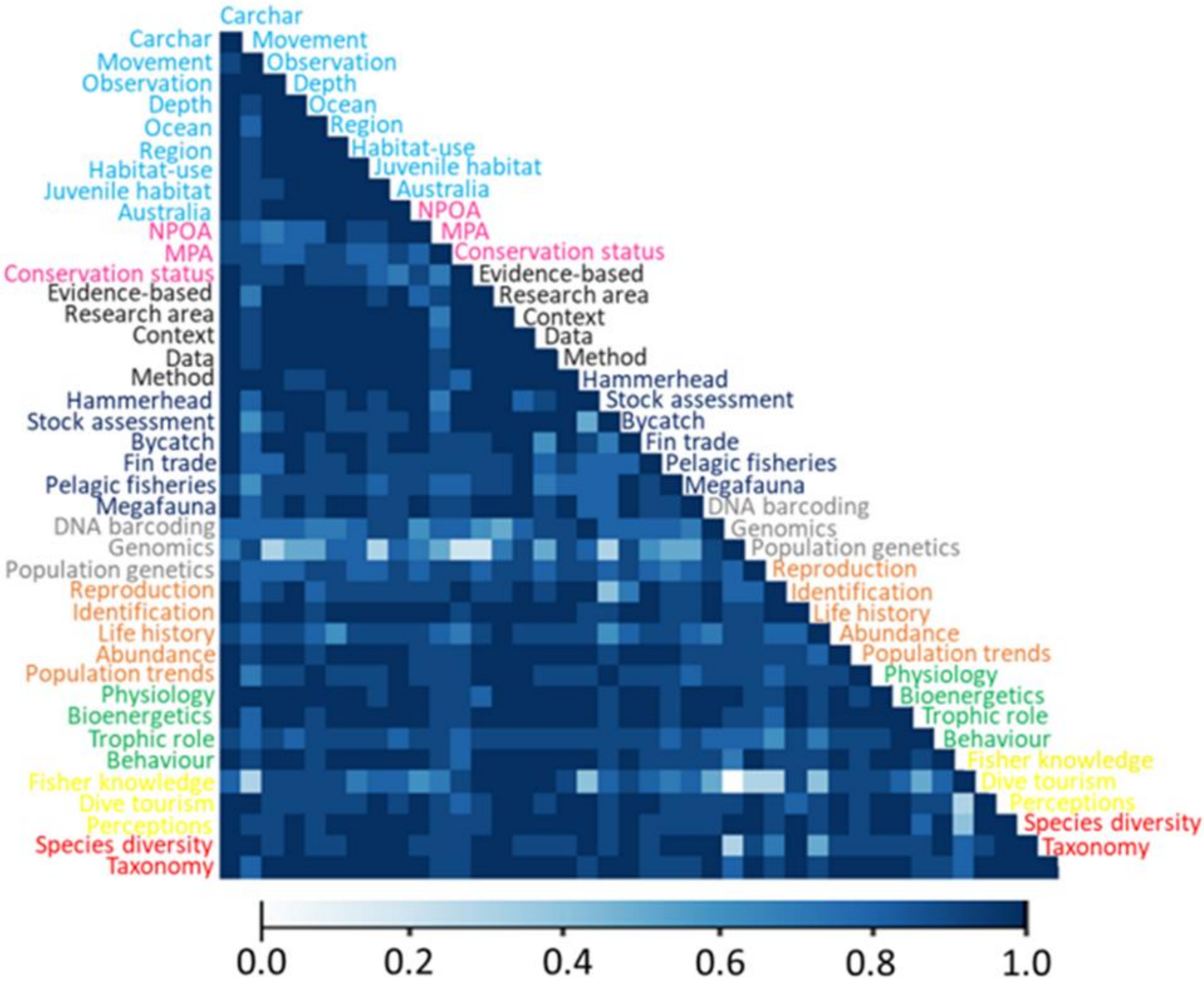

Figure 1.4. Topic co-occurrence distance matrix. Lower values (light blue) indicate topics that rarely co-occur within the corpus while higher values (dark blue) suggest topics frequently co-occur.

1.5. Discussion

This study provides a quantitative assessment of literature trends in shark conservation research published over the last 30 years. By applying a topic modelling approach, I identify key topics and themes and show that these vary in frequency, specialization, and popularity. Although extensive and diverse, findings found the scientific literature on shark conservation was dominated by ecological research, whilst socioeconomic research was comparatively scarce: only nine percent (n = 193) of the 2,261 articles analysed explicitly explored the human dimensions of shark conservation. Research into the status of species and geographic distribution was the most prevalent. However, results support previous work showing that shark research is taxonomically and geographically biased (Shiffman *et al.*, 2020).

Research output substantially increased in the mid-2000s coinciding with the adoption of shark fishing regulations by a number of Regional Fisheries Management Organisations (RFMOs). In 2004, parties to the International Commission for the Conservation of Atlantic Tunas (ICCAT) agreed to a binding recommendation that amounted to the world's first international regulation on shark finning (Lack and Sant, 2006). ICCATs approach has since been adopted by a number of RFMOs. Additionally, under the recommendation of the IPOA-sharks a number of RFMOs committed to collect data on catch, effort, discards and trade as well as information on the biological parameters of shark species; ICCAT (2004), Indian Ocean Tuna Commission (IOTC, 2005), Inter-American Tropical Tuna Commission (IATTC, 2005), South East Atlantic Fisheries Organisation (SEAFO, 2006), Western and Pacific Fisheries Commission (WCPFC, 2005).

The 40 identified topics in shark conservation research were grouped into nine broad research themes. Three themes (biogeography, genetics, and fisheries) encompassed 50% of all articles. Most topics within the overarching themes of genetics and fisheries showed consistent popularity between 1990 and 2020 suggesting that these themes reflect long-established research areas. Determining species distribution and habitat preference is considered fundamental to evaluating risks and implementing effective management measures (Madsen et al., 2020). Thus, it is unsurprising that 20% of articles analysed fell into the theme biogeography. Notably, tracking and passive modelling techniques have shown a marked increase in recent years, particularly telemetry studies (the second most prevalent topic within the corpus). Such studies focus on spatial and temporal movements to delineate habitat use, home ranges and long-distance movements or migratory patterns (Osgood and

Baum, 2015). Genetic data have also aided conservation and management efforts through detection of genetically distinct populations, identification of risk associated with demographic change and measurements of genetic connectivity (Domingues, 2018).

Additionally, the increasing prevalence of two socioeconomic topics (dive tourism and human perceptions) is a positive sign that researchers acknowledge the need for greater inclusion and consideration of human dimensions in shark conservation. However, studies continue to focus on perceptions of risk linked to shark attacks and the economic benefits of protecting sharks rather than potential impacts on local stakeholders (Jaiteh *et al.*, 2016; Zimmerhackel *et al.*, 2018). Few articles considered perceptions among fishing communities despite growing recognition of the need to integrate perceptions into resource management for the long-term efficacy of conservation initiatives (Turner et al., 2019). This imbalance is concerning as it is the social and governance context that ultimately determines the success or failure of conservation initiatives (Balmford and Cowling, 2006). Further, given the diverse contexts, livelihood dependence and cultural values associated with shark fisheries, consideration of socioeconomic issues is vital to sustainable shark conservation.

Changes in topic prevalence could also be linked to methodological developments or data gaps rather than a change in scientific interest. For example, an increase in studies evaluating shark conservation status, reflects improvements in monitoring, data quality and the increasing availability of information on catch trends, trade, and threats. Similarly, abundance was identified as an emerging topic with studies greatly increasing over the last decade (Osgood and Baum, 2015). This aligns with increased application of popular non-invasive techniques such as Baited Remote Underwater Videos (BRUVs) to monitor relative abundances (Phenix *et al.*, 2019). Conversely, studies assessing population trends remain limited due to the paucity of time-series data available for sharks (Cortés and Brooks 2018). Long-term data are vital to conservation management as it identifies at risk species and helps set recovery targets (Simpfendorfer *et al.*, 2011). In the absence of scientific data, extensive knowledge about marine resources is available in Local Ecological Knowledge (LEK). Defined as knowledge gained through observation and experience (Olsson and Folke, 2001), LEK can provide information about the distribution and relative abundance of species and exploitation (Turner *et al.*, 2015). The value of LEK has been demonstrated in a range of studies from carnivorous predators (Madsen *et al.*, 2020) to small mammals (Turvey *et al.*, 2014) however, its application remains limited for sharks.

Scientific innovation and advances are most likely to occur from interdisciplinary approaches to data collection and research compared with narrowly focused disciplinary studies (Luiz *et al.*, 2019). Thus, an insightful aspect of topic modelling is the ability to quantitatively assess co-occurrence among topics. Findings show that shark conservation research is relatively well integrated across scientific disciplines, with high topic co-occurrence across the majority of topics. However, there are notable exceptions including topics genomics and fisher knowledge which showed low correlation and poor integration with other topics, therefore representing opportunities for greater collaboration. Gaps between fisher knowledge and topics NPOA and MPA highlight the need for greater inclusiveness and collaboration among stakeholder groups in policy design and implementation. Limited application of fisher knowledge is likely due to concerns about the validity and accuracy of information (Smith *et al.*, 2017), despite growing recognition that integration of local and scientific knowledge systems provides a key opportunity to move towards sustainable ecosystem management at multiple scales (Hill *et al.*, 2020). Conversely, low correlation between fisher knowledge and topics within the theme of genetics and movement are to be expected given the technical methods and equipment utilised. Genomics showed low correlation with the contextual topic evidence-based suggesting that such data is poorly integrated into evidence-based decision making which could be a missed opportunity for stock-based fisheries management where stocks are defined by their genetic characteristics. This has been attributed to specialised methods and difficulties interpreting data thus such data is largely overlooked and neglected in practical management policies (Domingues *et al.*, 2018). Results therefore echo long-standing calls for better integration of genetic criteria and data from multiple knowledge sources to bridge gaps in shark conservation and improve management interventions.

Findings also suggest that research effort may be misaligned with threat: the Atlantic and Pacific oceans were the most studied areas according to the literature identified despite population depletion being particularly prevalent in the Indo-Pacific (Dulvy *et al.*, 2014; Dulvy *et al.*, 2021). The geographic bias observed is reflective of research investment with developed regions (e.g. Australia and the United States of America) making a disproportionately large contribution to the shark conservation literature while many developing countries lack the capacity for shark research (Shiffman *et al.*, 2020). Moreover, the early establishment of shark conservation research groups in the 1990s was dominated by researchers based in the United States of America (Castro, 2016). The lack of overlap between research effort and locations of high conservation concern has been acknowledged in other taxa (Ducatez and Lefebvre, 2014) but is particularly concerning for shark populations, as the main threat responsible for their global decline is overexploitation (Ducatez, 2019). Geographic bias also has consequences for the management of shark populations with the two countries (Australia and the United States of America) contributing most to research effort among the first to implement a Nation Plan of Action for the Conservation and Management of Sharks (Momigliano *et al.*, 2014).

Topic modelling provided a bottom-up view of shark conservation research over a 30-year period. However, limitations to this approach are acknowledged; the use of article abstracts could limit the information available to topic models, thus failing to capture some topics or leading to misinterpretation of study context (Westgate *et al.*, 2015). Furthermore, failure to identify a broader range or study species or geographic regions does not mean that research has not been conducted in these areas, rather it suggests that only select shark species and locations were studied in sufficient volume to be detected in this analysis. Nonetheless, quantitative assessments of literature trends in shark conservation research are a valuable approach to identify key topics, knowledge gaps and directions for future research. On the basis of these findings the following recommendations are made: (1) increase research effort on the human dimensions of shark conservation; (2) increase collaboration among institutions in developed regions and those leading in shark conservation research to increase research capacity across the Indo-pacific; (3) increase capacity to integrate complex genetic data in practical approaches for shark conservation and management and (4) improve data triangulation of multiple knowledge sources to address key data gaps including historical population trends. Addressing the above will ensure more holistic approaches to shark conservation for more effective management.

1.6. Conclusion

The scientific literature on shark conservation is extensive, but findings of this study suggest research continues to focus on biological and ecological concepts. While the increasing prevalence of research on dive tourism and human perceptions is a good sign that the importance of considering socio-economic dimensions in shark conservation is now recognised, studies on fisher perceptions and the incorporation of fisher knowledge into conservation planning and ongoing management remains limited. Greater consideration and inclusion of fisher perceptions is needed given that the ultimate causes of species declines are socio-political, and the behaviour of humans will ultimately determine the success of conservation outcomes.

Chapter 2 Ecological validation supports fisher knowledge of shark distribution and exploitation

2.1. Abstract

Twenty-five percent of the world's marine species assessed on the International Union for the Conservation of Nature (IUCN) Red List are classed as data-poor, constraining successful conservation outcomes. Considerable information about data-poor species exists in Local Ecological Knowledge (LEK), but concern about its validity, limits its application in management agendas. This study integrates multiple knowledge sources to assess temporal trends in shark abundance in the Maldives over a 50-year period and identifies abundance hotspots which are helpful for targeted management measures. Trends in abundance derived from LEK show that, since 1970, reef-associated and oceanic shark populations have declined by 69% and 67% respectively. Shark hot and cold spots identified in fisher interviews were validated with empirical BRUVs data (n = 50). BRUVs data showed that shark abundance was 2.5x higher at hot vs cold spots and 8x higher than regional averages for the Indian Ocean, thus advocating the use of spatially explicit LEK to provide fine-scale distribution data. Findings highlight potential application for a low-cost approach for monitoring data poor species and provide evidence required for use in both single species and ecosystem-based fisheries management. This research offers coastal nations worldwide a way forward to evidenced-based management especially where there is limited access to technology and resources for traditional data-heavy approaches to marine policy.

2.2. Introduction

Limited spatial and temporal data hinders the development of biodiversity conservation that is context-specific both on land and in the ocean (Bland *et al.*, 2017). Accurately determining species distribution, habitat preference and trends in population abundance is fundamental to evaluating risks and implementing effective management measures (Madsen *et al.*, 2020). Approximately 15% (17,154 out of 116,177) of species assessed on the IUCN Red List of Threatened Species are currently classified as data deficient (IUCN, 2021). This issue is particularly prevalent in marine systems where 25% of all marine species are listed as data deficient in comparison to 12% of terrestrial species (Broderick, 2015). Covering two-thirds of the planet, oceans contain the most biologically diverse ecosystems on earth (Mora *et al.*, 2011), yet understanding and protection of marine species is lagging in comparison to terrestrial systems (Broderick, 2015).

In remote and small island nations, the trade-off between knowledge acquisition and marine conservation action is particularly acute (Ban *et al.*, 2009; Peterson and Stead, 2011; Philpot *et al.*, 2015). Such nations have rich biodiversity, high dependence on ecosystem services and limited resources available for management (Gill *et al.*, 2019; Selig *et al.*, 2019). Supporting more than half of the world's marine biodiversity including seven of the world's 10 coral reef hotspots (CBD, 2011), island nations are considered a conservation priority, however management initiatives are often based on scarce or inconsistent data (Gill *et al.*, 2019).

In the absence of scientific data, Local Ecological Knowledge (LEK) contains valuable spatial and temporal information (Selina *et al.*, 2006; Coll *et al.*, 2014; Temple *et al.*, 2020). Defined as knowledge gained through observation and experience (Olsson and Folke, 2001) LEK is often acquired over many generations. Utilised as a low-cost method for data acquisition, LEK can provide information about the distribution and relative abundance of species (Taylor *et al.*, 2011; Frans and Augé, 2016; Azzurro *et al.*, 2019), habitat usage (Aswani and Lauer, 2006; Coll *et al.*, 2014) and exploitation (Moreno *et al.*, 2007; Turner *et al.*, 2015; Szostek *et al.*, 2017). However, concern about the validity and accuracy of LEK has frequently limited its incorporation into management agendas (Smith *et al.*, 2017).

Recent research has focused on developing methods to integrate and triangulate empirical and local knowledge to inform management and policy (Turner *et al.*, 2015), with numerous studies demonstrating the utility of LEK for characterizing long-term changes in species abundance (Anadón *et al.*, 2010; Beaudreau and Levin, 2014). However, map-based interviews are most commonly used to document spatial information in locations where fine scale scientific data are unavailable (Des Clers *et al.*, 2008), therefore, comparisons between social and ecological data are often not possible at the same scale (Turner *et al.*, 2015). Thus, limited work has been undertaken to assess comparability among spatial data sources (Mason *et al.*, 2019) despite recognition of its importance.

The need for spatial data to inform management is particularly urgent for sharks, which are among the most data deficient species, despite being considered the most threated marine vertebrate taxa globally (Dulvy *et al.*, 2017; Dulvy *et al.*, 2021). Currently 13.2% of shark species are classified as data deficient (Dulvy *et al.*, 2021), versus only 0.6% of 10,425 bird species (Amano *et al.*, 2016). As highly mobile coral reef predators (Roff *et al.*, 2016) sharks may play a key role in maintaining healthy reef ecosystems (Bascompte *et al.*, 2005; Robbins *et al.*, 2006; Tickler *et al.*, 2017) with their loss inducing complex changes in marine communities, resulting in ecological and socio-economic consequences (Ferretti *et al.*, 2010). Comparison and integration of LEK and scientific data could be a valuable way to understand and manage data poor fisheries and holds potential for shark conservation globally.

In the absence of historical data and effective monitoring for sharks, 17 countries have acted upon the precautionary approach to ban shark fishing, killing or extraction (Ward-Paige, 2017). In 2010, the Maldives became the world's second nation to enforce a total ban on shark fishing (Sinan *et al.*, 2011). Recent research suggests that Maldivian shark populations are comparitevely better than locations with no management in place (MacNeil *et al.*, 2020), however long-term data on shark abundance, catch trends and distribution patterns are limited (Ali and Sinan, 2015) and a major impediment in the evaluation of ban efficacy. There is an urgent need to develop and implement cost-effective approaches to elucidate trends in historical and contemporary abundance to discern the magnitude and direction of population change and improve future management, particularly in data-poor countries.

This study aimed to 1) assess temporal changes in shark abundance and spatial distribution over 50 years (1970-2019) using LEK and 2) validate contemporary LEK with ecological data (Baited Remote Underwater Videos) through comparison of fisher identified hot and cold spots.

2.3. Methods

3.3.1. Study site

The Maldives lies in the central Indian Ocean and is composed of approximately 1,200 islands distributed in 20 administrative atolls. The economy of the Maldives relies heavily on marine resources with an exclusive economic zone of 900,000 km^2 and very little land area (Zimmerhackel *et al.*, 2019). Tourism (inevitably linked to marine systems) and fisheries are the country's leading economic sectors contributing 28% and 3% of GDP respectively in 2018 (Ahusan, 2018).

A minor shark fishery existed in the Maldives for centuries and intensified in the 1970s following widespread motorization of fishing vessels (Sinan *et al.*, 2011). By the end of the

1980s, there were three main shark fisheries including oceanic sharks; reef sharks; and deepwater gulper sharks (Anderson and Hafiz, 1997). Declines in shark abundance led to a total ban on all shark fishing, capture, killing or extraction from Maldivian waters in March 2010 (Figure 2.1).

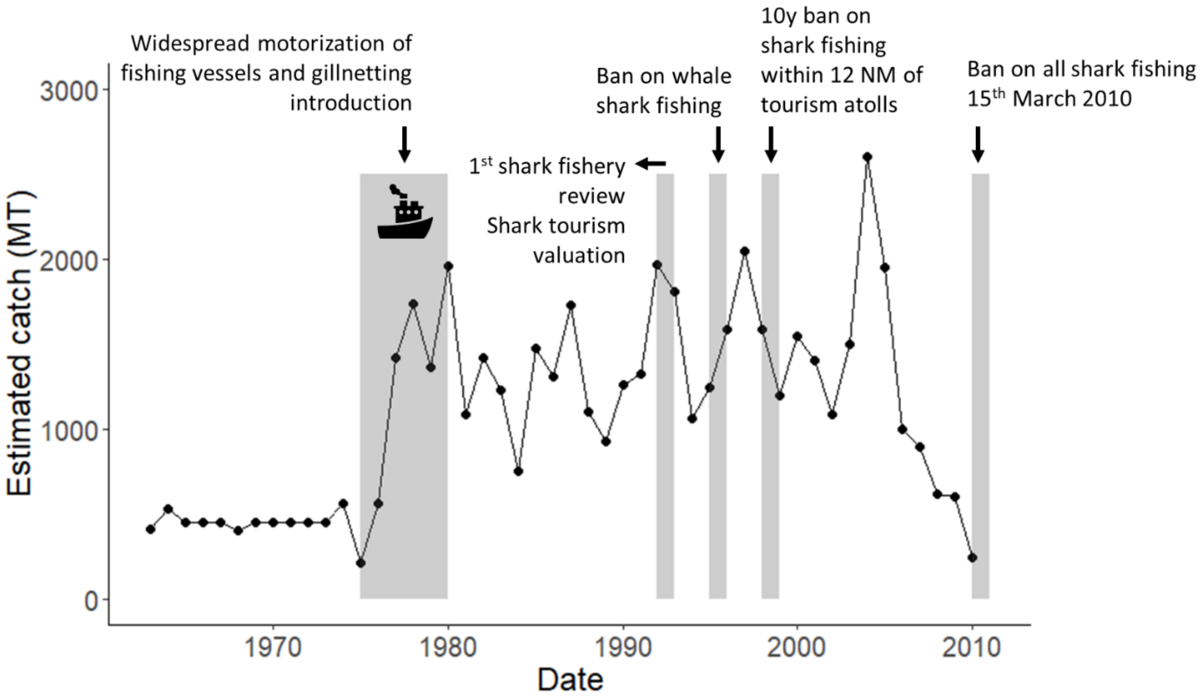

Figure 2.1. Timeline of key events in the Maldives shark fishery. Estimated catch is calculated from fin export data and represents all reef and oceanic species combined. Data source (Sinan et al. 2011).

This study was conducted in Dhaalu Atoll (Figure 2.2A), located on the western side of the Maldives archipelago (2° 50' N and 72° 50' N). Dhaalu atoll hosted the highest proportion of active shark fishers at the time of the ban (MRC, 2009), and was selected as the study area for this high density of potential respondents.

2.3.2. Interviews with resource users (LEK)

To document spatial distribution and temporal changes in shark abundance semi-structured, participatory mapping interviews were conducted. Between 2016 and 2019, interviews were conducted with 87 former shark fishers in five islands (Table 2.1). In total, 43% of fishers interviewed were full time shark fishers, while 57% engaged in shark fishing part-time. Forty-six percent targeted oceanic sharks, 19% reef-associated sharks and 35% targeted both reef and oceanic shark fisheries.

Table 2.1. Breakdown of interviewees.

Island	Interviews (n)	Mean age (years ± SD)	Mean fishing exp (years ± SD)
Bandidhoo	21	55.9 ± 10.6	32.2 ± 14.1
Kudahuadhoo	17	62.8 ± 6.2	32.5 ± 17.7
Maaenboodhoo	11	56.4 ± 13.7	31.7 ± 11.9
Meedhoo	28	54.9 ± 14.1	32.9 ± 12.9
Rinbudhoo	10	36.8 ± 12.2	19.1 ± 14.9
Total:	**87**	**54.2 ± 13.0**	**31.2 ± 13.7**

Interviewees were contacted via snowballing methods (Bernard, 2006), in which study participants recommended other knowledgeable individuals to participate, or by approaching fishers at island ports. Data collection was undertaken by Danielle Robinson, and three local research assistants. All research assistants were trained by Danielle Robinson. Interviews were conducted in Maldivian (Dhivehi) and in pairs to minimise any interviewer bias.

Each interview started by presenting fishers with photographs of focal shark species including blacktip reef (*Carcharhinus melanopterus)*, whitetip reef (*Triaenodon obesus),* grey reef *(Carcharhinus amblyrhynchos)*, tawny nurse (*Nebrius ferrugineus)*, silky (*Carcharhinus falciformis)*, silvertip (*Carcharhinus albimarginatus)*, tiger (*Galeocerdo cuvier)*, scalloped hammerhead *(Sphyrna lewini),* bignose *(Carcharhinus altimus)* and oceanic whitetip (*Carcharhinus longimanus).* These species were chosen as they were frequently targeted in reef and oceanic fisheries (Table A3) and consequently should represent a higher proportion of landings/ sightings. Fishers were asked to: 1) identify species they frequently captured; and 2) report the best days catch (number of individuals) for each species identified or highest number of sharks sighted in a single day if the year given was post shark sanctuary implementation (2010).

Fishers were then asked to draw on laminate maps to mark areas they frequently encountered (caught/ sighted) sharks from the earliest date they could remember to the present day. Where possible the following attributes were recorded for each area: (1) shark species; (2) the approximate year(s); (3) the average and maximum number of sharks and (4) average and maximum shark size. Fishers were asked to mark areas based on their own observations and permitted to mark an unlimited number of areas. On separate maps fishers were also asked to mark their common fishing grounds. The approach used for the mapping exercise followed previous studies designed to elicit local spatial knowledge (Hall and Close, 2007; Turner *et al.*, 2015).

2.3.4. Ecological surveys (LEK validation)

Baited Remote Underwater Videos (BRUVs) were used to quantify reef shark abundance at 10 sites in April 2019. Sites were selected based on maps generated in fisher interviews and encompassed perceived shark hotspots, representing areas with high probability of occurrence and high abundance, and reef areas not selected (control sites) by any respondent (herein referred to as cold spots). Five BRUV replicates were deployed at each site resulting in 50 individual deployments equating to ~3,500 minutes of footage.

BRUVs were deployed at an average depth of 9.3 m ± 1.0 m and set with a minimum of 24 hours between each replicate. This depth was chosen primarily for comparative purposes between sites and to ensure continuous reef habitat as reef composition was more variable at greater depths. For each BRUV, a single GoPro Hero 4 camera was attached to a stainless-steel frame with a detachable bait arm holding a plastic-coated wire mesh bait bag. Bait consisted of 1 kg of guts and discards from a range of oily fish species: *Elagatis bipinnulata*, *Sphyraena barracuda* and *Sarda orientalis*. BRUVs were set manually with a free-driver guiding BRUVs onto substrate to avoid damage to reef and deployed with polypropylene ropes and surface marker buoys to aid retrieval. All BRUVs were deployed during daylight hours (09:00 – 17:00) and left to record for 70 minutes, allowing bait to disperse and leaving 60 minutes of footage to analyse. Cameras were set to record at 60 frames per second/1080p resolution in wide field of view to maximize detection rates. For each BRUV, the maximum number of sharks seen in a single frame (MaxN) was determined for each species, as a metric of relative abundance to avoid double-counting individuals (MacNeil *et al.*, 2020).

2.3.5. Data analysis

To detect whether LEK revealed a significant trend in the abundance of each shark species across years (i.e., increasing, declining) regression analyses were conducted with the best days catch reported by each respondent (number of individuals) and date (year) as variables. Three regression types (exponential, polynomial and linear) were tested. Model fit was assessed by comparing r^2 values (Bender *et al.*, 2014). The level of statistical significance was set at $p < 0.05$. Reported abundance for tawny nurse and bignose sharks were excluded from further analysis because of low sample sizes of fewer than 15 respondents. To estimate abundance change between 1970 and 2019, the best days catch reported by all fishers were grouped by decade (i.e. 1970 - 1979) and values averaged. Percentage abundance change was then calculated based on the average abundance in the 1970s and 2010s.

Maps were obtained from 79 of the 87 interviewees. Individual maps were photographed or scanned and georeferenced using a minimum of 3 ground control points per map (Oniga *et al.*, 2018). Areas where fishers reported frequent shark encounters were outlined and converted to vector-based polygons for each respondent, species, and time period (Figure 2.2B). Individual polygons were overlaid and overlapping locations summed (Figure 2.2C). Polygons were then converted to a raster image (Figure 2.2D) and visualized using heat maps, from which mean values per cell were derived for a 100 m^2 grid.

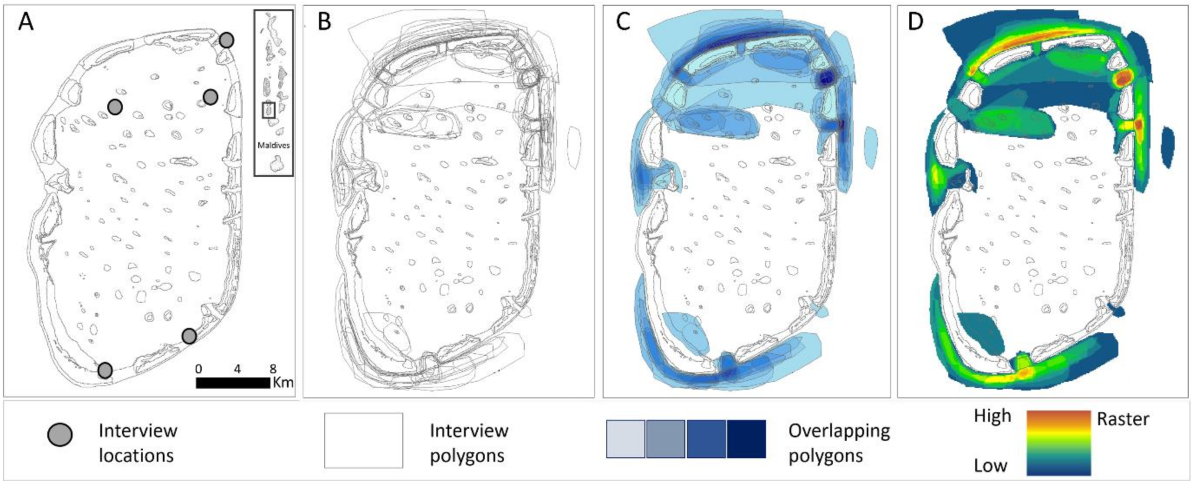

Figure 2.2. Participatory mapping process to document spatial Local Ecological Knowledge (LEK). A) Interviews were conducted on five islands in Dhaalu Atoll, B) Individual polygons drawn by fishers were geo-referenced, C) polygons over-laid to create and D) a single raster layer of summed values.

To assess historical trends in reef shark distribution polygons drawn by fishers were grouped into three time periods (1980-1989, 1990-1999, 2000-2009). Values for overlapping polygons were divided by the number of fishers actively fishing during each period. Heat maps display the perceived spatial distribution of reef sharks as the percentage of respondents that marked each grid cell.

For contemporary (2010 - 2019) shark sightings individual polygons were also weighted based on the mean shark abundance reported for each area. The output was visualised using heat maps to display perceived abundance and spatial distribution patterns with hotspots representing areas with high probability of occurrence and high abundance. Map processing was completed in ArcMap 10.6.1 (ArcGIS, 10.6.1). Fisher identified hotspots were then validated with BRUV data by comparing observed shark abundance and species richness at perceived hot and cold spots using Mann Whitney U tests. Probability of shark occurrence (BRUVs data) was also compared across hot and cold spots.

2.4. Results

2.4.1. Historical trends in abundance

At the species level, interview data revealed significant declines in shark catch/ sightings between 1970 and 2019 for seven species including grey reef, whitetip reef, blacktip reef, silvertip, scalloped hammerhead, silky and ocean whitetip sharks (Figure 2.3). Conversely tiger shark catch appeared to increase between 1970 and 2010 although no significant trend was found (Figure 2.3). Catch trends suggest that over a fifty-year period (1970 – 2019) the abundance of reef-associated, and oceanic sharks declined by approximately 69% and 67% respectively. Abundance trends for reef-transient species varied (Figure 2.3).

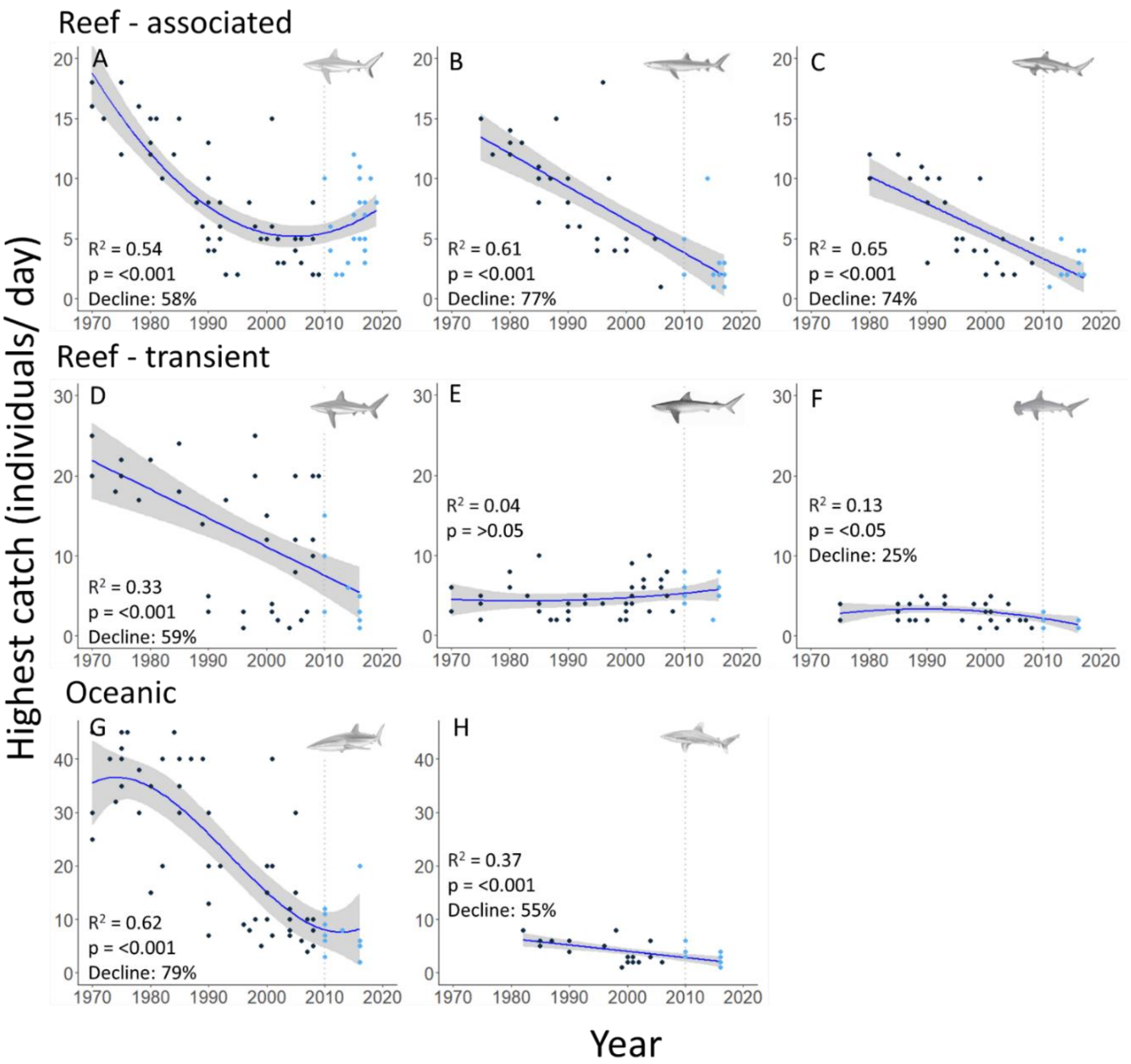

Figure 2.3. Highest shark catch reported by fishers, from 1970 to 2019. Second order polynomial regressions were fitted for grey reef (A) and scalloped hammerhead sharks (F). Linear regressions were fitted for whitetip reef (B), blacktip reef (C), silvertip (D), tiger (E) and oceanic whitetip sharks (H). A third order polynomial regression was fitted for silky sharks (G). Vertical lines indicate implementation of the Maldives shark sanctuary, data reported after this date or considered shark sightings (light blue points).

2.4.2. Historical trends in distribution

Maps of perceived spatiotemporal trends showed a substantial (>60%) decline in reef shark distribution between 1980 and 2010 (Figure 2.4, Table 2.2). Shark hotspots (areas marked by >40%) declined by >80%.

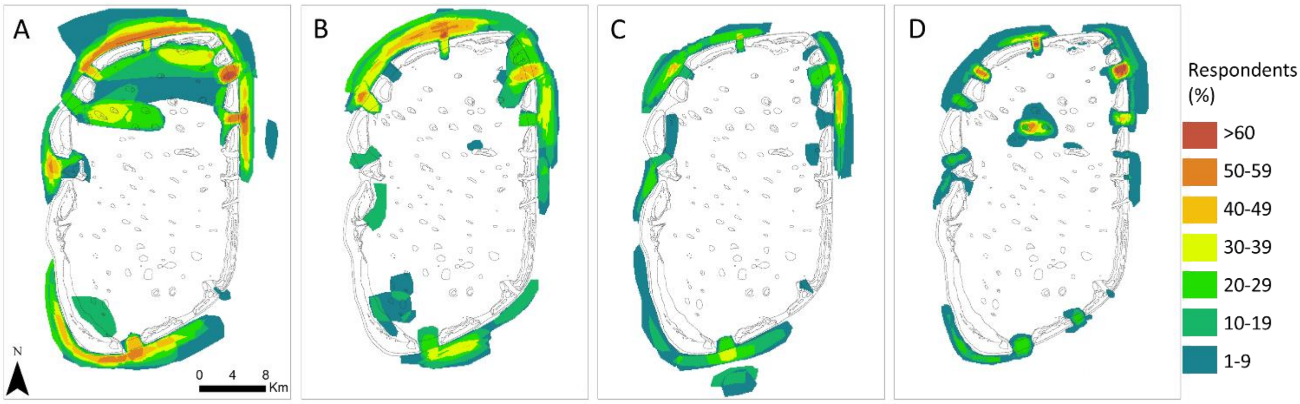

Figure 2.4. Perceptions of shark distribution in A) 1980s, B) 1990s, C) 2000s and D) 2010s. Colour represents probability that a respondent observed sharks in the area, standardised by the number of interviewed fishers who were active in each decade (1980 (n = 41), 1990 (n = 46), 2000s (n = 36), 2010s (n = 47). All interviewed fishers had prior experience of targeted shark fishing, data reported post 2010 (D) represent shark encounters while reef fishing.

Table 2.2. Perceived spatiotemporal trends in shark distribution. Values represent the area marked by respondents during each time period.

	>40% of respondents		>20% of respondents		Total	
Decade	**Area (km^2)**	**Decline (%)**	**Area (km^2)**	**Decline (%)**	**Area (km^2)**	**Decline (%)**
1980s	45.5		180.9		416.6	
1990s	39.3	-13.6	105.9	-41.4	248.7	-40.3
2000s	3.1	-93.2	46.3	-74.4	189.4	-54.5
2010s	6.3	-86.2	30.6	-83.1	164.2	-60.6

2.4.3. Validation of contemporary LEK

Participatory maps of contemporary distribution and abundance suggest that shark hot spots were located on the outer reef slopes and in close proximity to atoll channels (Figure 2.5A, 2.5C).

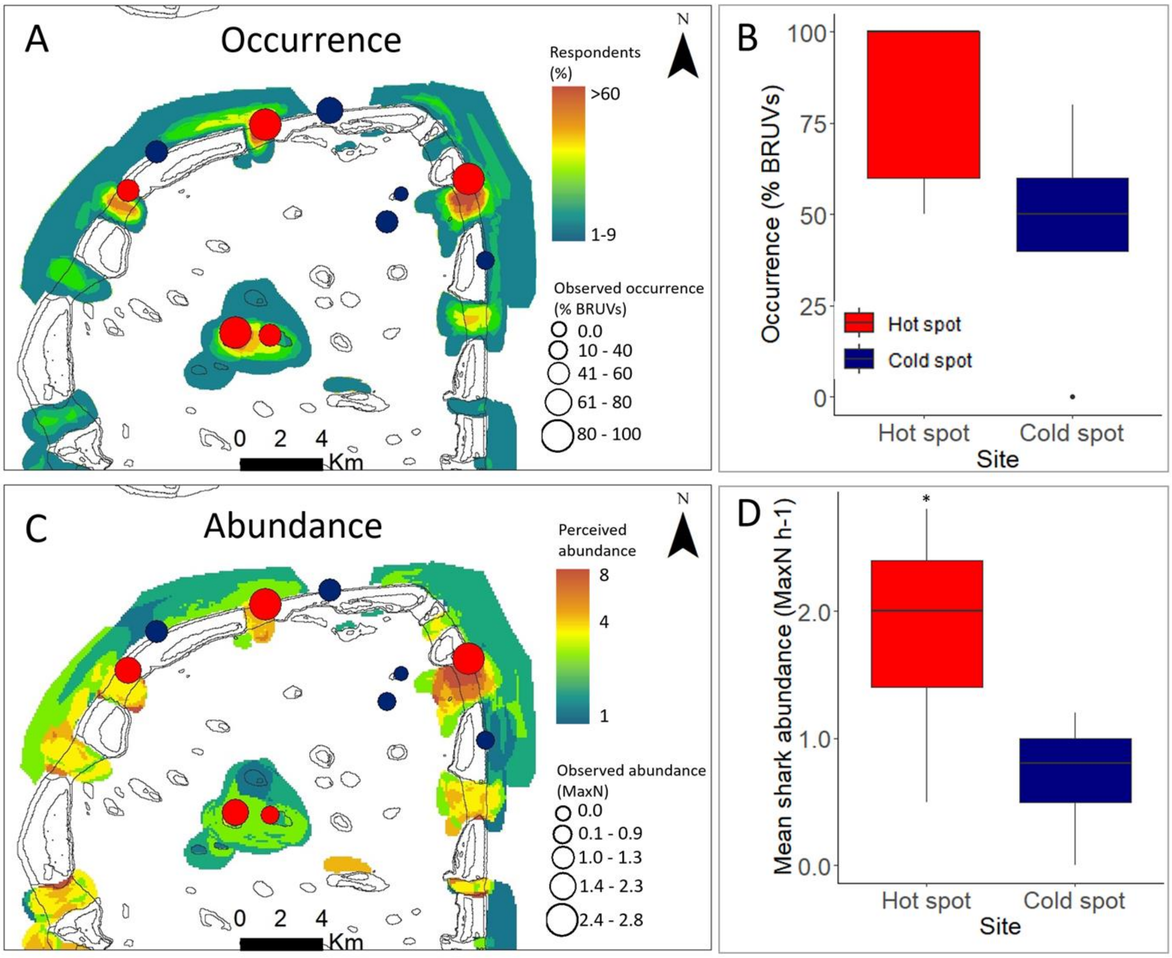

Figure 2.5. Validation of contemporary (2010-2019) shark distribution and abundance. Maps represent perceptions of shark distribution (A) and abundance (B) with Baited Remote Underwater Videos (BRUVs) data overlaid. Empirical (BRUVs) data comparing probability of shark occurrence (C) and average shark abundance at hot and cold spots.

In total 43 sharks were recorded on BRUVs deployed (n = 25) at perceived hotspots with at least one shark recorded on 84% of deployments (Figure 2.4B). Comparatively, 17 sharks were recorded on BRUVs deployed (n = 25) at cold spots with sharks recorded on 44% of deployments. Shark abundance (1.91 ± 1.38 hr^{-1} vs 0.73 ± 0.91 hr^{-1}) was significantly higher (~ 2.5 times) at perceived hot vs cold spots (Figure 2.5D, Mann-Whitney = 389.5, $p < 0.01$). To account for spatial differences shark abundances at inner and outer atoll sites were also compared; abundance was significantly higher at outer atoll hot vs not spots (Mann-Whitney = 165.0, p = 0.02) and inner atoll hot vs not spots (Mann-Whitney = 51.0, p = 0.03).

The probability of shark occurrence and abundance was also higher at hot vs cold spots for each species recorded (Table 2.3) and significantly so for tawny nurse sharks (Mann-Whitney, W = 333, $p < 0.05$). Species richness was also greater at hot vs cold spots (3.2 ± 0.84 hr^{-1} vs. 2.0 ± 1.26 hr^{-1}) although not significant (Mann-Whitney, W = 19.5, p = 0.08). At hotspots, there was a positive correlation between perceived and observed abundance (r^2 (3) = 0.78, p = 0.12) at the site level, however fishers overestimated abundance.

Table 2.3. Summary of shark occurrence and abundance on Baited Remote Underwater Videos (BRUVs). MaxN represents the maximum number of each shark species observed in a single frame. Significant differences marked *.

Species		Site	Total (n)	Occurrence	MaxN hr^{-1}
Common name	Latin name			(% BRUVs)	(mean ± SD)
Grey reef	*C. amblyrhynchos*	Hot	13	32.0	0.57 ± 0.84
		Cold	3	12.0	0.13 ± 0.34
Whitetip reef	*T. obesus*	Hot	11	40.0	0.48 ± 0.59
		Cold	6	24.0	0.26 ± 0.45
Blacktip reef	*C. melanopterus*	Hot	9	36.0	0.39 ± 0.50
		Cold	6	24.0	0.26 ± 0.45
Tawny nurse	*N. ferrugineus*	Hot	8	32.0	0.34 ± 0.48*
		Cold	2	8.0	0.08 ± 0.29
Lemon	*N. brevirostris*	Hot	1	4.0	0.04 ± 0.21
		Cold	0	0.0	0.00
Silvertip	*C. albimarginatus*	Hot	1	4.0	0.04 ± 0.21
		Cold	0	0.0	0.00

2.5. Discussion

In both terrestrial and marine systems, the inability to triangulate spatial data is a major hindrance in the incorporation of LEK into management plans (Turner *et al.*, 2015). To my knowledge this is the first time that quantitative information on shark abundance and spatial distribution derived from fisher LEK have been validated. Here the validation of LEK with ecological assessments using an established technique for monitoring mobile predators (BRUVs) advocates the application of LEK to provide fine-scale distribution data. Inclusion of such data in conservation policy is especially pertinent for data-poor species and regions that lack the capacity to collect empirical data (Temple *et al.*, 2020). In the continued absence of spatial and historical data for marine predators (Posen *et al.*, 2020), the methods described also provide a low-cost approach to identify key areas and the evidence required for both single species and ecosystem-based fisheries management. Specifically, LEK showed high potential for the documentation of species distribution and relative abundance trends, however, did lack precision for absolute abundance with fisher community reported abundance overestimating observed abundance.

Local Ecological Knowledge (LEK) also provided an opportunity to assess and compare trends in relative shark abundance over a 50-year period in a region with limited temporal data. From a conservation standpoint, the most important population trends include the perceived decline in oceanic whitetip and silky sharks, species classified as critically endangered and vulnerable (IUCN, 2021). For both species, reported declines (55% and 79% respectively) were similar to global estimates of abundance change (Pacoureau *et al.*, 2021). Further, perceived trends for silky sharks were consistent with catch reported to the FAO, indicating a substantial decline around early 2000 (FAO, 2020). Perceived declines in reef shark abundance (~70%) also align with scientific surveys conducted in the Chagos Archipelago (Graham *et al.*, 2010) and the eastern Pacific Ocean (White *et al.*, 2015) and contribute to available evidence that suggests abundances are now substantially lower than historical baselines (Osgood and Baum, 2015). Conversely, respondents could have failed to perceive accurate population trends for scalloped hammerhead and tiger sharks as neither were a target species in the shark fishery and were only ‘occasionally’ taken (Anderson and Hafiz, 1997). It is also plausible that tiger shark populations were exploited in a traditional shark fishery prior to the 1960s (Anderson and Hafiz, 1997) and thus declines were not captured in this data.

Substantial declines in the spatial extent of shark distribution and occurrence rate may also be attributed to fisheries exploitation (Worm and Tittensor, 2011). Temporal distributions align with perceived abundance trends with substantial declines in distribution reported in the 2000s. This supports previous studies which show positive correlations between species range and abundance (Brodie *et al.*, 1998; Worm and Tittensor, 2011). Findings also show that occurrence hotspots were relatively stable over time and therefore represent important sampling locations for the collection of high-quality empirical data. Despite the total area mapped remaining low in the 2010s, hotspot area increased suggesting that atoll channels may support remnant reef shark populations. These patterns attest to the notion that declines in perceived occurrence was due to a reduction in abundance rather than shifts in fishing effort as population declines are often accompanied by reducing densities in marginal habitats while core habitat areas maintain high densities (Santos *et al.*, 2019).

Similar to other studies in which LEK is appreciated for its site-specificity (Joa *et al.*, 2018), areas mapped by fishers during interviews were not randomly distributed but rather created hotspots in specific locations. Validation of contemporary hotspots shows that LEK provided reliable information about the presence and relative abundance of reef sharks over a larger spatial range than ecological surveys, including for populations observed in low densities. Observed abundance was significantly higher at hot vs cold spots, >2.5x higher than averages for the Maldives (Clarke *et al.*, 2013) and 8x higher than the regional average for the Indian Ocean (MacNeil *et al.*, 2020). Identified hotspots should therefore be a high priority for consideration in any future revisions of the shark sanctuary. At the site level, comparisons of perceived occurrence and abundance with empirical BRUVs data show that fishers consistently identified major hotspots but showed greater inconsistencies regarding minor hotspots. Studies utilising LEK to document fishing effort (Turner *et al.*, 2015) and socio-ecological hotspots (Alessa *et al.*, 2008) also reported similar findings.

This study represents one of the longest spatiotemporal data sets for reef sharks in the Indian Ocean. Importantly, data suggests that current populations remain substantially lower than historical baselines despite anecdotal reports of increased abundance in the region following implementation of the shark sanctuary (Ali and Sinan, 2015). Contextualising present-day populations and preventing 'shifting baseline syndrome' (Pauly, 1995) is timely given recent discussion in March 2021 to reopen the Maldives shark fishery. Assessments of population change are vital for evaluating progress against conservation targets, yet temporal assessments of marine predators are often infeasible using conventional ecological techniques (Parry and Peres, 2015). Validation of contemporary LEK shows that fisher's spatial knowledge is reliable and increases trust in historical data which cannot be validated. However, comparisons of absolute abundance suggest that fishers tend to overestimate abundance at hotspots and underestimate at cold spots, thus perceptions of species decline may not be as great in magnitude as reported.

As with other approaches, the interview methods used have limitations: (1) documenting temporal trends relies on memory recall for species abundance and distribution resulting in potential spatial and temporal inaccuracy; (2) without explicit shark absence mapping by participants, there is ambiguity as how to interpret areas that were not mapped. Here unmapped locations were designated as cold spots however this does not indicate the absence of sharks. In fact, observed shark abundance was still relatively high at cold spots (0.73 ± 0.91 sharks per hour) when compared to local averages (Clarke *et al.*, 2012); (3) spatial data will be constrained by both fishing effort and sample coverage and hotspot maps will not encompass all areas of high shark abundance within the atoll. Nonetheless, findings demonstrate the accuracy of LEK in mapping predator abundance and distribution over time.

This approach can be broadly applied to data poor contexts to reconstruct change, identify important areas for management and inform the conservation of endangered species in both marine and terrestrial systems. Key examples range from large-bodied charismatic species (e.g. whales) whose large spatial extent can be resource intensive (Frans and Augé, 2016; Madsen *et al.*, 2020) to elusive (e.g. seahorses) and rare species (e.g. small mammals) that may otherwise by difficult to study (Turvey *et al.*, 2014; Zhang and Vincent, 2017). Economically, costs associated with the interview protocol described were substantially lower than empirical data collection (see table A4 for cost breakdown). Furthermore, participatory mapping is an effective communication tool to engage with resource users and allow marine stakeholders to participate in decision making processes (Selgrath *et al.*, 2017).

2.6. Conclusion

Through the triangulation of data sources and validation of fishers' spatial knowledge this study shows that LEK can provide fine scale distribution data that can inform decision making and evidence-based management. Findings also provide historical context to current population trends, and therefore facilitate more accurate assessments of species status and inform recovery targets. This research utilises rapid, low-cost methods which can readily be applied to data poor species and regions to reveal historical trends to inform contemporary management.

Chapter 3 First evidence for ecological efficacy of a shark sanctuary for Maldivian reef shark populations

3.1. Abstract

Marine Protected Areas (MPAs) and more recently shark sanctuaries are widely applied policy instruments to protect vulnerable shark populations. However, empirical evidence on the ecological effectiveness of these approaches to reduce declines and aid population recovery is limited. Ideally monitoring of marine predators would be conducted before and after conservation action and in control and treatment areas. Yet, for most regions such data are unavailable and ecological effectiveness is commonly evaluated spatially by comparing species abundance inside and outside of MPAs. This is subject to a range of biases, particularly that MPAs are typically designated in areas of high species abundance and thus long-term time series data are needed. Here cost-effective approaches to monitoring were utilised to monitor temporal population trends in Maldivian reef shark populations over a 5-year period (2016-2020). Baited Remote Underwater Videos (110 sites, 464 hours of footage) and citizen science data (2,024 dives) showed that reef shark populations were stable with no significant change in abundance between years. Relative shark abundance was similar between data types (Baited Remote Underwater Videos': 0.71 ± 0.83 sharks per hour, citizen science: 0.91 ± 1.94 sharks per dive) and in line with other protected regions. Given the relatively short timeframe since sanctuary implementation and the low intrinsic rebound potential for reef sharks (~15 years doubling time) population stability is a positive sign that sanctuaries can effectively reduce fishing mortality enough to maintain shark populations and therefore could be an effective management tool for the conservation of reef sharks. However, abundance remains below remote islands deemed to be pristine, suggesting populations are relatively healthy but not yet recovered from earlier exploitation. Patterns described represent important contemporary baselines against which future change can be quantified and management interventions evaluated.

3.2. Introduction

The loss of biodiversity is among the most critical environmental problems globally, threatening key ecosystem services and human well-being. Currently 39% of species assessed on the IUCN red list (16,306 of 41,415) are threatened with extinction with the extinction rate increasing by 100 times in the past century compared to the average rate over the past 10 million years (IPBES, 2019). Protected Areas (PAs) are a widely advocated tool to address this crisis, playing a key role in maintaining sustainable population levels (Gray *et al.*, 2016) and minimising habitat loss. Globally, PAs cover 15.0% of land area and 7.4% of the ocean (Rodrigues and Cazalis, 2020). The post-2020 global framework aims to expand this coverage to 30% by 2030 in both terrestrial and marine systems (CBD, 2020a). However, opportunistic rather than systematic designation of PAs (MacKeracher *et al.*, 2018) and a focus on percentage coverage without evaluation of PA efficacy may lead to failure to achieve conservation goals (Shrestha *et al.*, 2021).

In response to mounting evidence of substantial, widespread, and ongoing declines in the abundance of sharks worldwide (Pacoureau *et al.*, 2021) Marine Protected Areas (MPAs) are increasingly advocated as a tool for restoring and protecting shark populations (Dulvy *et al.*, 2017; MacKeracher *et al.*, 2018) with approximately one third of ocean area protected designated exclusively for sharks (MacKeracher *et al.*, 2018). Broadly defined as any spatial protection within which extractive activities are either partially restricted or fully prohibited, other terms which fall under the shark MPA category include reserves, sanctuaries, parks, no-take zones, fishery exclusion zones, and closed areas. In the last decade, MPAs for shark conservation have been established at an unprecedented rate, yet their effectiveness in reducing declines and aiding population recovery is often implicitly or explicitly assumed in many practical situations (Ribas *et al.*, 2020).

Measuring the ecological efficacy of MPAs for sharks can be challenging due to limited temporal data and shark life history traits characterised by slow growth, long life, large adult size, late sexual maturity and reproduction, long gestation period and reduced fecundity (Cortés, 2000). Thus, MPA effectiveness is commonly evaluated spatially by comparing ecological or biological measures (e.g. shark density, size, biomass, species richness) inside and outside of protective boundaries (Robbins *et al.*, 2006; Bond *et al.*, 2012; Goetze and Fullwood, 2013; MacNeil *et al.*, 2020). While such evaluations are important and many have shown that shark abundance is higher within MPAs relative to comparable fished areas (Bond *et al.*, 2012; MacNeil *et al.*, 2020), they don't account for differences in initial shark densities and habitat quality and can often mask the occurrence of slow population declines within MPAs (Bond *et al.*, 2017; Geldmann *et al.*, 2019). Moreover, MPAs are not randomly located but often biased towards remote regions with low levels of exploitation (Geldmann *et al.*,

2019) thus, spatial comparisons may present misleading results as to MPA effectiveness (Bond *et al.*, 2017).

Ideally monitoring of shark populations would be conducted before and after sanctuary implementation and in control and treatment areas yet, baseline data are notably absent for reef shark populations globally (Bond *et al.*, 2017). In the Maldives, shark populations were not monitored prior to implementation of the shark sanctuary in 2010 (Ali and Sinan, 2015), however, empirical data from fisher interviews shows substantial declines (~69%) in reef shark abundance over the last half a century (see Chapter 2). Standardized time-series data and cost-effective approaches to monitoring population change within the sanctuary are therefore important to establish contemporary baselines against which future change can be measured to evaluate the ecological efficacy of the sanctuary.

Baited Remote Underwater Videos (BRUVs) are one of the most accessible, non-destructive, and highly replicated tools to quantify fish assemblages across large spatial scales (Espinoza et al., 2020, MacNeil et al., 2020). BRUVs can avoid many of the biases and ecological impacts associated with extractive and traditional sampling methods (Cappo et al., 2004, Caldwell et al., 2016). For example, BRUVs can sample over a wide range of habitats not suitable for fishing (Espinoza *et al.*, 2020) and are less confounded by behavioural biases associated with Under Water Visual Census (Lowry *et al.*, 2012). Citizen science initiatives are also promoted as a simple and cost-effective alternative to traditional approaches, particularly for the study of conspicuous marine species and megafauna inhabiting nearshore areas and coral reefs (Vianna et al., 2014, Ward-Paige et al., 2018).

In this study, BRUVs and citizen science datasets were used to quantify and monitor shark abundances inside the Maldives shark sanctuary. Specifically, to: 1) quantify shark abundance and diversity to provide baseline data post sanctuary implementation; and 2) investigate temporal trends in shark abundance to assess sanctuary efficacy.

3.3. Methods

3.3.1. Study site

Fieldwork was conducted in North Malé Atoll (4°18’34.5”N, 73°25’26.4”E). Located on the eastern side of the atoll chain, North Malé Atoll covers a total surface area of 1568 km^2 (Beetham and Kench, 2014). It has an atoll perimeter of 161 km, 117.9 km of which is shallow edge reef while 43.1 km is deeper channels (Beetham and Kench, 2014), promoting water exchange between the adjacent open ocean and the atoll lagoon. In 2010, the Maldives declared its entire Exclusive Economic Zone (EEZ) a shark sanctuary, prohibiting the fishing of all sharks, the retention of sharks caught as bycatch, and the possession, trade, and sale of sharks and shark products.

3.3.2. Baited Remote Underwater Videos (BRUVs)

Baited Remote Underwater Videos (BRUVs) were used to quantify the distribution, diversity and relative abundance of reef-sharks. In total, 464 BRUVs were deployed on inner atoll reefs in North Malé Atoll between 2016 and 2020 (Table 3.1). In 2016, a preliminary study was conducted with BRUVs deployed in May and June. From 2017 – 2020 BRUVs were deployed between January and April during the north-east monsoon season. BRUVs were deployed on coral-reef habitat at an average depth of 8.3 ± 1.5 m, this depth was chosen primarily for comparative purposes (i.e. ease of comparing similar reef habitats at this depth which are more variable deeper).

Table 3.1. Summary of annual Baited Remote Underwater Videos (BRUVs) deployed.

Year	BRUVs deployed (n)
2016	49
2017	102
2018	105
2019	107
2020	101
Total:	**464**

A BRUV unit consisted of a GoPro HERO 4 camera attached to a stainless-steel frame, with a mesh bait bag suspended 1 m in front of the camera (Figure 3.1). BRUVs were deployed with 6 mm polypropylene ropes and surface marker buoys to facilitate retrieval. Adjacent deployments were separated by a minimum of 600 m to reduce the likelihood of sharks moving between replicates and ensure independence (Cappo et al. 2004; Goetze et al. 2018). Bait type and amount were kept constant (1 kg scombrids) and all BRUVs were deployed for 70 minutes to ensure there was 60 minutes of analysable footage. Date, time, location (latitude and longitude) and depth were recorded in situ for each deployment. BRUVs were deployed during daylight hours (09:00–17:00) to reduce bias associated with diurnal changes in shark behaviour (Willis et al., 2006) and to aid detection and species identification.

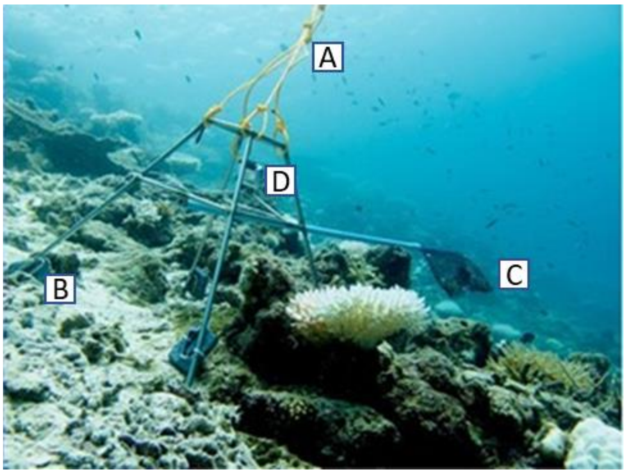

Figure 3.1. Baited Remote Underwater Video (BRUV) array during deployment: A) rope to surface buoy, B) weighted legs, C) bait-filled mesh bag on bait arm (pvc pipe), D) GoPro hero 4+ camera and housing.

During video processing, 43 deployments were excluded from analysis as (1) the camera angle had moved and was facing straight up or straight down or (2) there was an issue with SD cards or camera batteries and 60 minutes of analysable footage was not available. Consequently, only 419 deployments were included in the final dataset. For each BRUV deployment the maximum number of sharks seen in a single frame (MaxN) was determined for each species, as a metric of relative abundance to avoid double-counting individuals, and Time of first arrival (TOFA). Video analysis began after a settlement period (min 02:00–max 07:00 min) had elapsed (Kiggins *et al.*, 2018). The settlement period was characterised as over when all sand or sediment had settled, and visibility returned to normal.

3.3.3. Citizen science

Data were collected from dive guides working as employees of Banyan Tree Vabbinfaru and Angsana Ihuru Resorts in North Malé Atoll. Standard dive logs were completed after each boat dive between January 2016 and December 2020. A total of six guides recorded information for 2,024 dives at 36 sites. For each dive the date, dive site visited, dive time, depth, number of divers in the group, species and counts of individual sharks sighted were recorded. Each completed log provided observations from a single dive with each dive lasting 52.8 ± 5.0 minutes.

Dive guides participating in the survey had extensive knowledge of the Maldives marine environment and shark species. They also received training from Banyan Tree Marine Labs marine biologist and were instructed to report the total number of individual sharks of each species observed during the entire dive. Dive guides were conservative with counts and where possible they reduced repeated counts by observing features that permitted individual shark identification (e.g., marks, pigment patterns).

To assess temporal patterns in abundance data was filtered to only include records of the three most frequently visited dive sites and sites with consistent shark observations. These sites are known to be aggregations or hotspots of charismatic megafauna, including reef sharks, manta rays and turtles. A total of 141 dives were recorded at Hulhangu kandu, 145 at Okkobe thila and 127 at Lankan Manta point.

3.3.4. Analysis

To test for a consistent trend in shark abundance over the time series the influence of the numerical value 'year' on abundance was investigated for both BRUVs and citizen science data sets. For the BRUVs dataset, Generalised Linear Mixed Models (GLMM) were developed with the R package lme4 (Bates *et al.*, 2015) with site as a random effect to account for spatial variance in BRUVs deployments between years. Generalised Linear Models (GLMs) were used for the citizen science dataset as surveys were conducted at fixed dive sites. A multi-stage testing procedure as outlined by Campbell et al. (2021) was followed, first fitting data with a Poisson GLM(M) and then conducting preliminary tests to ensure the distributional assumptions of the Poisson GLM(M)s were not violated (Figure 3.2). GLMs were tested for overdispersion using the AER package (Cameron and Trivedi, 1990) and GLMMs using a function developed for mixed-effect models in lme4 (Bolker, 2021). Models were then tested for zero-inflation (Campbell, 2021). Model residuals for BRUVs data showed no indication of overdispersion (Table A5) or zero-inflation (Table A6) and thus Poisson GLMMs were fitted. Model residuals for citizen science data showed overdispersion (Table A7) but not zero-inflation (Table A8) and thus negative binomial GLMs were fitted. All analyses were carried out using R Studio version R version 3.5.3 (R Core Team, 2019).

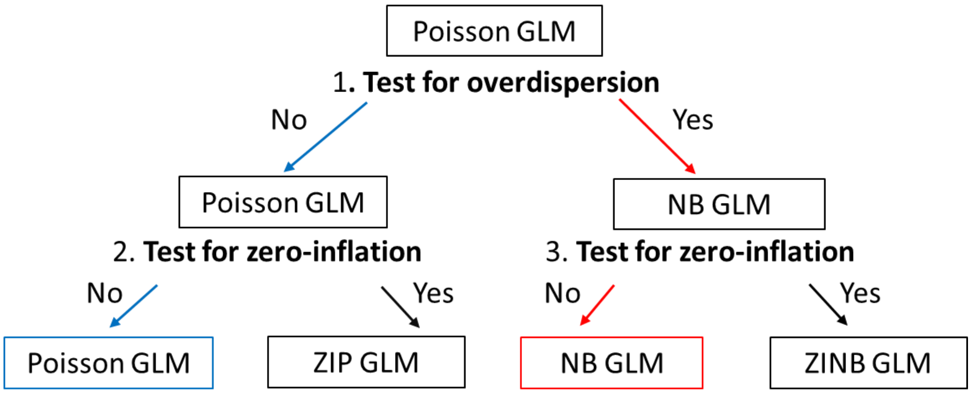

Figure 3.2. Model selection criteria adapted from Campbell et al. 2021. A Poisson Generalised Linear Model (GLM) was the starting point. Model residuals were then tested for overdispersion and zero-inflation. Blue lines represent Baited Remote Underwater Video data and red lines citizen science data.

For each species, after accounting for site effects, the year coefficient was used to calculate the percentage increase or decrease in relative abundance annually over the 5-year study period for BRUVs data (White *et al.*, 2015). Power analysis was also conducted on models using BRUVs data to assess the influence of year on all sharks. Power analysis was carried out using the SIMR package for power analysis on GLMMs using simulation (Green and MacLeod, 2016).

3.4. Results

3.4.1. Baited Remote Underwater Video (BRUVs)

Throughout the survey period a total of 299 sharks were observed from 8 species (Table 3.2) representing 2 families (n = 419 samples). The number of sharks recorded per deployment varied between 0 and 7, and species richness varied between 0 and 3.

Table 3.2. Summary of shark sightings and abundance on Baited Remote Underwater Video deployments from 2016 - 2020. MaxN represents the maximum number of each shark species observed in a single frame.

Common name	Species	Total individuals (n)	Occurrence (% BRUVs)	MaxN hr-1 (mean ± SD)
Blacktip reef	*Carcharhinus melanopterus*	121	27.7	0.29 ± 0.48
Tawny nurse	*Nebrius ferrugineus*	92	19.3	0.22 ± 0.52
Whitetip reef	*Triaenodon obesus*	74	17.4	0.18 ± 0.39
Grey reef	*Carcharhinus amblyrhynchos*	5	1.2	0.01 ± 0.11
Tiger	*Galeocerdo cuvier*	3	0.7	0.01 ± 0.08
Silky	*Carcharhinus falciformis*	2	0.5	0.004 ± 0.07
Silvertip	*Carcharhinus albimarginatus*	1	0.2	0.002 ± 0.05
Lemon	*Negaprion brevirostris*	1	0.2	0.002 ± 0.05

Relative shark abundance for all species combined averaged 0.71 ± 0.83 sharks per hour between 2016 and 2020 (Figure 3.3A) and showed no significant trend over time (Table 3.3). At the species level there was no significant temporal trend in blacktip reef, whitetip reef and tawny nurse shark abundance (Table 3.3). At least one shark was recorded on 52% of deployments (Figure 3.3B).

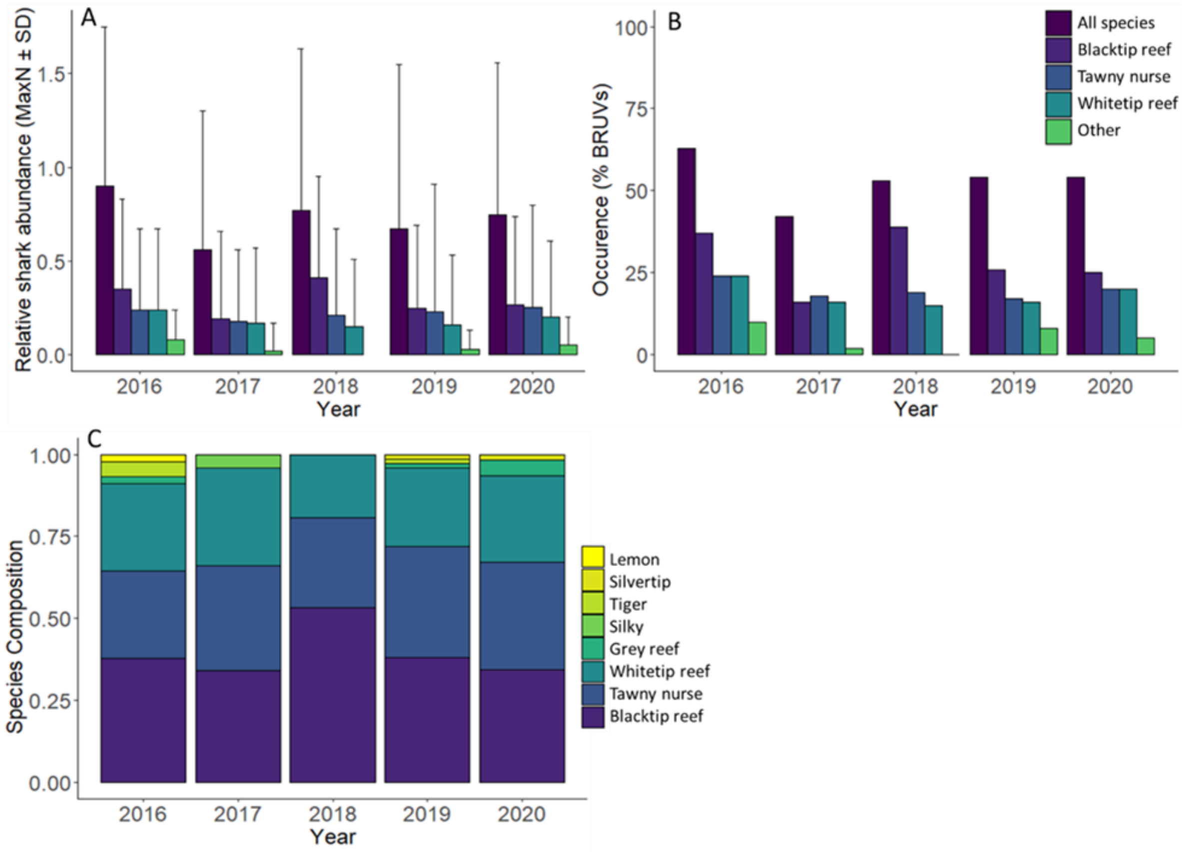

Figure 3.3. A) Relative shark abundance, B) shark occurrence and C) species composition recorded on Baited Remote Underwater Videos from 2016-2020.

Species composition was also consistent between years with black-tip reef, white-tip reef and tawny nurse sharks comprising >90% of shark sightings (Figure 3.3C). After accounting for site effects, it was estimated that all sharks showed an annual increase of 1.0% (95% CI: -2.8% - 3.1%) between 2016 and 2020. Whitetip reef sharks were estimated to have declined by 0.2% (95% CI: -2.02% -2.4%).

Table 3.3. Generalised Linear Mixed Models (GLMMs) examining the influence year on shark abundance from Baited Remote Underwater Videos from 2016-2020. The variance and standard deviation associated with the random effect site are also given.

	Model	Estimate	Std.error	Z-value	Pr(>|z|)
Fixed effect (Year)	All sharks	0.011	0.047	0.241	0.809
	Blacktip reef	-0.031	0.074	-0.414	0.679
	Tawny nurse	0.071	0.088	0.809	0.419
	Whitetip reef	-0.015	0.092	-0.161	0.872
		Variance	**Std.Dev**		
Random effect (Site)	All sharks	0.093	0.305		
	Blacktip reef	0.231	0.480		
	Tawny nurse	0.002	0.004		
	Whitetip reef	0.567	0.753		

Power analysis indicated that the annual sample size needed to detect the obtained effects for all sharks at >80% power and the 0.05 significance level was 81 BRUVs deployments (power 82%, 95% CI 78 – 83%), thus the annual sample size in this study was sufficient. However, the study would need to run for 16 years to have ≥80% power to detect an effect of year at the specified size (0.011) detected in the model for all sharks (Figure 3.4).

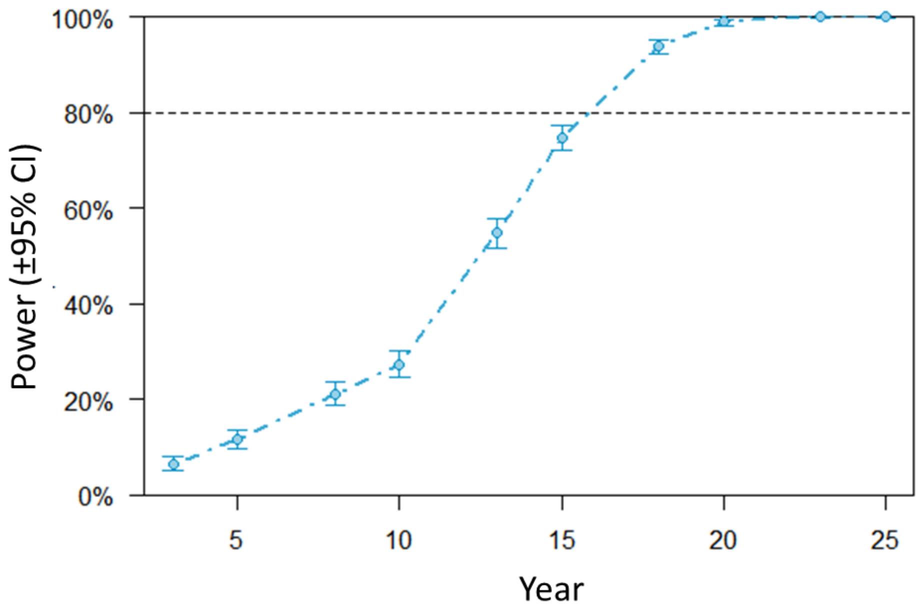

Figure 3.4. Power (± 95% CI) of Generalised Linear Mixed Model for all sharks to detect a fixed effect with size of 0·011, calculated over a range of sample sizes using the powerCurve function. The number of distinct values for the variable 'Year' is varied from 3 to 25.

Reef sharks were ubiquitous across survey sites, however sites in the centre of the survey area consistently supported relatively higher abundances (Figure 3.5). It was more common to record different species on each BRUVs than multiple individuals from the same species.

Mapping of individual species distribution provided no clear patterns in spatiotemporal distributions.

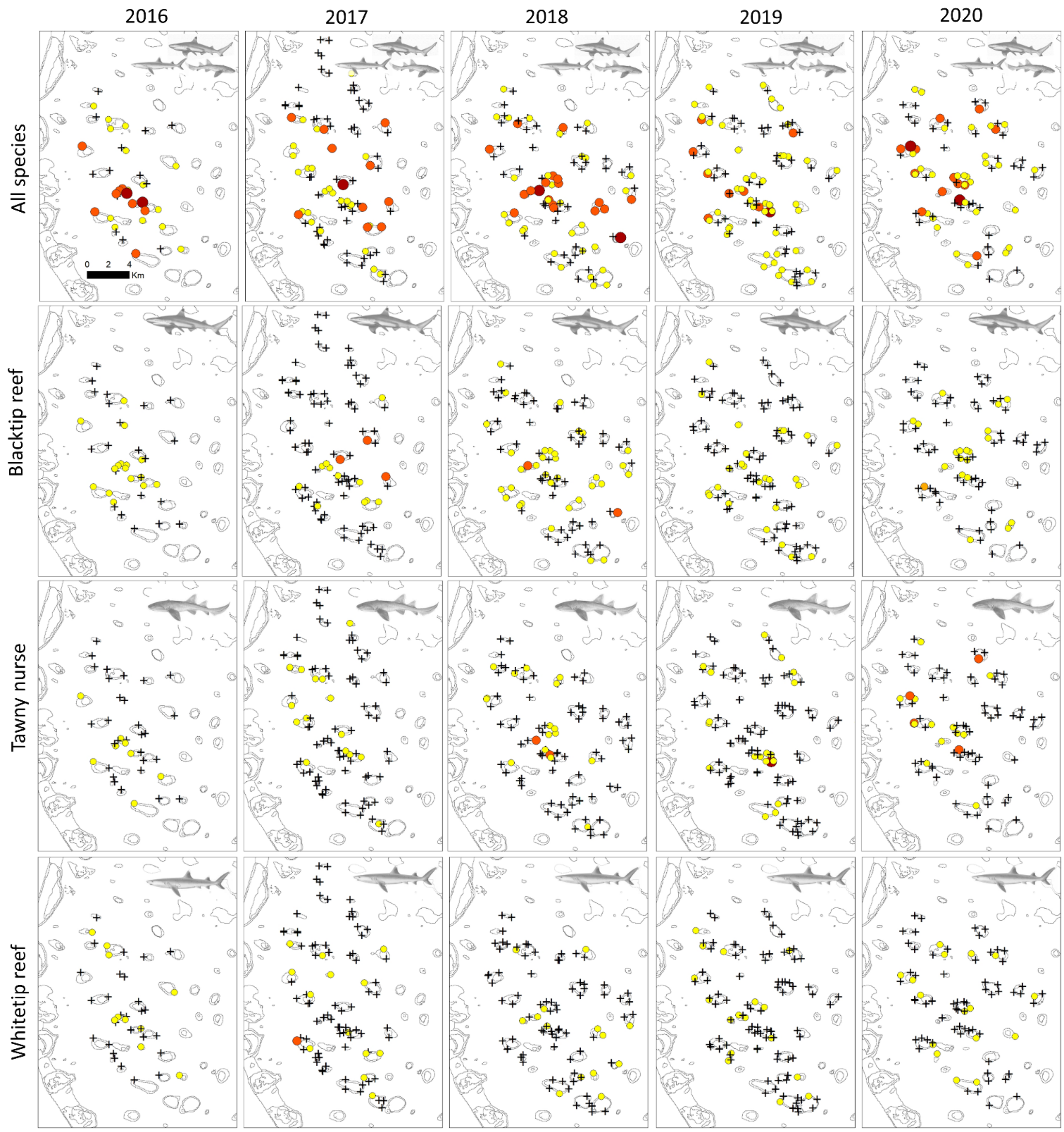

Figure 3.5. Shark spatiotemporal distribution. Points represent relative abundance on each Baited Remote Underwater Video deployment from 2016-2020. No sharks (+), 1 shark (yellow dot), 2 sharks (orange dot), 3 sharks (red dot).

3.4.2. Citizen science

Shark sightings were recorded on 2,024 dives between 2016 and 2020 at 36 sites in North Male Atoll. A total of 1,844 sharks were reported from 5 species and 3 families (Table 3.4). Whitetip reef sharks were the most frequently encountered species, occurring on 29.2% of dives. Blacktip reef, grey reef and tawny nurse sharks were reported on <10% of dives (Table 3.4).

Table 3.4. Summary of shark sightings and abundance from citizen science datasets from 2016-2020.

Species	Common name	Total Individuals	Occurrence (% Dives)	Average/ dive (mean ± SD)
Whitetip reef	*Triaenodon obesus*	1224	29.2	0.60 ± 1.36
Blacktip reef	*Carcharhinus melanopterus*	303	7.8	0.15 ± 0.81
Grey reef	*Carcharhinus amblyrhynchos*	211	5.1	0.10 ± 0.65
Tawny nurse	*Nebrius ferrugineus*	104	4.2	0.05 ± 0.28
Leopard	*Triakis semifasciata*	3	0.1	0.001 ± 0.03
	Total:	**1,844**	**35.9**	**0.91 ± 1.94**

Overall, the spatiotemporal distribution of reef sharks across dives sites appears consistent between years (2016-2020). Whitetip reef sharks were ubiquitous across dive sites and were reported in highest densities in atoll channels and outer edge reefs (Figure 3.6). Grey reef sharks were also sighted at outer atoll and channel sites, however they were rarely encountered on inner atoll reefs.

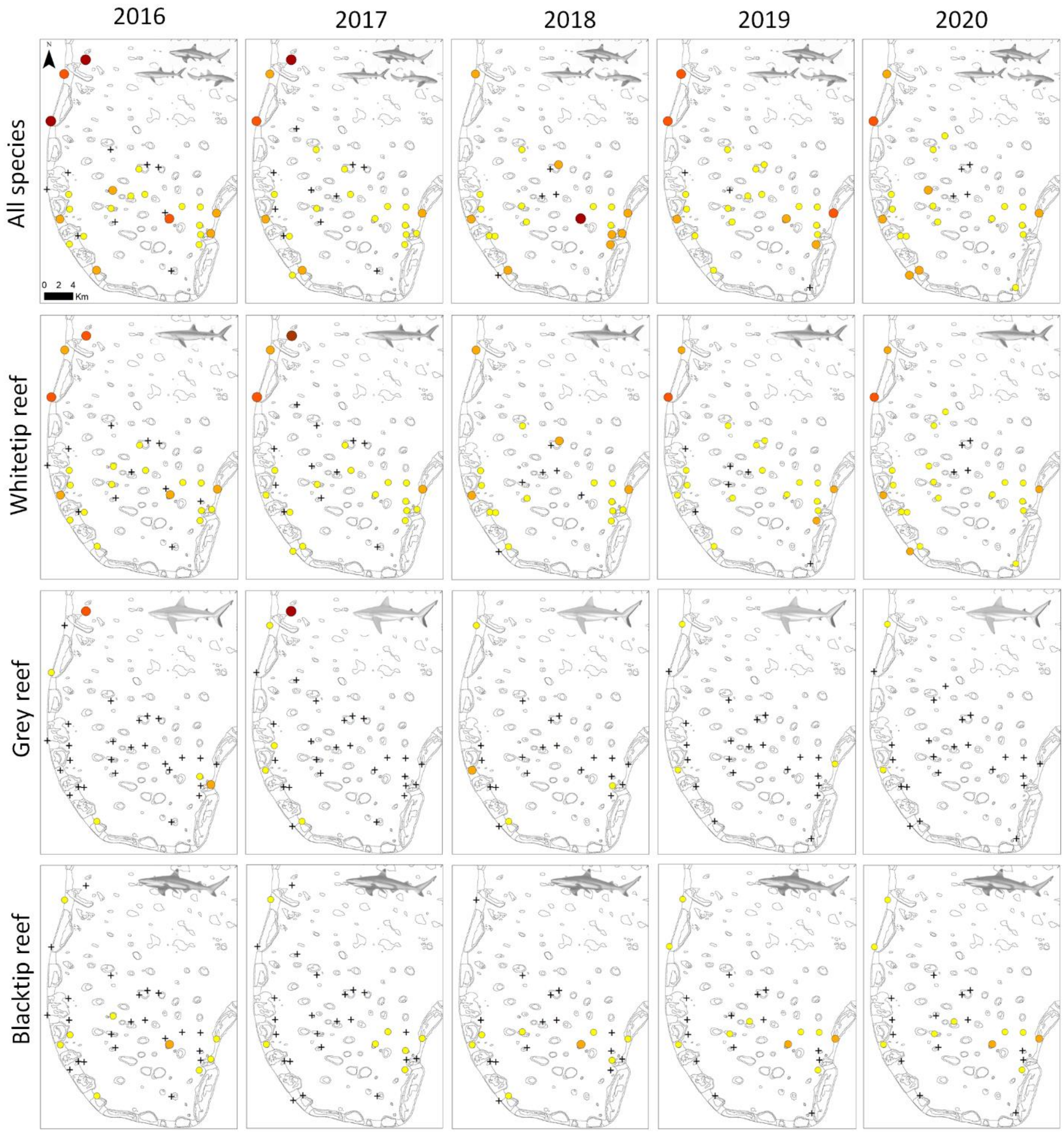

Figure 3.6. Shark spatiotemporal distribution. Points represent average abundance (total shark sightings/ number of dives) reported by dive guides from 2016-2020. No sharks (+), 0.1 - 1 shark (yellow dot), 1.1 -3 sharks (light orange dot), 3.1 - 5 sharks (dark orange dot), 5.1 + sharks (red dot).

The final dataset, filtered to only include records of the most frequently visited dive sites and sites with consistent shark observations, included data for 413 dives at 3 sites over a period of 5 years (Figure 3.7). At each site total shark abundance showed no significant temporal trend over the time-series (Table 3.5).

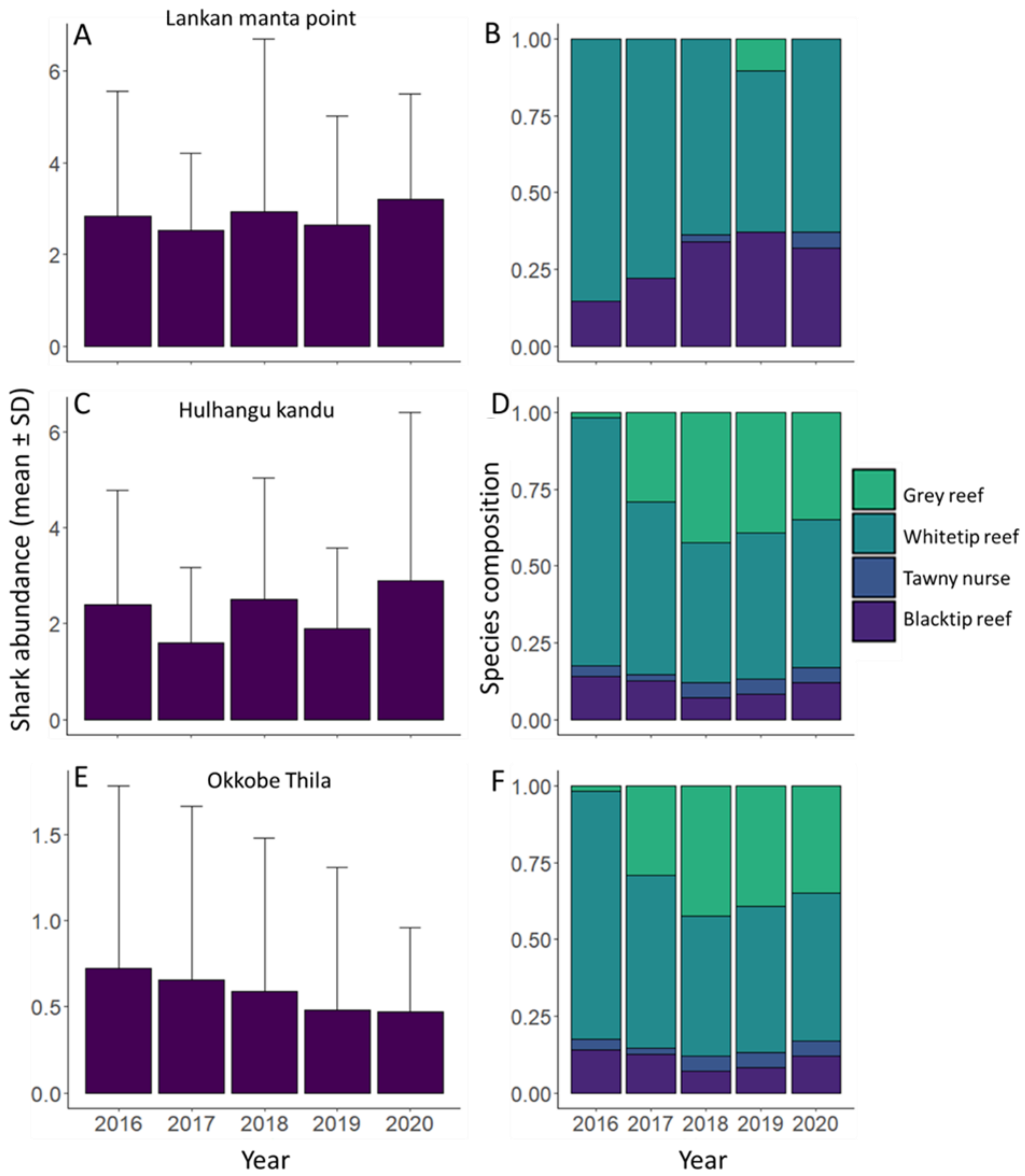

Figure 3.7. Shark abundance and species composition from citizen science surveys conducted between 2016-2020 at Lankan Manta Point (A-B), Hulhangku Kandu (C-D) and Okkobe Thila (E-F).

Table 3.5. Negative binomial Generalised Linear Models examining the influence of year on shark abundance from citizen science surveys from 2016-2020.

Model	Estimate	Std.error	Z-value	p-value
Lankan Manta Point	0.0735	0.0714	1.029	0.304
Hulhangu kandu	0.0461	0.0615	0.750	0.453
Okkobe Thila	-0.1585	0.1019	-1.556	0.123

3.5. Discussion

MPAs and more recently shark sanctuaries are widely applied management options to protect vulnerable shark populations. However, there is little published information that empirically examines ecological effectiveness (Bond *et al.*, 2017). By analysing BRUVs and citizen science data over a 5-year period (2016-2020) this study provides empirical evidence that shark population abundance and species composition is stable within one of the world's first established shark sanctuaries. Considering the relatively short timeframe since the sanctuary was established and the rebound potential of species studied the observed population stability may indicate true population recovery from fisheries exploitation pre-2010. Examples of increasing (Espinoza *et al.*, 2014) or even stable (Bradley *et al.*, 2017) reef shark populations in such environments are rare. Findings represent the first comprehensive baseline survey of Maldivian reef shark populations and will be an important reference point to evaluate the long-term performance and ecological efficacy of the sanctuary.

Standardized time series data sets like this one are very limited for marine predators (Gormley *et al.*, 2012; Bond *et al.*, 2017) yet essential to assess whether or not conservation measures (i.e. sanctuaries) are effective in restoring or maintaining populations. There was no significant trend in reef shark abundance over time, showing that the population is stable within the timeframe surveyed. Given the k-selected life history traits of sharks including slow growth, late sexual maturity, long lifespans, long gestation periods and small brood sizes (Smith *et al.*, 1999), population recovery is inherently slow, especially where populations are already severely depleted (Simpfendorfer, 2000). Moreover, the relatively short duration (10 years) since sanctuary implementation will not cover the full trajectory of population change, thus population increase would not be feasible within the surveyed time frame (Rizzari *et al.*, 2014b). Rebound potential for one of the dominant species recorded (whitetip reef sharks) suggests low recovery capabilities with a reported intrinsic rebound potential of 0.05 yr^{-1} (r_{2M}), equating to a doubling time of approximately 14.6 years (Smith *et al.*, 1999). This is supported with the results of the power analysis, which suggests that the study would need to run for 16 years to detect an effect of year on shark abundance, thus long-term assessments of population change will be vital to assess efficacy of shark sanctuaries.

To evaluate management efficacy, contemporary trends in shark abundance should also be contextualised to historical baselines. Yet, few long-term datasets exist for sharks in coral reef ecosystems (Roff *et al.*, 2016; Ferretti *et al.*, 2018) with no ecological data available for the

Maldives. The lack of ecological data for shark abundance means explicit comparisons pre and post sanctuary implementation cannot be made to quantify population change. However, data presented in Chapter 2 represent the most comprehensive documentation in Maldivian shark populations to date and suggests significant declines in shark abundance between 1970 – 2019. This downward trajectory is also supported by catch estimates (based on export date) for the region and reports from resource users in the fisheries and tourism sector, with substantial declines in shark abundance reported in the 1990s/ 2000s (Anderson and Juaharee, 2009; MRC, 2009; Sinan *et al.*, 2011; Ali and Sinan, 2015). Considering the magnitude of decline reported pre sanctuary implementation, the duration since its establishment and the intrinsic rebound potential of species studied, the observed population stability between 2016-2020 shows that sanctuary regulations have reduced fisheries exploitation enough to halt population declines and suggests that regulations are effectively conserving reef shark populations. Moreover, the patterns described represent important contemporary baselines against which future changes can be quantified.

Based on published data collected using the BRUVs technique, shark abundance in this study was substantially greater than heavily fished locations, such as the eastern red sea, where shark abundance was <0.01 hr^{-1} (Spaet *et al.*, 2016), and above regional estimates for the Indian Ocean, Western Atlantic, Central Pacific and Western Pacific (MacNeil *et al.*, 2020). Abundance was similar to locations with comparable protection including Fiji and Indonesia; 0.8 hr^{-1} (Goetze and Fullwood, 2013; Jaiteh *et al.*, 2016), however remains below remote locations including New Caledonia; >2.5 hr^{-1}, (Juel et al. 2018) and Palmyra Atoll; blacktip reef sharks >2 hr^{-1} (Bradley *et al.*, 2017). Combined, these results support previous studies and imply that Maldivian reef shark populations are relatively healthy in comparison to fished locations (MacNeil *et al.*, 2020) but remain below regions deemed to be unexploited. Further, other studies continue to report ongoing declines in shark populations within MPAs (Graham *et al.*, 2010; White *et al.*, 2015). From a conservation perspective population stability and relatively high abundance in comparison to other regions is encouraging and supports claims that nationwide shark sanctuaries can benefit reef shark populations (MacNeil *et al.*, 2020). However, contemporary trends must be set in the context of the significant declines that occurred in previous decades (see Chapter 2) to avoid insufficient protection status resulting from an underestimated baseline and inflated harvest quotas if the fishery were to reopen

(Lotze *et al.*, 2011). Consideration of the human dimensions and fisher compliance is also important to ensure ecological efficacy long term.

The rate of annual abundance change in this study was also substantially smaller than studies conducted in comparative locations; in this study all sharks showed an annual increase of 1.0% (95% CI: -2.8% - 3.1%) and whitetip reef sharks declined by 0.2% (95% CI: -2.02% -2.4%). At Cocos Island, Costa Rica whitetip reef sharks are estimated to have declined 3.67% annually (95% CI: 3.62% - 3.71%) between 1993 and 2013 despite the area being designated as an MPA since 1984 (White *et al.*, 2015). Similarly, a study conducted in the Chagos Archipelago reported a 90% decline in reef shark abundance between 1975 and 2006, equating to an annual decline of 3.33% (Graham *et al.*, 2010). Larger confidence intervals in this study may be attributed to the shorter timeframe over which trends were analysed with BRUVs data available for 5 years compared to 21 for the Cocos Island data.

This study builds on previous evidence that BRUVs (Acuña-Marrero *et al.*, 2018; Goetze *et al.*, 2018; MacNeil *et al.*, 2020) and citizen science initiatives (Vianna *et al.*, 2014; Ward-Paige *et al.*, 2018) are capable of providing robust estimates of relative shark abundance, distribution and diversity. Although it is difficult to compare abundance estimates between studies that use different abundance indices, both methods used in this study were broadly comparable. Both BRUVs and citizen science datasets indicate that shark populations are stable within North Malé Atoll and relative abundance was similar between datasets (BRUVs: 0.71 ± 0.83, Citizen science: 0.91 ± 1.94). Higher abundance in citizen science surveys is attributed to survey location as dive sites are often chosen based on the likelihood of shark sightings with higher survey effort at outer atoll sites, while BRUVs were primarily deployed across inner atoll sites. Species composition varied between datasets; black-tip reef, tawny nurse and white-tip reef sharks were the most abundant species on BRUVs footage while white-tip reef sharks dominated diver reported sightings. This is attributed to differences in survey depth with dives deeper than BRUVs deployments and differences in survey locations. Findings also advocate the use of BRUVs and citizen science initiatives as accessible and rapid approaches for the long-term monitoring of shark populations. In this study citizen science provided a substantial amount of data over select sites while BRUVs provided a snapshot over a larger geographic area.

Considering the spatial distribution of both diver reported and BRUVs surveys shark species do not show homogeneous distributions across the atoll. Grey reef and whitetip reef sharks were more common on outer edge reefs and atoll channels. This finding is comparable with previous research which observed grey reef sharks in greater densities on outer reef slopes that are associated with strong currents (Papastamatiou *et al.*, 2006; Field *et al.*, 2011; Rizzari *et al.*, 2014b). Blacktip reef sharks occupied inner atoll reefs, agreeing with existing studies (Papastamatiou *et al.*, 2009a; Chin *et al.*, 2013). The tawny nurse shark was found in similar abundance across both inner and outer atoll reefs. Importantly, data suggests that in oceanic atoll systems, both inner and outer atoll reefs are important habitats for vulnerable shark populations and adds weight to a study conducted by Skinner *et al.* (2020) which suggests that the importance of atoll lagoons for reef predators have been previously undervalued. This contradicts the majority of exiting studies which suggest predators show preference for edge habitats (Phillips *et al.*, 2004), including sharks which have been shown to be significantly less abundance in reef lagoons (Dale *et al.*, 2011; Rizzari *et al.*, 2014b). The identification of key habitats or locations that support high shark densities is important to prioritise conservation efforts and to assess risk to threats such as overfishing (Acuña-Marrero *et al.*, 2018). Moreover, improved understanding of shark distribution and occurrence is valuable from and ecotourism perspective (Gallagher and Hammerschlag, 2011). Shark dive tourism generates approximately US$14.4 million annually in the Maldives (Zimmerhackel *et al.*, 2019). BRUVs data shows that shark abundance was consistently high in the centre of the survey area on reefs surrounding Banyan Tree and Angsana resorts. Regulation under the Maldives Tourism Act allows tourist resorts to ban extractive activities including fishing in a 500-1000 m radius from the island, protecting coral reefs around individual resorts (Moritz *et al.*, 2017) and thus offers additional protection to shark populations.

This work highlights the value of temporal data sets for assessing the efficacy of MPAs and to inform management decisions. While the majority of existing literature has compared abundance inside and outside of MPAs (Robbins *et al.*, 2006; Bond *et al.*, 2012; Goetze and Fullwood, 2013; MacNeil *et al.*, 2020), standardised temporal studies are important to assess population trends within MPAs (Bond *et al.*, 2017). In March 2021, the Maldives Ministry of Fisheries, Marine Research and Agriculture (MoFA) opened discussions to consider reopening the shark fishery and lifting sanctuary regulations implemented in 2010. A perceived increase in shark abundance was cited as one of the reasons behind this decision however, after sharing of preliminary findings from this study it was confirmed that the ban would be retained. The stability of reef shark populations indicates that sanctuaries may be an effective conservation approach. However, data will need to be collected long-term (for a minimum of 16 years) to assess population trends with certainty. A cost-effective approach to collect this data long-term would be tri-annual BRUVs deployments and annual collection of citizen science data.

3.6. Conclusion

The study provides the first empirical evidence to show that shark sanctuary regulations - if implemented and complied with - can halt or mitigate declines in fisheries mortality enough to maintain populations and thus could be an effective approach to conserve and recover reef shark populations. Data represents a population baseline post-sanctuary implementation from which the future magnitude and direction of change can be assessed to evaluate the long-term efficacy of this conservation approach.

Chapter 4 Drivers of reef shark abundance within a mid-oceanic shark sanctuary

4.1. Abstract

As coral reef ecosystems come under increasing pressure from climate change and fisheries exploitation, understanding how species that rely on these habitats may respond to changes within their environment is important for tailored management interventions. An improved understanding of patterns in reef shark abundance and the key drivers which influence their spatial distribution and habitat-use is urgently required to identify threats and evaluate spatial management plans for achieving conservation and fisheries sustainability goals. This study used a combination of Baited Remote Underwater Videos (BRUVs) and Underwater Visual Census (UVC) collected across 48 sites within North Malé Atoll to assess the influence of a range of abiotic (reef complexity, current velocity, distance to Malé and distance to the atoll edge) and biotic variables (live coral cover, fish species richness and the biomass of key fish groups known to be shark prey) on shark abundance. Results indicated general and species-specific patterns in abundance which were primarily characterised by prey availability. The abundance of all sharks showed significant positive relationships with herbivore, piscivore and planktivore biomass. Blacktip reef sharks showed a significant positive correlation with piscivore biomass and significant negative correlation with live coral cover. Both current direction and speed significantly influenced whitetip reef shark abundance, with abundance increasing during flood tides and as current strength increased. Whitetip reef sharks also showed a significant positive correlation with herbivore biomass. Tawny nurse shark abundance was influenced by mean current velocity, with abundance greatest at low current speeds regardless of tidal direction. Tawny nurse sharks also showed a significant positive relationship with reef structural complexity. The importance of prey availability in predicting variation in reef shark abundance is consistent with studies of predator distribution in both marine and terrestrial systems and supports the need for ecosystem level measures rather than species-specific policies to support shark recovery. By providing an improved understanding of shark habitat-use and drivers of spatial distribution this research will facilitate the identification of critical shark habitat at local scales, thus findings outlined in this study could provide a basis for future advice on spatial planning and conservation management to enable prioritisation of marine resource use.

4.2. Introduction

Coral reefs are among the most biodiverse ecosystems on the planet, supporting the highest diversity of fishes in the ocean (Connell, 1978) and directly supporting over 500 million people through key services, including fisheries, tourism, and coastal protection (Hoegh-Guldberg *et al.*, 2019). However, they are also among the most threatened ecosystems (Hughes *et al.*, 2018). Intensifying anthropogenic disturbance ranging from local (e.g. overfishing, development) to global (e.g. climate change) in scope (Putnam *et al.*, 2017) have resulted in the loss of about 50% of coral reefs since the early 1980s (De'ath *et al.*, 2012). Most recently, an unprecedented period of extreme oceanic temperatures, exacerbated by the 2015/16 El Niño event, led to the longest coral bleaching event ever recorded (Eakin *et al.*, 2019). Around 70% of the world's coral reefs were impacted leading to a substantial loss of coral cover (Hughes *et al.*, 2018; Eakin *et al.*, 2019)

At large spatial and temporal scales, coral reef habitats have significantly influenced the distribution, diversification, and behaviour of sharks through provision of important ecological functions including prey sources, refugia from predation and nursery habitats (Roff *et al.*, 2016). Sharks are also considered to play important ecological roles, connecting reef habitats to offshore ecosystems and maintaining balance through their regulation of community structure (Bascompte *et al.*, 2005; Robbins *et al.*, 2006; Tickler *et al.*, 2017). Similar to global trends in coral reef decline, widespread exploitation has led to substantial declines in shark populations over the past half a century (Roff *et al.*, 2018; Pacoureau *et al.*, 2021) with 32% of all elasmobranchs threatened with extinction (Dulvy *et al.*, 2021).

Numerous studies have reported correlations between shark density and reef condition, with high coral cover and structural complexity associated with high shark densities (Espinoza *et al.*, 2014; Rizzari *et al.*, 2014b; Acuña-Marrero *et al.*, 2018) and degraded reef states with higher macroalgae cover and more frequent outbreaks of crown-of-thorn starfish associated with lower shark density (Sandin *et al.*, 2008). Moreover, sharks are considered to be the most diverse and abundant marine predators (Frisch *et al.*, 2016; Dulvy *et al.*, 2017) exerting significant influence on the structure and function of associated ecosystems (Tickler *et al.*, 2017). Studies suggest that changes in shark abundance can induce complex community changes, including trophic cascades and mesopredator release, through changes in prey abundance or behaviour (Myers *et al.*, 2007; Ferretti *et al.*, 2010). On coral reefs, studies have linked declines in shark abundance to changes in the composition of teleost fish communities, particularly grazing species, impacting reef resilience (Ruppert *et al.*, 2013; Barley *et al.*, 2017). Studies have demonstrated multi-directional interactions between coral reef state and shark populations: degraded coral reefs can have negative effects on shark abundance (Espinoza *et al.*, 2014), and equally declines in shark abundance can have negative implications for coral reefs (Robbins *et al.*, 2006). Measures to support the recovery of shark populations could therefore contribute to sustaining or improving the health of coral reef ecosystems or vice versa.

Marine Protected Areas (MPAs) are a key spatial management tool used for the protection of coral reef biodiversity among other goals and are increasingly advocated as a strategy to protect and restore shark populations (Knip *et al.*, 2012; Espinoza *et al.*, 2014). Most recently, Large-scale Marine Protected Areas (LMPAs) and shark sanctuaries have emerged as popular management approaches (Ward-Paige, 2017; MacKeracher *et al.*, 2018). However, they are often implemented with little prior knowledge of the spatial distribution and habitat use of species they are designed to protect (Speed *et al.*, 2010; Rizzari *et al.*, 2014b; Ward-Paige and Worm, 2017). Existing research has primarily focused on pelagic shark species (Coffey *et al.*, 2017; Vaudo *et al.*, 2017) or quantifying spatial and temporal movement patterns (Speed *et al.*, 2010). In light of current and projected anthropogenic impacts on marine systems, understanding which factors influence shark habitat use on coral reef ecosystems is increasingly important for targeted management measures. Identifying species-specific habitat associations can facilitate identification of critical habitats and is essential to assess risk of exposure to habitat degradation, fishing and climate change (Espinoza *et al.*, 2014). However, at local scales, understanding of the interacting variables which drive reef shark distribution remains limited, hindering effective ecosystem-based management approaches (Espinoza *et al.*, 2014; Acuña-Marrero *et al.*, 2018).

Examining the relationships between coral reef habitat and sharks ideally requires data from locations where shark populations are abundant, and distribution isn't influenced by human extraction. A recent global analysis of reef shark populations showed that shark sanctuaries support a 50% higher relative abundance than nations without sanctuary status (MacNeil *et al.*, 2020). In 2010, the Maldives became the world's second nation to declare its entire Exclusive Economic Zone (EEZ) a shark sanctuary prohibiting all commercial and artisanal shark catch (Ali and Sinan, 2015). Moreover, the Maldives presents a valuable opportunity to assess drivers of shark distribution in a changing environment. Following the global 2016 coral bleaching, the Maldives experienced widespread coral loss (Ibrahim *et al.*, 2017; Perry and Morgan, 2017b) with more than 70% of corals bleaching (Ibrahim *et al.*, 2017). In the Southern Maldives, coral cover on shallow (<5 m depth) reefs declined from an average of 25.6% (± 5.8 S.D) to 6.3% (± 1.9 S.D) (Perry and Morgan, 2017a). Similarly, a study of 10 reefs in North Malé Atoll showed substantial declines from 29.9% (± 9.8 S.D) live coral cover in 2015 to 14.8% (± 7.1 S.D) in 2016 (Alsagoff and Newman, 2016). The overarching goal of this study was to advance our understanding of local scale drivers of reef-associated shark abundance and spatial distribution. Specifically, this study investigated the influence of a range of biotic and abiotic variables on the abundance of reef sharks within the Maldives shark sanctuary. Analysis focused on three shark species, the blacktip reef, whitetip reef and tawny nurse shark, which were the most commonly encountered species recorded on Baited Remote Underwater Videos (BRUVs).

4.3. Methods

4.3.1. Ethics statement

Sampling was conducted under Ministry of Fisheries and Agriculture permits (30-D/INDIV/2019/97, 30-D/INDIV/2020/41). All procedures were approved by the Newcastle University Animal Ethics Committee.

4.3.2. Study area

Surveys were conducted in North Malé Atoll (4°26’09.5”N, 73°30’01.5”E) which is located in the centre of the double chain of the archipelago on the eastern side. The atoll perimeter consists of an outer reef slope separated by deeper channels, while the atoll lagoon contains reef platforms. Surveys were conducted during the northeast monsoon (January to March) in 2019 and 2020.

4.3.3. Shark abundance: Baited Remote Underwater Videos (BRUVs)

Baited Remote Underwater Videos (BRUVs) were used to quantify the relative abundance of reef-sharks across inner atoll reefs and atoll channels (Figure 4.1A). In total, 109 BRUVs were deployed at inner atoll sites between 4th February and 3rd March 2019 and 50 BRUVs at outer edge and channel sites between 1st - 15th February 2020. BRUVs were deployed on coral-reef habitat at an average depth of 8.3 m (± 1.5 S.D), this depth was chosen primarily for comparative purposes (i.e. ease of comparing reef habitats at this depth which are more variable deeper). A BRUVs unit consisted of a GoPro HERO 4 camera attached to a stainless-steel frame, with a mesh bait bag suspended 1 m in front of the camera. Adjacent deployments were separated by a minimum of 500 m to reduce the likelihood of sharks moving between replicates and ensure independence (Cappo *et al.*, 2004; Goetze *et al.*, 2018). Bait type and amount were kept constant (1 kg scombrids) and all BRUVs were deployed for 60 minutes. Date, time, location (latitude and longitude) and depth were recorded in situ for each deployment. BRUVs were deployed during daylight hours (09:00–17:00) to reduce bias associated with diurnal changes in shark behaviour (Willis and Babcock, 2000) and to aid detection and species identification.

For each BRUV deployment the maximum number of sharks seen in a single frame (MaxN) was determined for each species, as a metric of relative abundance to avoid double-counting individuals, and Time of first arrival (TOFA). Video analysis began after a settlement period (min 02:00–max 07:00 min) had elapsed (Kiggins *et al.*, 2018). The settlement period was characterised as over when all sand or sediment had settled, and visibility returned to normal.

The BRUVs dataset used here was not collected specifically to examine shark distribution patterns but rather temporal trends in abundance (Chapter 3). Thus, to ensure that BRUVs locations corresponded to the locations of Underwater Visual Census (UVC) surveys and avoid any sampling bias, BRUVs were analysed at the site level (48 sites). To standardize the sampling effort, the total hours of video (soak time) were summed for each site. Relative abundance was defined as the total MaxN of each species per site divided by the effort (MaxN hrs^{-1}). This approach was justified for a number of ecological reasons, including: 1) the inner atoll lagoon reefs in the Maldives are classified as small circular ‘patch reefs’ and are typically small covering an average reef area of 0.53 km^2 (Naseer and Hatcher, 2004); 2) home ranges for the studies species are small at <1 to 10km^2 (Papastamatiou *et al.*, 2009b; Osgood and Baum, 2015), and; 3) individual sharks recognised through markings were often resident at individual patch reefs (Robinson, personal observation).

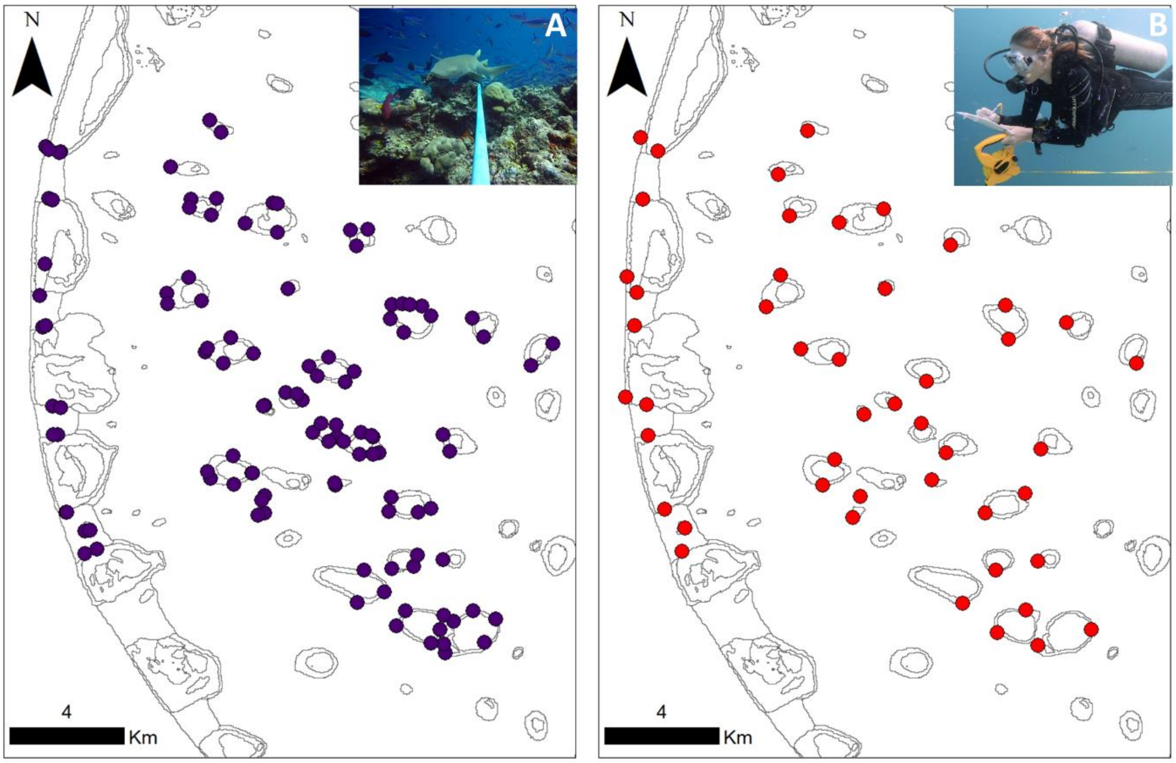

Figure 4.1. Survey locations across North Malé Atoll for A) Baited Remote Underwater Videos (BRUVs) and B) Underwater Visual Census (UVC) surveys.

4.3.4. Predictor variables

Predictors were selected on the basis of studies in the scientific literature with a focus on variables influencing shark distribution and local scales (Tickler *et al.*, 2017; Acuña-Marrero *et al.*, 2018; Goetze *et al.*, 2018). UVC was carried out at 48 sites (Figure 4.1B) to record benthic and fish communities. Inner atoll sites were surveyed between 13th February and the 22nd March 2019, outer atoll sites between 22nd January and 12 February 2020. At each site, one 30 x 5 m transect was laid parallel to the reef at 5-8 m depth. Substrate type was recorded every 50 cm (from 0.5 m to 30 m: 60 points per transect) and classified into the following broad categories: live coral, dead coral, soft coral, macroalgae, turf algae, coralline algae, sponge, cyanobacteria, rock, rubble or sand. Habitat structural complexity was visually assessed on a 6-point scale from 0 to 5, where 0 = no vertical relief, 1 = low and sparse relief, 2 = low but widespread relief, 3 = moderately complex, 4 = very complex and 5 = exceptionally complex (Polunin & Roberts 1993). Coral recruits were recorded using a 50 x 50 m quadrat photographed either side of the transect at 0, 10, 20 and 30 m (8 quadrats per transect). Abundance and size to the nearest 5 cm of all individual fish within 11 key families (*Acanthuridae, Balistidae, Carangidae, Chaetodontidae, Haemulidae, Holocentridae, Labridae, Lethrinidae, Monacanthidae, Mullidae, Pomacentridae, Scaridae, Scombridae and Zanclidae*) considered to be shark prey were recorded (Tickler *et al.*, 2017; Goetze *et al.*, 2018). Fish were primarily recorded to genus level but where feeding preference (trophic groupings) varied they were recorded at the species level (See Table A9). Fish biomass was determined using known length-weight equations, using the most common species observed within each family, available from www.fishbase.org (Froese and Pauly, 2021). A 5-minute roaming survey was also conducted, recording the presence of all individual fish species observed (species richness). The same observers were used throughout the surveys to prevent observer bias (Willis and Babcock, 2000). Surveyor 1 (Danielle Robinson) conducted fish surveys while surveyor 2 conducted benthic surveys and photographed the site. A training period was carried out prior to data collection to ensure accurate species and benthos identification and size estimates (Wilson *et al.*, 2007).

Distance from each site to the nearest atoll edge and the atolls capital city Malé were obtained from ArcGIS software. Current velocity data was shared by researchers from the Department of Earth Science and Engineering, Imperial College, London who were collaborating with Banyan Tree Marine Labs. Current data was collected using the Thetis coastal ocean model, a 2D and 3D flow solver built upon the Firedrake finite element solver framework (for more details please see (Rasheed *et al.*, 2021b)). The tidal model simulated current flow across North Malé Atoll for a period of one month (January 2018). Data were then extracted at each of the UVC survey sites using an interpolator. Velocity was chosen as both current speed and direction have been shown to influence shark movement (McInturf *et al.*, 2019). Negative current velocities represent ebb tides (when the water level is falling) while positive values represent flood tides in a landward direction (water level is rising).

Table 4.1. Predictor variables included in Generalised Additive Models (GAMs).

Predictor variables	Description	Data Type	Range	Mean ± SD
Biotic				
Live coral cover	Live hard coral cover (%)	Continuous	0 - 46	13.9 ± 13.7
Species richness	Fish species richness (n)	Continuous	45 - 79	62.9 ± 8.6
Corallivore	Square-root transformed Biomass of key fish functional groups (g/ 30m^2)	Continuous	0 - 2,153	360 ± 511
Planktivore			150 - 4,941	2,233 ± 1,512
Invertivore			294 - 12,442	2,818 ± 2,438
Piscivore			124 - 14,712	4,038 ± 3,357
Herbivore			1,501 - 19,346	7,004 ± 3,990
Omnivore			733 - 31,357	6,101 ± 6,091

Abiotic				
Distance to atoll edge	Proxy for degree of exposure – can indicate the level of access by sharks to open and/or deeper waters (km)	Continuous	4.8 - 11.2	7.9 ± 1.9
Distance to atoll capital Malé	Proxy for human impact - Malé has the highest population density and only fish market (km)	Continuous	5.8 - 28.7	16.5 ± 4.9
Current Velocity	Mean current velocity obtained from tidal flow models (meters/ second (m/s)	Continuous	-0.4 - 0.2	-0.0 ± 0.2
Reef complexity	Visual estimation of complexity (6-point scale)	Categorical	1.0 - 4.0	2.7 ± 0.7

4.3.5. Data analysis

Models were developed to investigate the influence of biotic and abiotic variables on reef shark abundance across North Malé Atoll. Shark abundance (derived from MaxN) was set as the response variable and independent variables outlined in Table 4.1 were used as predictors. Individual models were run for: 1) all sharks, 2) blacktip reef, 3) whitetip reef and 4) tawny nurse sharks. Relationships between predictor variables were evaluated using Pearson's correlation coefficients to identify correlated variables. Distance to atoll edge was strongly correlated with current velocity, hard coral cover, planktivore biomass and herbivore biomass (Pearsons correlation > 0.35) and therefore not included in models (Goetze *et al.*, 2018). Variance inflation factors for the remaining predictor variables were below the recommended cut-off of three (Zuur, 2012).

Exploratory scatterplots revealed that the relationship between response variable (shark abundance) and several predictor variables were non-linear so a Gaussian Generalised Additive Model (GAM) was chosen to model the data. GAMs are similar to Generalised Linear Models (GLMs) in that they relate a response variable to one or multiple independent (predictor) variables, however they have the property of exploring non-linearity in the relationships using smoothers with no assumption on the shape of the relationship (McClanahan *et al.*, 2016).

Predictors were used to construct all possible models, using the 'dredge' function implemented in the MuMin package and following an information-theoretical framework (Burnham and Anderson, 2002). Model sizes were limited to only three terms (size = 3) and k in the GAMs was limited to five to avoid overfitting the data. Information theoretic (IT) approaches are more transparent than traditional backwards selection approaches as they allow all good candidate models to be identified and then compared (Fisher *et al.*, 2018). Where several models differ in their data fit by small amounts, IT approaches allow model averaging such that predictions properly account for model uncertainty. Model average parameters were calculated for the 'top model set' which included models within two Akaike information criterion (AICc) of the top model. Models with AICc values differing by less than two units show weak evidence for favouring one over the other (Burnham and Anderson, 2004). This enabled the relative importance of different variables to be properly explored, by summing the model weights for each variable (Fisher *et al.*, 2018). The relative importance of each variable was visualised using a heatmap. For the final models, Q-Q plots and residual histograms were used to inspect model residuals and variance and to ensure that model assumptions were not violated.

4. 4. Results

4.4.1. Habitat characteristics

There was high variation in the benthic composition (Figure 4.2A across survey sites). Bare-rock and rubble were the dominant substratum types with an average cover value of 30.3 ± 10.6 (S.D) and 18.2 ± 10.4 (S.D) respectively. Live coral cover ranged from 0% to 53% with an average of 13.9 ± 13.7 (S.D). Live coral composition was dominated by boulder coral growth forms (Figure 4.2B).

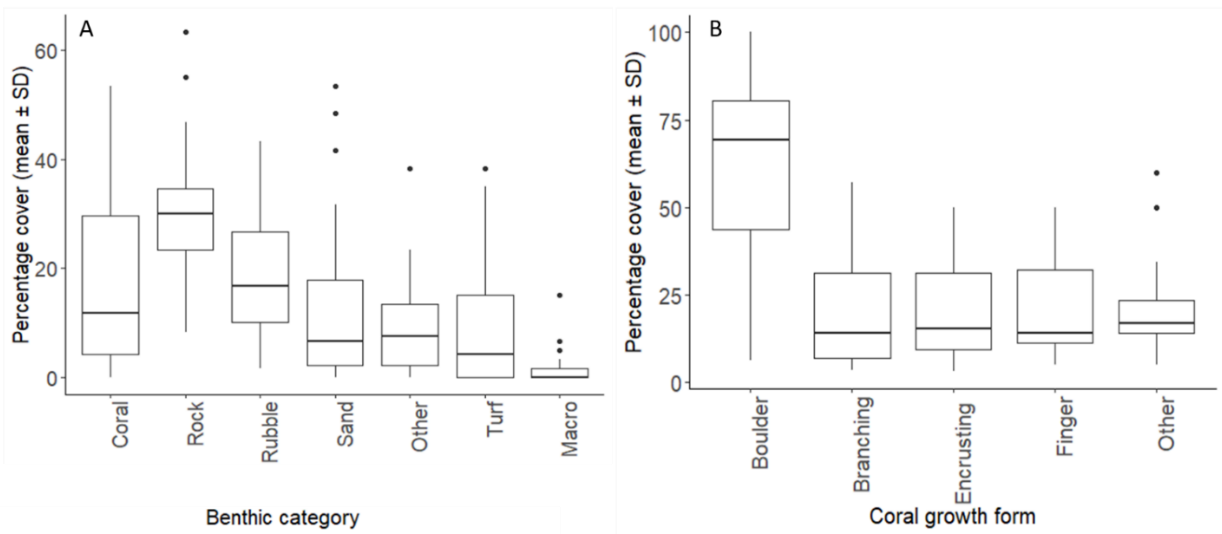

Figure 4.2. Mean benthic substrate cover (±SD) and B) percentage cover of each live coral growth form (mean ± SD).

4.4.2. Summary of shark abundance

A total of 124 individual sharks from 6 species and 2 families were recorded (n = 159 BRUVs deployments). The number of sharks recorded per deployment varied between 0 and 7 (0.78 ± 0.94 hr^{-1}) with at least one shark recorded on 57.2% of deployments. Blacktip reef, tawny nurse and whitetip reef sharks were the most sighted species and represented over 93% of the total shark abundance. At the site level, blacktip reef sharks were the most widely distributed occurring at 60% of all sites (Table 4.2). Standardised relative shark abundance at the site level varied between 0 and 2.2 (0.81 ± 0.56 hr^{-1}).

Table 4.2. Summary of shark sightings and abundance at the site level. MaxN represents relative shark abundance defined as the total MaxN of each species per site divided by the effort (MaxN hrs−1).

Common name	**Species**	**Occurrence (% sites)**	**MaxN hr-1 (mean ± SD)**
Blacktip reef	*Carcharhinus melanopterus*	60	0.32 ± 0.38
Tawny nurse	*Nebrius ferrugineus*	49	0.28 ± 0.39
Whitetip reef	*Triaenodon obesus*	45	0.21 ± 0.31
All species		93	0.81 ± 0.56

4.4.3. Drivers of shark abundance and spatial distribution

Model averaging confirmed that there were a number of candidate models for each shark species that performed equally well (Table 4.3). Retained models for all sharks indicated strong support for the importance of key prey groups: herbivore biomass was included in all retained models and variable importance (VI) was high (0.79, Figure 4.3). For blacktip reef sharks retained models indicated strong support for coral (VI: 0.98) and piscivore biomass (VI: 0.62). Models for whitetip reef and tawny nurse sharks showed strong support for the importance of current velocity (Table 4.3, Figure 4.3) which was retained in all models (VI: ≥ 0.95).

Table 4.3. Best Generalised Additive (GAM) models (within two AICc of the top model).

Model terms											**Model support**			
Herb	**Pisc**	**Plank**	**Inver**	**Omn**	**Corr**	**SR**	**Coral**	**Comp**	**Vel**	**Dist**	**df**	**AICc**	**Delta**	**Weight**
All species														
X	X	X									6	72.2	0	0.25
X	X										4	72.9	0.73	0.17
X		X									5	74.1	1.91	0.09
X	X		X								5	74.2	2.01	0.09
X		X					X				7	74.3	2.07	0.08
Blacktip reef														
	X						X		X		7	31.7	0	0.22

	X						X				4	32.1	0.41	0.18
	X	X					X				5	33.1	1.47	0.11
		X			X		X				6	33.4	1.73	0.09
	X						X			X	5	33.6	1.95	0.08
	X					X	X				5	33.7	2	0.08
Whitetip reef														
X									X		7	14.4	0	0.28
									X		5	17.9	0.45	0.22
X								X	X		8	18	0.58	0.21
X							X		X		9	18.5	1.08	0.16
								X	X		6	19.2	1.72	0.12
Tawny nurse														
		X						X	X		7	38.7	0	0.19
								X	X		6	39.1	0.36	0.16
X		X							X		6	39.2	0.52	0.15
		X							X		5	39.4	0.7	0.14
X							X		X		8	39.9	1.24	0.11
	X							X	X		7	40.1	1.38	0.09
	X	X						X	X		9	40.5	1.83	0.08

Details of model terms are given in Table 4.1: Herb = herbivore biomass; Pisc = piscivore biomass; Plank = planktivore biomass; Inver = invertivore biomass; omn = omnivore biomass; Corr = corralivore biomass; SR = fish species richness; Coral = hard coral cover; Comp = reef complexity; Vel = mean current velocity; Dist = distance to Malé. X's indicate inclusion in the model, but not direction or strength of effect.

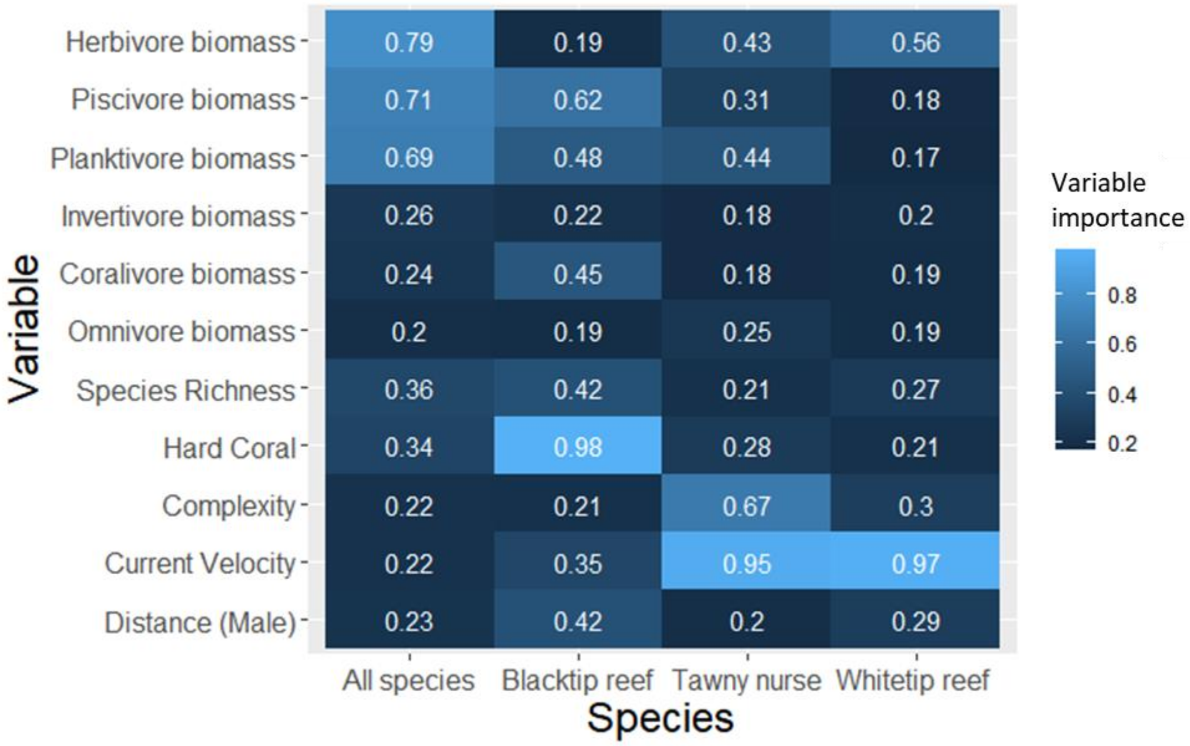

Figure 4.3. Variable importance scores from a full-subsets analyses exploring the influence of abiotic and biotic variables on reef shark abundance.

The best models explained 35.4%, 31.8%, 36.7% and 35.1% of the deviance for all sharks, blacktip reef, whitetip reef and tawny nurse sharks respectively (Table 4.4.). Six predictor variables, including herbivore biomass, piscivore biomass, planktivore biomass, mean current velocity, hard coral cover and reef structural complexity, showed significant effects (GAM, $p < 0.05$) on shark abundance (Table 4.4, Figure 4.4).

Table 4.4. Variables and parameters of the final Generalised Additive Models (GAMs). Sign: whether the fitted relationships are predominately positive or negative; edf: estimated degrees of freedom for the model smooth terms (edf > 1 indicates a nonlinear relationship); DEV: degree of explained variance; *p < 0.05, **p < 0.01.

Model	Predictor variables	Sign	(edf)	p value	Sig.	DEV (%)
All sharks	Piscivore biomass	+	1.8	0.037	*	35.4
	Herbivore biomass	+	1.0	0.038	*	
	Planktivore biomass	+	1.0	0.733		
Blacktip reef	Coral	-	1.0	0.002	**	31.8
	Piscivore biomass	+	1.0	0.009	**	
Whitetip reef	Mean current velocity	+	3.1	0.011	*	36.7
	Herbivore biomass	+	2.6	0.148		
Tawny nurse	Mean current velocity		3.2	0.002	**	35.1
	Reef complexity	+	1.0	0.025	*	

The abundance of all sharks showed a positive relationship with herbivore, piscivore and planktivore biomass (Figure 4.4). Blacktip reef shark abundance showed a negative relationship with hard coral cover and a positive relationship with piscivore biomass. Both current direction and speed influenced whitetip reef shark abundance, with abundance increasing during flood tides and as current strength increased (velocities > 0.0 m/s). Herbivore biomass also had a positive influence on whitetip reef shark abundance. Tawny nurse shark abundance was influenced by mean current velocity, which had a dome shaped response pattern, where abundance was greatest at low current speeds regardless of tidal direction. Tawny nurse shark abundance also showed a positive relationship with reef structural complexity.

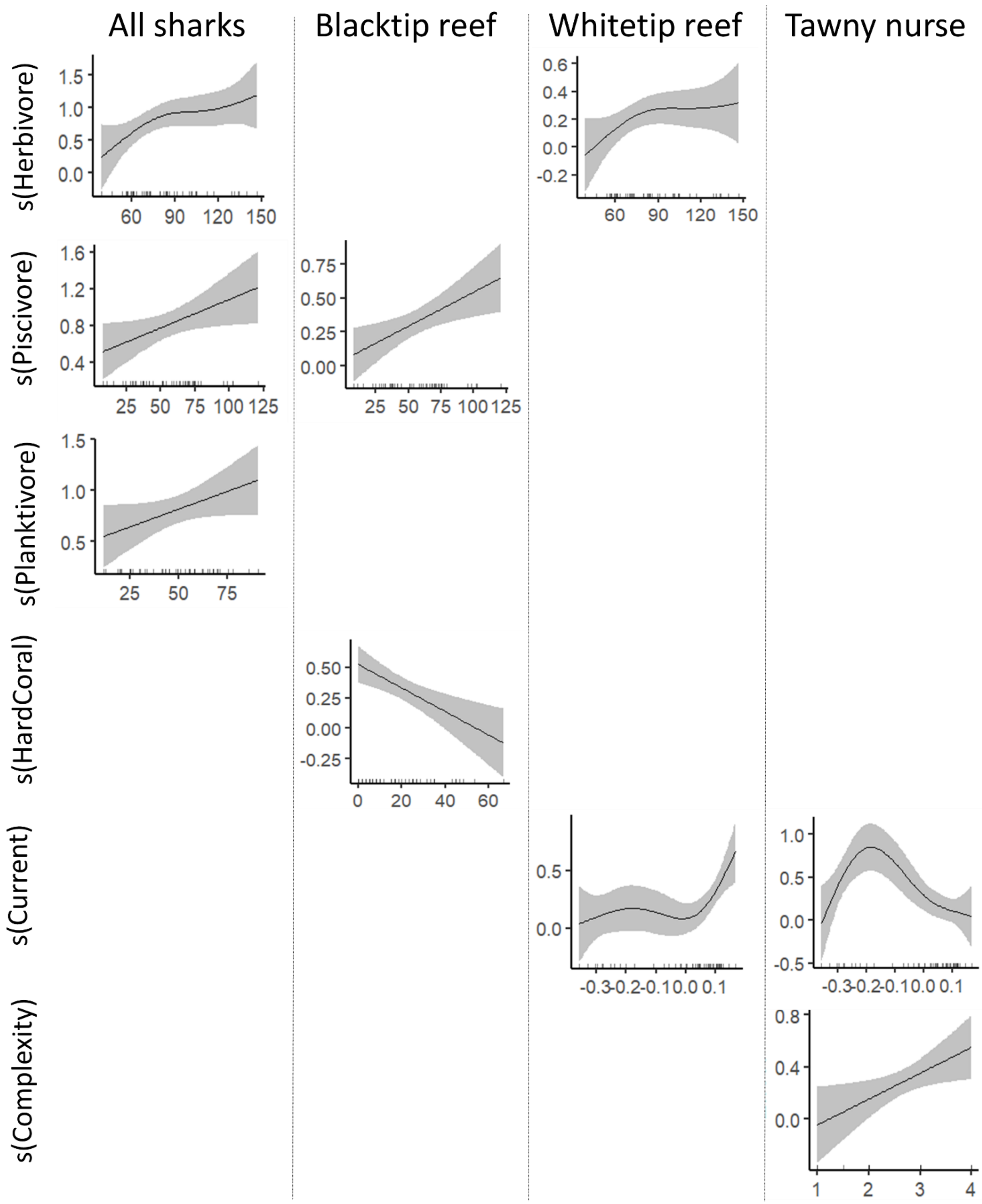

Figure 4.4. Smoothers of predictor variables retained in the best models for each shark species. Black lines: fitted Generalised Additive Model (GAM); grey shaded areas: SE.

4.5. Discussion

Given the lack of ecological data for reef shark species, this study provided a valuable contribution to understanding species-specific habitat associations in response to a range of abiotic and biotic drivers. Despite the overlapping distributions of the three species considered, results indicated general and species-specific patterns in abundance which were primarily characterised by prey availability. The importance of prey-availability suggests that management efforts may meet limited success unless the broader ecosystem effects of fishing are considered. This raises uncertainty over the long-term efficacy of species-specific policies, such as shark sanctuaries, which still permit catch of other commercially important species such as reef fish within protective boundaries.

4.5.1. Key drivers

Consistent with studies of mobile predator distribution in both marine (Cade *et al.*, 2021) and terrestrial systems (Keim *et al.*, 2011), findings here suggest that prey availability exerts a strong influence on the abundance and spatial ecology of reef sharks. On reef systems, positive correlations between prey and shark abundance have been reported theoretically by comparing shark abundance within and outside of reserves and between habitats (Goetze and Fullwood, 2013; Rizzari *et al.*, 2014b), however, empirical studies to show direct correlations between reef shark distribution and prey are limited (Tickler *et al.*, 2017). Reef sharks depend on coral reef fishes for more than 70% of their diet (Papastamatiou *et al.*, 2006), thus on-going depletion of prey species is likely to have indirect implications for shark populations.

Once considered one of the most underexploited reef fisheries in the Indian Ocean (MacNeil *et al.*, 2015), studies now suggest that the Maldivian reef fishery is approaching maximum sustainable yield (Sattar, 2014). Indeed, the positive relationship between shark abundance and piscivore biomass in this study elucidates a relationship between reef fishing pressure and shark distribution. Numerous studies show significant correlations between piscivore density and fishing intensity (see review by Nash and Graham, 2016) with piscivore populations considered an important indicator of fishing pressure, particularly in multi-species fisheries (Jennings and Polunin, 1997). Given the small spatial scale of this study, piscivore biomass (in addition to being an important prey group for sharks) may be a better indicator of fishing pressure than distance to the capital Malé, as all reefs surveyed were easily accessible by humans.

A second overarching insight from this study is that localised declines in live coral have little impact on reef shark populations with a negative relationship found between blacktip reef shark abundance and hard coral cover. This could be attributed to this species' preference for sheltered inner atoll reefs and shallow lagoons (Papastamatiou *et al.*, 2009a; Chin *et al.*, 2013), which suffered relatively higher live coral loss during the 2016 coral bleaching than sites closer to atoll edges. While this finding could imply that reef sharks are robust to climate induced coral loss, studies were conducted during the initial stages of coral reef degradation (three years post bleaching) and may not pick up bleaching induced declines in fish communities. Declines in reef structural complexity can take over five years (Wilson *et al.*, 2006), thus at the time of this study it is likely reefs still maintained abundant prey communities. This is supported by empirical studies which show there is no short-term change in fish biomass and yield associated with mass bleaching (McClanahan *et al.*, 2002; Grandcourt and Cesar, 2003; Graham *et al.*, 2007).

The positive relationship between shark abundance and reef complexity concurs with previous empirical studies on coral reefs (Rizzari *et al.*, 2014b; Desbiens *et al.*, 2021) and corroborates the above observation that losses of reef complexity will have far greater negative impacts on reef sharks than live coral loss. Structurally complex habitats provide important refuge supporting the accumulation of fish biomass and productivity (Rogers *et al.*, 2014; Newman *et al.*, 2015; Rogers *et al.*, 2018) and thus can be considered a proxy for prey availability (Desbiens *et al.*, 2021). While other species in this study showed a significant positive relationship with prey groups, the tawny nurse shark is a nocturnal species that rarely forages during the day, this likely precluded a significant relationship between nurse shark abundance and prey groups directly. The association of nurse sharks with complex habitats could also be linked to behavioural activity, as this bottom dwelling species commonly shelters under large coral overhangs and caves.

Current velocity was a significant influential variable in model selection for both whitetip reef and tawny nurse sharks. The importance of current velocity in explaining variance in the relative abundance of reef sharks has been linked to foraging tactics and energy conservation (Vianna *et al.*, 2013; Schlaff *et al.*, 2014; Desbiens *et al.*, 2021). Studies have also made the indirect link between current and increased prey availability (Garla *et al.*, 2006; Vianna *et al.*, 2013). In this study an increase in whitetip reef shark abundance during flood tides and strong current flow may be linked with tidally driven prey migrations (Papastamatiou *et al.*, 2009b) with flood tides transporting nutrient rich water into shallow inner atoll lagoons (Green *et al.*, 2019). Moreover, in the Maldives whitetip reef sharks are often associated with strong currents, typically around atoll channels and passes where they rest on sandy bottoms (Robinson, personal observation). Although this species can breathe while stationary through a process known as buccal pumping, stronger currents in such areas could facilitate respiration by passively passing oxygenated water over their gills (Kelly *et al.*, 2019). The dome-shaped relationship between current velocity and tawny nurse shark abundance suggests that regardless of tidal direction (flood vs ebb) this species is more strongly affiliated with weaker currents. Tawny nurse sharks are unlikely to be as dependent on current flow for either foraging or energy conservation as they primarily forage within reef confines and close to the reef substrate (Motta *et al.*, 2008) and breathe primarily via buccal pumping.

A number of considerations were accounted for when interpreting the study findings. Firstly, BRUVs used to quantify shark abundance across sites were only deployed at easily accessible depths (9.2 m ± 1.1 m (SD) and during daylight hours. Peak densities of reef sharks may occur at night and at depths greater (e.g. 30-40m) than surveyed (Chapman *et al.*, 2007), but these results are likely to reflect relative differences between species, if not absolute abundances, regardless of time of day. Secondly, studies to evaluate species-habitat distributions are influenced by spatio-temporal scale, variables considered, and the sampling and analysis methods used (Whittingham *et al.*, 2006; Yates *et al.*, 2015). It was not possible to include all possible drivers of abundance in this study. Sea surface temperature (Vianna *et al.*, 2013), depth (Tickler *et al.*, 2017), salinity (Yates *et al.*, 2015) and primary productivity (Nadon *et al.*, 2012) have also been related to the habitat use of reef sharks. However, within the spatial scale considered here it is unlikely that the above variables showed enough variability to influence abundance across sites, with conditions in oceanic reef systems more stable than coastal ecosystems (Heupel and Simpfendorfer, 2014). The correlative nature of results in this study also means that the relative strength in variables such as fish biomass versus physical and environmental variables in predicting shark abundance should be interpreted carefully. Biological measures could be acting as proxies for other variables that were not measured or considered in this study. However, identification of correlations between predator distribution and prey availability in other predatory taxa and systems suggests that prey is a common driver of spatial variation in predator abundance in coral reef ecosystems (Heupel and Simpfendorfer, 2014; Tickler *et al.*, 2017).

4.5.2. Management implications

The conservation and recovery of shark populations is a primary goal and intended outcome for establishing shark sanctuaries (Heupel *et al.*, 2019). However, this study suggests that multi-pronged management approaches that combine sanctuary regulations with measures to reduce pressure on reef fisheries may be necessary to facilitate the long-term resilience of reef shark populations. Declines in prey availability due to a combination of fishing pressure and climate-induced reef degradation could have indirect implications for the management of reefs sharks. Thus, there is an urgent need to evaluate the current status of reef fisheries, the extent of reef fishing pressure and fisheries overlap with shark populations to better understand how great a threat fishing is to reef sharks within sanctuary boundaries compared with other threats. Collation of regional demographic and landings data is also recommended to assess livelihood dependence on this fishery.

The importance of conserving prey to conserve predators has been highlighted in multiple studies considering a range of terrestrial (Ripple *et al.*, 2014; Wolf and Ripple, 2016) and marine predators (Bearzi *et al.*, 2006; Tickler *et al.*, 2017). Moreover, comparisons of shark abundance between fished, no-fishing and no-entry zones, indicate that no-entry zones or well enforced no-take zones are needed to protect reef sharks (Robbins *et al.*, 2006; Frisch and Rizzari, 2019). However, establishing such restrictive MPAs in the regions which have enacted shark sanctuaries is challenging as most sanctuaries are located in developing countries throughout the tropics where fisheries play an important role in food security and livelihood (Ward-Paige, 2017). In such locations, identification of critical habitats for stricter spatial management may be a way forward that promotes shark conservation while accounting for the livelihood needs of fishing communities. The identification of important variables influencing shark abundance in this study will facilitate the identification of critical shark habitat at local scales, providing a basis for future spatial planning and conservation management.

Strict protection of critical habitats may also aid enforcement as no-entry zones are relatively easier to police via aerial surveillance and satellite monitoring, with evidence of fishing not needed for prosecution (Frisch and Rizzari, 2019). Capacity to effectively enforce regulations is currently lacking in many shark sanctuaries (Davidson, 2012; Chapman and Frisk, 2013; Vianna *et al.*, 2016; Dulvy *et al.*, 2017) with illegal shark fishing reported in a number of sanctuaries (Vianna *et al.*, 2016; Bradley *et al.*, 2019). Even low levels of fishing mortality can substantially reduce reef shark populations (Robbins *et al.*, 2006). The dominant reef sharks in the Maldives are slow growing, late maturing and have small brood sizes compared to other fishes (Smith *et al.*, 1999). Combined these traits curb population growth rates and increase vulnerability to overfishing.

4.6. Conclusion

This research has identified key drivers of reef shark abundance and will have implications for the management of sharks within the Maldives and the design of MPAs more generally. Findings are particularly relevant in light of increasing anthropogenic impacts on coastal ecosystems and global efforts to conserve reef shark populations. Results suggest that impacts on prey availability either through targeted fishing pressure or climate-induced habitat decline could negatively impact reef shark populations.

Chapter 5 Fisher perceptions of shark sanctuary impact and drivers of support

5.1. Abstract

Global declines in shark populations have led to the rapid implementation of shark sanctuaries in 17 coastal nations. A critical determinant in the success of such policies is mitigating human behaviour that has a negative impact on health of ecosystems and co-creating local support for conservation initiatives. However, there is a paucity of evaluative research into the human dimensions of shark conservation and socio-economic factors underpinning human behaviour are rarely incorporated into context-specific shark conservation strategies. Herein semi-structured interviews were used with 103 fishers to examine their perceptions of shark sanctuary impact, governance, and compliance in the Maldives. Linked to this, key variables were identified from the interviewees that influenced their level of support for sanctuary regulations. Perceptions varied both within and across fisher groups, however positive perceptions were consistently associated with pelagic pole-and-line fishers. Negative livelihood impacts were most commonly reported by former shark fishers (86%) and small-scale reef fishers while perceptions of ecological effectiveness was viewed positively by all fisher groups. Perceptions of governance related to the sanctuary, including representation (voice), inclusiveness, and transparency were viewed negatively by most (>53%) respondents irrespective of fishery. Structural Equations Models (SEM) identified key characteristics and perceptions that significantly influenced fisher support for the Maldives shark sanctuary. Perceptions of poor representation (voice) and high rates of shark depredation strongly undermined support. Target fishery also directly influenced sanctuary support, which; was high among pelagic pole-and-line fishers, varied among pelagic handline fishers and low among reef fishers. Fisher age, economic dependence on fishing and whether they previously targeted sharks indirectly influenced levels of support. Findings confirm the importance and value of understanding resource-user perceptions and help identify management actions that could increase support for the shark sanctuary including: 1) increased stakeholder participation in decision making and management; 2) improved transparency, particularly in relation to shark population trends; and 3) mitigation of negative economic impacts through improved livelihood opportunities during sanctuary implementation and ongoing management.

5.2. Introduction

Globally the pressures of overexploitation, habitat loss, pollution and climate change are intensifying (Geldmann *et al.*, 2014; Maxwell *et al.*, 2016) and biodiversity is disappearing at an unprecedented rate (Kindsvater *et al.*, 2018). Halting global biodiversity loss is central to the Convention on Biological Diversity (CBD) and Sustainable Development Goals (UN, 2015) and a range of conservation approaches have been implemented (Aguoru *et al.*, 2015; Johnson *et al.*, 2017). However, success to date has been limited: the 2010 CBD target was not achieved (Butchart *et al.*, 2010; Hoffmann *et al.*, 2010) and none of the 2020 Aichi biodiversity targets were fully achieved (CBD, 2020b).

Failure to achieve global biodiversity targets has been attributed to a range of factors (Johnson *et al.*, 2017) including, but not limited to, inadequate funding (Waldron *et al.*, 2017) and rising pressures: specifically increasing human population size and per capita consumption which offsets efforts to mitigate biodiversity decline (Johnson *et al.*, 2017). Moreover, given that human activities (i.e. Illegal wildlife trade, deforestation, and unsustainable exploitation of natural resources) are among the key threats to biodiversity (Maxwell *et al.*, 2016), an important determinant of conservation success is human behaviour (Nilsson *et al.*, 2020) yet in most societies, conservation is not integrated with human behaviour studies or socio-economic evidence-based planning (Seddon *et al.*, 2016).

Positive human responses and behaviour towards conservation initiatives can be crucial for both short and long-term effectiveness (Rohe *et al.*, 2017; Bennett *et al.*, 2019). Given that many ecological benefits may not be realised short-term the longevity of conservation initiatives is often key to conservation success (Edgar *et al.*, 2014). Behaviour towards conservation efforts can be influenced by a range of factors including individual demographics and socioeconomic status (Arjunan *et al.*, 2006), livelihood alternatives (Peterson and Stead, 2011), place attachment (Morishige *et al.*, 2018), social norms and values (Jones *et al.*, 2008; Chan *et al.*, 2016). Perceptions can also be useful predictors of behaviour and levels of support (Peterson and Stead, 2011), directly influencing decision making and resource use (Turner *et al.*, 2019) and providing insight into the extent of voluntary compliance with regulations (Peterson and Stead, 2011).

The integration of perceptions into conservation and natural resource management is therefore important and can enhance the long-term equitability and effectiveness of conservation initiatives (Turner *et al.*, 2019). Defined by Bennett (2016) as "the way an individual observes, understands, interprets, and evaluates an object, action, experience, individual, policy, or outcome" perceptions provide invaluable insight into drivers of local support for conservation and should be central in toolkits for monitoring, evaluating, and adapting conservation policies. In particular, local perceptions aid understanding of socio-economic impacts (Ezebilo and Mattsson, 2010; McNeill *et al.*, 2018) and ecological outcomes of conservation (Hargreaves-Allen *et al.*, 2011), the acceptability of management action and governance (Turner *et al.*, 2014; Bennett *et al.*, 2019).

Research to date has focused on perceptions of Protected Area (PA) and Marine Protected Area (MPA) impacts and efficacy (West *et al.*, 2006; Bragagnolo *et al.*, 2016; Oldekop *et al.*, 2016; Allendorf, 2020). Comparatively, resource-user perceptions towards blanket-bans has received little attention. Blanket-bans in wildlife trade and/ or exploitation are the most severe restriction under the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) and often implemented as a last resort. Bans are typically either reactive in response to imminent population collapse (i.e. the Atlantic cod fishery) or proactive to protect populations at risk of collapse due to life history strategies and overexploitation (i.e. sharks). Garnering support for proactive measures is considered more difficult as they are often implemented as precautionary measures for data poor species or regions and data regarding stock status is limited. However, both reactive and proactive bans on wildlife are known to have perverse consequences for people and wildlife. They can drive trade underground if regulations are not perceived as legitimate among resource users (Conrad, 2012), lead to negative socio-economic impacts, undermine monitoring efforts and fail to address underlying drivers of exploitation (Cooney and Jepson, 2005; Booth *et al.*, 2019).

Blanket-bans can be met with opposition from resource users for a wide range of cultural and socio-economic reasons (Tatar, 2014). For example, the safari hunting ban in Northern Botswana led to a reduction of tourism benefits to local communities, including income and employment opportunities, resulting in negative attitudes towards conservation and an increase in poaching (Mbaiwa Joseph, 2018). Similarly, hunting bans in southern Africa were viewed negatively due to negative impacts on income and well-being (Strong and Silva, 2020). In South Korea a moratorium on commercial whaling met opposition from locals due to whales being considered an important part of food culture and fishers believe their livelihoods had been negatively impacted (MacMillan and Han, 2011).

Ongoing declines in global shark populations (Pacoureau *et al.*, 2021) has led to a shift from target-based conservation measures which focus on sustainable exploitation of sharks (i.e. fishing quotas, permits, species-specific restrictions) to limit-based measures that ban all exploitation (Shiffman and Hammerschlag, 2016b). These blanket-bans on shark fishing have been rapidly implemented with 17 coastal countries declaring their Exclusive Economic Zones (EEZ) shark sanctuaries since 2010 (Ward-Paige, 2017; Chapman *et al.*, 2021). Despite the proliferation of shark sanctuaries, data paucity, an urgent need to implement protection and the inherent complexity of global shark fisheries means sanctuaries have been implemented with limited understanding of complex socio-economic and human dimensions (MacKeracher *et al.*, 2018; Collins *et al.*, 2020b). Bans on shark fishing will likely have severe socio-economic impacts in many regions given the high global value of shark fisheries (~US$1 billion (Dent and Clarke, 2015)) and the fact that 40% of landings come from countries with low or medium Human Development Indices (Dulvy *et al.*, 2017). Moreover, in many small island developing states, shark fishing is intrinsically linked to the well-being and cultural identity of coastal communities (Booth *et al.*, 2019; Glaus *et al.*, 2019). With significant research gaps on the human dimensions of shark conservation, greater inclusion of local people is needed in management planning and evaluation (MacKeracher *et al.*, 2018; Mizrahi *et al.*, 2019).

Enhancing policymakers understanding of the human dimensions of shark conservation and addressing societal concerns will require utilising social sciences to complement ecological data. Empirical studies aimed at examining fisher perceptions relating to the conservation and management of sharks are therefore needed. This study examined fisher perceptions of the Maldives shark sanctuary. Specifically, fisher perceptions of a) ecological effectiveness; b) socio-economic impacts; c) governance principles; and d) compliance with sanctuary regulations. Support for the Maldives shark sanctuary and alternative conservation approaches were also investigated.

5.3. Methods

Semi-structured surveys were conducted with fishers from January - April 2019. Fishers were targeted using opportunistic and snowball sampling (Bernard, 2006) with surveys conducted on local islands in North Malé and Dhaalu Atoll or at Malé fish market (Figure 5.1). In total, 103 interviews were conducted with reef and tuna fishers (the latter herein referred to as pelagic fishers). The survey contained questions related to: (a) basic demographic information;

(b) perceptions of ecological effectiveness, social impacts, governance, and management; (c) perceptions of compliance with sanctuary regulations; and (d) fisher support for a range of shark conservation approaches (see supporting materials for survey questions – Table A10). A combination of open-ended and closed questions were used in each section, with some Likert scale rapid response questions used to ascertain support for conservation approaches and perceptions of governance.

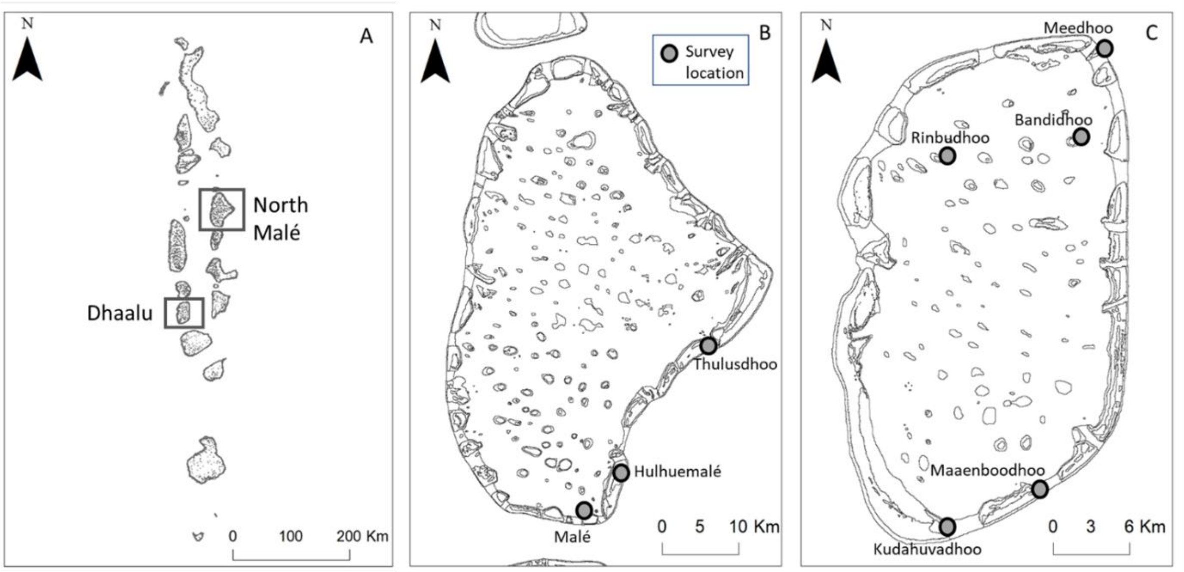

Figure 5.1. Study location. A) The Maldives is an archipelago of 26 natural atolls, consisting of 1190 coral reef islands in the Indian Ocean. North Malé Atoll is located on the eastern side (4.4167° N, 73.5000° E) and Dhaalu Atoll the west (2.8469° N, 72.9461° E) of the archipelago, B) interview locations in North Malé Atoll and C) interview locations in Dhaalu Atoll.

Semi-structured questions were used to ensure all participants were asked the same questions but allowed individuals to add detail to responses. Survey questions were piloted with fishers outside of the target population to determine suitable wording and approximate interview time frame. Data collection was undertaken by the Danielle Robinson (DR) supported by three local research assistants. All research assistants were trained by the DR. Interviews were conducted in Maldivian (Dhivehi) and in pairs to minimise any interviewer bias.

5.3.1. Ethics statement

Participants were informed of both the survey motivation and the intended use of the data collected and subsequently verbal consent was sought before the survey was undertaken. Participant's names were not recorded and anonymity of their responses was assured. Further, participants were informed of their right to decline any question that they were unwilling or unsure about answering and informed that, should they so wish, the interview could be ended at any time. Interviews were not facilitated with either monetary or material motivation. Ethical approval for the survey was sought from and granted by the ethics review board at Newcastle University.

5.3.2. Data analysis

Qualitative data based on open-ended responses were coded into themes using QSR NVivo 10. Different themes of response were identified for each of the open-ended questions before a more deductive approach was used to group responses into related themes. For example, responses relating to the question "How could compliance with shark sanctuary regulations be improved?" included "increase awareness of the importance of sharks" and "share information on shark status" both of which were grouped under the theme "awareness and communication".

To test for direct and indirect relationships a piecewise Structural Equation Model (SEM) was used to identify effect pathways and investigate the relative effects of different variables on fisher support for the Maldives shark sanctuary. A SEM was chosen as human behaviours are subject to interacting factors including past experiences, knowledge, perceptions and demographics. The first stage of the SEM analysis included an overall *a priori* model, containing hypothetical pathways of influence (Figure 5.2).

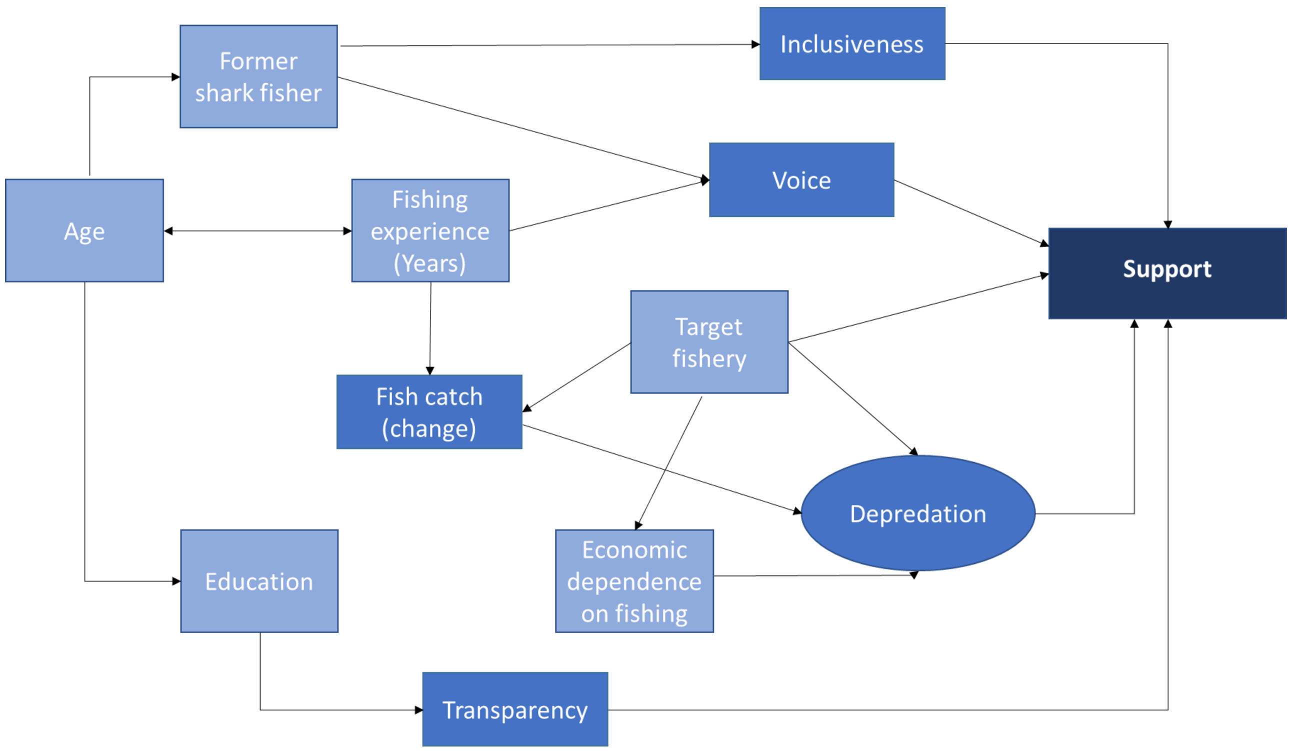

Figure 5.2. A priori Structural Equation Model (SEM) containing all hypothesised pathways of influence. Arrows represent hypothesised causal relationships. Fisher characteristics: light

blue boxes, fisher perceptions: darker blue rectangles, composite variable for variable for depredation: dark blue oval and the dependent variable for support: darkest blue rectangle.

The *a priori* model included variables for demographics, fishing practice, economic dependency, and respondent perceptions (Table 5.1, Figure 5.2). Fisher perceptions of catch and gear lost to shark depredation were strongly correlated (Pearsons correlation r = 0.75) and thus were combined into a composite variable 'depredation' representing the total combined influence of both variables.

Table 5.1. Dependent and independent variables included in the Structural Equation Model (SEM).

Covariate	Question/ Description	Data type
Dependent Variable		
Support	Please indicate the degree to which you support the shark sanctuary.	Ordinal (1: strongly oppose, 2: oppose, 3: support, 4: strongly support)
Demographics		
Age	How old are you?	Categorical (1: 18-24, 2: 25-34, 3: 35-44, 4: 45-54, 5: 55-64, 6: >65)
Education	Level of education	Categorical (1: primary, 2: secondary, 3: higher education, 4: university)
Fishing practices		
Experience	How long have you been a fisher (years)?	Continuous (Range: 1 – 56)
Shark fisher	Have you ever fished specifically for sharks?	Binary (0: np, 1: yes)
Target fishery	What is your target fishery?	Categorical (1: Pelagic PL, 2: Pelagic HL, 3: reef)
Fish catch	Compared with 10 years ago, has the number of fish that you catch…?	Categorical (1: NA (< 10 years fishing experience), 2: increased, 3: no change, 4: decreased)
Income		
Economic dependence on fishing	What proportion of your total household income is from fishing?	Continuous (Range: 15 -100)
Depredation		
Catch lost (%)	On average, what percentage of your daily catch is lost to sharks?	Continuous (Range: 0 - 95)
Gear lost (%)	On average, what percentage of your gear is damaged by sharks daily?	Continuous (Range: 0 - 80)
Depredation composite	Composite variable representing the combined influence of catch and gear lost.	Continuous (Range: 0 – 120)
Governance indicators		
	Please indicate if you agree/ disagree with the following statements:	
Voice	The opinions of fishers were/ are considered during sanctuary design, planning and management.	

Inclusiveness	Fishers can participate in decision-making and management activities.	Ordinal (1: strongly disagree, 2: disagree, 3: agree, 4: strongly agree)
Transparency	Information about how and why conservation decisions are made, and fisheries data are readily available.	

To build the simplest significant working model variables which were non-significant contributors to the observed correlation structure in the data were removed from the *a priori* model. Modification indices were used to identify overlooked significant pathways which were theoretically justifiable (Lefcheck, 2016). Variance inflation factors (VIF) were calculated for all drivers in the final model with correlation considered acceptable (VIF < 3) (Grewal *et al.*, 2004). Model fit was determined using Fisher's C statistic and coefficients of determination (R^2) values (Lefcheck, 2016). The piecewise structural equation model (SEM) was conducted using the piecewise SEM package (Lefcheck, 2016). All statistical analyses and data visualization were performed in R v3.5.3 (R Core Team, 2017).

5.4. Results

5.4.1. Overview of respondents

In total, 103 fishers were interviewed face-to-face in North Malé (n = 66) and Dhaalu Atolls (n = 37), Maldives. Interviewees were exclusively male with an average age of 46.0 ± 10.9 (SD) and had 23.6 ± 13.2 (SD) years of fishing experience. Twenty-six percent (n = 27) were pelagic pole-and-line (PL) fishers, 18% (n = 19) pelagic handline (HL) fishers and 55% (n = 57) were reef fishers. Fishing was the only occupation for 81% of fishers and the majority (67%) stated that 75-100% of their household income came from fishing. Thirty-five percent (n = 36) of fishers interviewed were former shark fishers, 75% of which moved to the reef fishery following implementation of the shark sanctuary, 16% moved to the pelagic-HL fishery and 9% moved to the pelagic-PL fishery.

5.4.2. Perceptions of ecological effectiveness, social impacts, and governance

All fishers interviewed were aware of the shark fishing ban, however, perceived reasons for its implementation varied. The most common reasons cited included: 1) because sharks are important for tourism (55%, n = 57/ 103): and 2) because shark stocks were overexploited (27%, n = 28/ 103), while 14% (n = 14/ 103) of fishers were unsure.

Perceptions of ecological effectiveness were very positive with 90% of fishers reporting an increase in shark abundance. Conversely perceptions of socio-economic impacts and governance were varied. Negative livelihood impacts were reported by 54% of respondents due to direct (loss of shark fishing revenue) and indirect (loss of catch due to shark depredation) costs. Former shark fishers were significantly more likely to report direct economic losses (Mann-Whitney U = 579.5, $p = < 0.001$) with 86% (n = 31/ 36) reporting a decline in income following sanctuary implementation vs 51% (n = 34/ 67) of fishers that did not historically target sharks. There were significant differences in indirect costs between fisheries, with reef fishers reporting significantly higher economic losses than pelagic-HL and pelagic-PL fisheries (Kruskal-Wallis chi-squared = 24.9, df = 6, $p = < 0.001$). Reef fishers reported a 25.3% loss in daily earnings due to the combined influence of catch and gear depredation while a daily loss of 3.0% and 0.1% was reported by pelagic-HL and pelagic-PL respectively (see Chapter 6 for a detailed breakdown of perceptions relating to shark depredation).

Governance indicators relating to community involvement in conservation planning and implementation – that is, voice and inclusiveness were viewed negatively, with the majority of respondents disagreeing with statements (See Table 5.1, Figure 5.3). Perceptions of transparency in decision making was varied both within and across fisheries but viewed most positively by pelagic-PL fishers (Figure 5.3). Most former shark fishers interviewed (72%, n = 26/ 36) did not believe that assistance and training was available to access alternative livelihood opportunities.

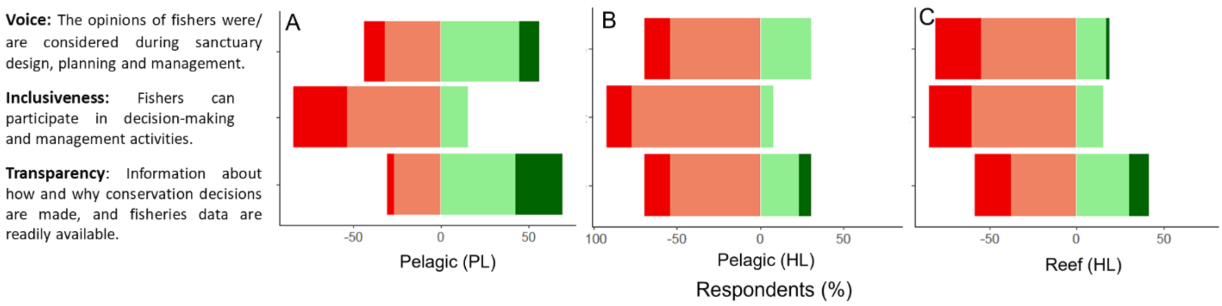

Figure 5.3. Perceptions of governance indicators relating to community involvement in sanctuary design and implementation. A) pelagic pole-and-line fishers; B) pelagic handline fishers; and C) reef fishers. Colour code for Likert-type responses: strongly disagree/ disagree (reds); agree/ strongly agree (greens).

5.4.3. Perceptions of compliance with sanctuary regulations

Thirty-seven percent of all fishers (19% of pelagic-PL; 62% of pelagic-HL; 40% of reef) interviewed reported illegal shark fishing within the sanctuary. The primary driver for non-compliance was income (78%) with a number of fishers (n = 5) stating that “shark fins sell for a high price on the black market". Additional reasons listed included to reduce shark disturbance (9%), bycatch (6%) and for food (6%).

Fishers reporting illegal shark fishing were asked how compliance could be improved and responses fell into three main themes: 1) stricter enforcement; 2) target-based management rather than the blanket-ban in place, specifically spatial closures in areas not deemed to be important for tourism; and 3) improved awareness and communication (Table 5.2).

Table 5.2. Responses volunteered by respondents reporting illegal shark fishing (n = 38/ 103) when asked "How could compliance be improved?". Example responses are direct quotes taken from interviews.

Primary themes of response	Respondents % (n)	Example responses
Enforcement	52 (n = 20/ 38)	"Stricter enforcement and fines" "Customs authorities need to be more vigilant, fins still exported"
Target-based management	24 (n = 9/ 38)	"Open shark fishing outside of the atoll" "Allow shark fishing in certain areas so that tourism is not effected" "Allow regulated fishing – sharks are a big problem now" "Allow shark fishing in deeper water"
Awareness & communication	14 (n = 5/ 38)	"Increase awareness about the importance of sharks" "Listen to fishers – understand problems" "Older generation still want to fish sharks"

5.4.4. Support for shark conservation approaches

Forty-two percent of fishers believe that shark conservation was required, however the best approach for this was not unanimous. Year-round closures in certain areas, spatial closures and finning bans receiving the greatest support among all fishers (Figure 5.4A), however levels of support for each approach varied between fisheries. Pelagic-PL fishers showed greatest support for the shark sanctuary, finning bans and gear restrictions (Figure 5.4B). Pelagic-HL and reef fishers generally showed reduced support as the severity of restrictions increased (Figure 5.4C-D). Overall, support for the Maldives shark sanctuary appeared highly variable; pelagic pole-and-line fishers (PL) were mostly supportive, reef fishers expressed opposition and support varied among pelagic handline (HL) fishers (Figure 5.4).

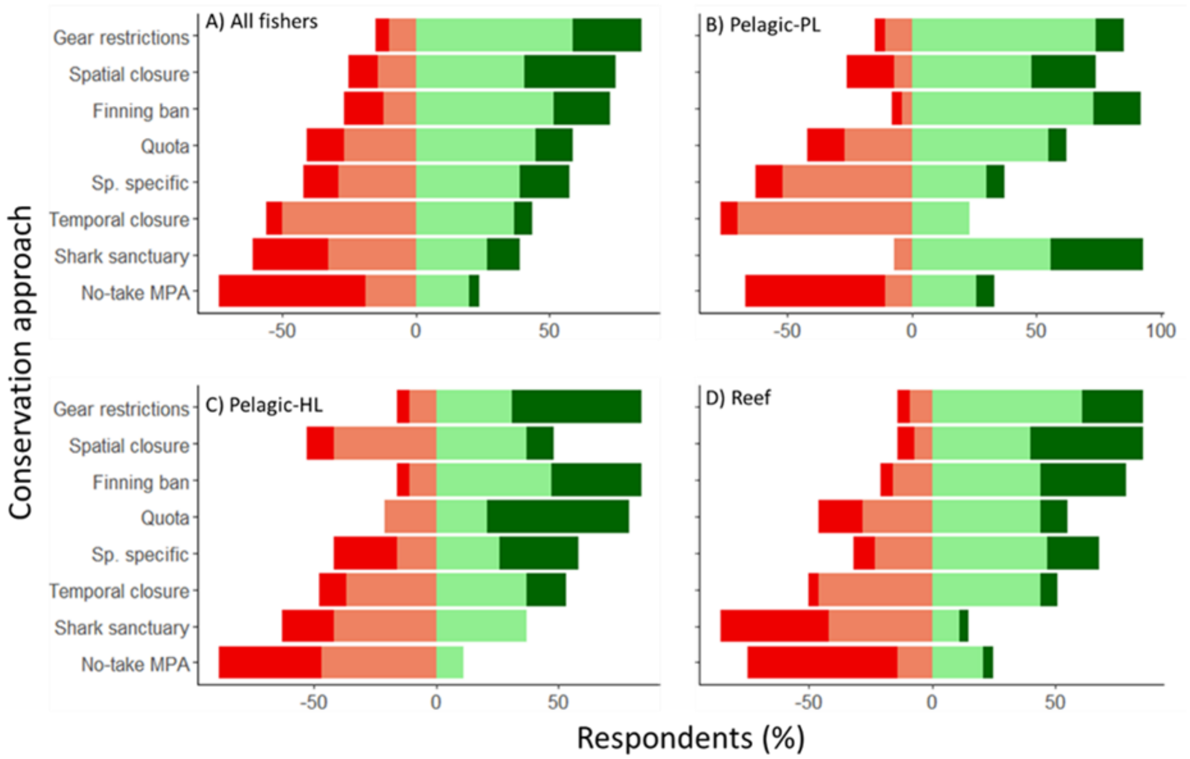

Figure 5.4. Fisher support for a range of shark conservation approaches. A) all fishers; B) pelagic-PL fishers; C) pelagic-HL fishers; and D) reef fishers. Support for shark sanctuary refers explicitly to the Maldives shark sanctuary. Responses were based on a 4-point Likert scale. Colour code for Likert-type responses: strongly oppose/ oppose (reds); support/ strongly support (greens).

5.4.5. Drivers of support for the Maldives shark sanctuary

The full SEM, including all hypothesised pathways (Figure 5.1), provided a poor fit to the observed data (Fisher's C = 168.27; df = 32; p < 0.001) and many variables were non-significant contributors to the observed correlation structure in the data (Table 5.3).

Table 5.3. Figure 5.5. Parameter estimates for the full a priori Structural Equation Model (SEM). A p value < 0.05 (*p < 0.05, **p < 0.01, ***p <0 .001) indicated a significant relationship between response and predictor variable. Alternative livelihood support is abbreviated to Alt.livelihood support.

Response	Predictor	Estimate	Std. Error	DF	Crit. Value	p value	Std. Estimate	Sig.
Years	Age	6.84	0.93	89	7.39	0.000	0.62	***
Shark fisher	Age	0.10	0.04	89	2.39	0.019	0.25	*
Education	Age	0.22	0.13	89	1.70	0.091	0.18	
Income	Education	1.47	0.23	88	0.66	0.511	0.07	
Income	Fishery	-14.23	3.94	88	-3.61	0.001	-0.36	***
Voice	Years	-0.01	0.05	88	-0.36	0.719	-0.04	
Voice	Shark fisher	-0.53	0.15	88	-3.51	0.001	-0.35	***
Fish catch	Years	0.01	0.01	88	0.29	0.775	0.03	
Fish catch	Fishery	0.58	0.12	88	4.66	0.000	0.45	***

Depredation	Fishery	13.35	2.86	87	4.67	0.000	0.46	***
Depredation	Fishcatch	1.69	2.07	87	0.81	0.417	0.08	
Depredation	Income	0.25	0.07	87	3.91	0.000	0.34	***
Transparency	Education	-0.01	0.07	89	-0.14	0.886	-0.02	
Inclusiveness	Shark fisher	-0.21	0.13	89	-1.56	0.080	-0.16	
Support	Inclusiveness	0.12	0.09	84	1.42	0.159	0.08	
Support	Voice	0.76	0.09	84	8.44	0.000	0.58	***
Support	Transparency	0.02	0.06	84	0.39	0.694	0.02	
Support	Depredation	-0.01	0.01	84	1.99	0.049	-0.13	*
Support	Fishery	-0.38	0.09	84	-4.43	0.000	-0.32	***

The final SEM revealed several significant effects (Figure 5.5, Table 5.4) and provided a good fit to the data (Fisher's C = 14.36; df = 32; p = 0.57) accounting for 73% of the variation in fisher's support for the shark sanctuary. Support for the shark sanctuary was directly influenced by target fishery, perceptions of depredation and voice. Sanctuary support was significantly lower among reef fishers and highest among pelagic pole-and-line fishers. Fishers reporting higher levels of depredation also showed significantly lower support. Conversely, fishers that believed they were well represented (voice) and their opinions considered during sanctuary design, implementation and management showed significantly greater support.

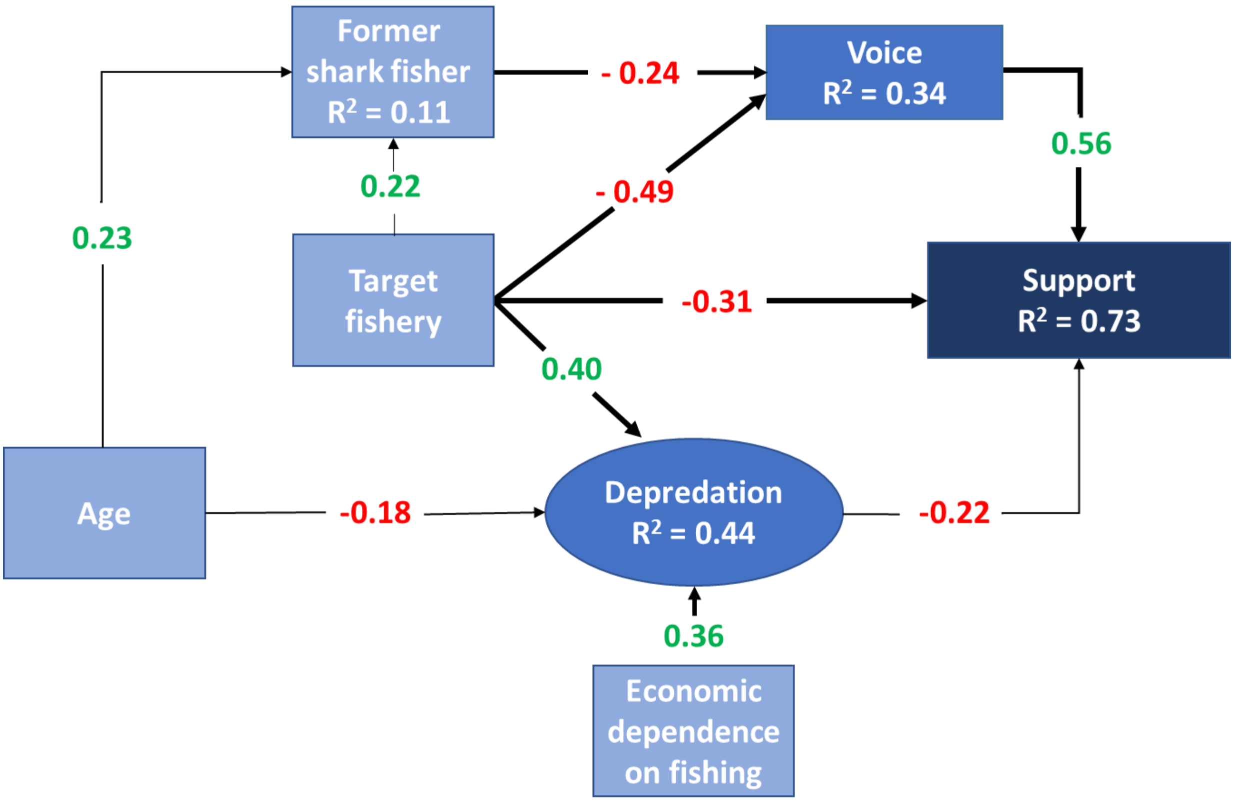

Figure 5.5. Final piecewise Structural Equation Model (Fisher's C statistic = 14.36, p = 0.57), representing the effects of fisher perceptions, demographics and fishery characteristics on support for the Maldives shark sanctuary. Hypothesised causal relationships (one-headed

arrows) were weighed with standardised path coefficients. Line thickness represents pathway significance with thicker lines being variables with a greater influence (See Table 5.4). The values in rectangles are the R^2 values for those dependent variables. Green values represent positive paths, and red ones are indicative of negative relationships.

Voice was directly influenced by target fishery (reef fishers held the most negative opinions in relation to voice, pelagic pole-and-line fishers most positive) and former shark fishers (those who previously targeted sharks held more negative opinions in relation to voice). Depredation was significantly influenced by income (those with higher economic dependence on fishing reported higher rates of depredation), age (younger fishers reported higher rates of depredation) and fishery (reef fishers reported higher rates of depredation, pelagic pole-and-line fishers the lowest). Older fishers and those now working within reef fisheries were more likely to have targeted shark fisheries prior to sanctuary implementation (Figure 5.4).

Table 5.4. Parameter estimates for the final Structural Equation Model (SEM). A p value < 0.05 (*p < 0.05, **p < 0.01, ***p < 0.001) indicated a significant relationship between response and predictor variable.

Response	**Predictor**	**Estimate**	**Std. Error**	**DF**	**Crit. Value**	**p value**	**Std. Estimate**	**Sig.**
SharkFisher	Age	0.09	0.04	88	2.24	0.027	0.23	*
SharkFisher	Fishery	0.13	0.06	88	2.14	0.035	0.22	*
Depredation	Fishery	11.69	2.52	87	4.64	0.000	0.40	***
Depredation	Income	0.27	0.06	87	4.21	0.001	0.36	**
Depredation	Age	-3.74	1.64	87	-2.28	0.025	-0.18	*
Voice	Fishery	-0.44	0.08	88	-5.46	0.000	-0.49	***
Voice	SharkFisher	-0.35	0.12	88	-2.65	0.009	-0.24	**
Support	Fishery	-0.37	0.09	87	-4.33	0.000	-0.31	***
Support	Voice	0.74	0.09	87	8.32	0.000	0.56	***
Support	Depredation	-0.01	0.01	87	1.98	0.040	-0.22	*

5.5. Discussion

Understanding links between perceptions and support for conservation is important to evaluate the long-term sustainability of conservation initiatives (Peterson and Stead, 2011; Stead, 2018; Korda *et al.*, 2021). Limited empirical research on fishers' perceptions of and support for shark sanctuaries has been undertaken to date, despite the rapid implementation of this conservation approach in complex socio-ecological systems (Ward-Paige, 2017). This study examined the perceptions of fishers from three different fisheries in the Maldives, the world's second shark sanctuary. A key finding is the perception of unequal livelihood impacts among fisher groups and the identification of key characteristics (age, fishery, economic dependence, former shark fisher) and perceptions (depredation impact, voice) that influence fisher support for the shark sanctuary. Findings have a number of important implications for policy makers for both the ongoing conservation of Maldivian shark populations and the future implementation of sanctuaries in other regions.

Regardless of fishery, most respondents (85%, n = 88/ 103) did not believe that they were able to participate in decision making related to sanctuary design and implementation (inclusiveness). Similarly, respondents within reef and pelagic-HL fisheries did not believe their opinions were considered (voice), however the majority (56%, n = 15/ 27) of pelagic-PL fishers did. Diverging perceptions between fisher groups highlight the importance of local context in determining the relative importance of variables and how they influence support for the sanctuary. For example, feelings of poor representation among reef fishers could be due to abrupt management decisions made in relation to shark conservation in 2009, with a ban on reef shark fishing implemented without engagement or formal consultation with stakeholders or identification of alternative livelihood opportunities for shark fishers (Sattar, 2010; Ali and Sinan, 2014). Conversely, concerns raised by the pelagic-PL fishing community appear to have influenced shark management from as early as 1981 (Ali and Sinan, 2015). Prior to sanctuary implementation, commercial tuna fisheries in the Maldives were in conflict with the pelagic shark fishery as fishers believed the harvesting of sharks associated with tuna schools had a detrimental impact on the availability of tuna (Sinan *et al.*, 2011). Pressure from the tuna fishing industry led to restrictions on shark fishing in the vicinity of tuna schools in, and around seamounts and Fish Aggregation Devices (FADs) where tuna aggregate (Sinan *et al.*, 2011). The prioritisation of commercial, high value fisheries like tuna occurs globally, and small-scale reef fisheries remain notably marginalised in conservation frameworks with management effort and political interest focused on industrial fleets (Cohen *et al.*, 2019). Yet, in many coastal nations small-scale fisheries support a much larger number of fishers in terms of jobs and income (Selig *et al.*, 2019) thus greater inclusiveness of this sector is important to improve perceptions across the wider community.

Fisher perceptions also highlight the need for greater transparency as most respondents (54%, n = 56/ 103) did not believe they were well informed about why and how decisions for shark conservation had been made and the majority (55%, n = 57/ 103) stated that it was to benefit tourism. While it is widely acknowledged that pressure from the tourism industry influenced the management decision (Ali, 2015; Ali and Sinan, 2015) there is a general lack of awareness for shark population declines which could influence levels of support for and compliance with regulations, with other studies documenting increased support when fishers understand the need for an MPA (Christie *et al.*, 2009; Pollnac *et al.*, 2010; Hoelting *et al.*, 2013). While it is acknowledged that this is largely due to a lack of data in the region, contemporary assessments of shark populations using cost-effective approaches (Chapter 3) should enable greater sharing of information moving forwards.

Perceptions of livelihood impact varied, with former shark fishers and reef fishers most likely to report livelihood losses. Most former shark fishers interviewed in this study (75%, n = 27/ 36) moved to the reef fishery following implementation of the sanctuary, thus negative perceptions of livelihood impact among reef fishers (both direct and indirect) are likely to be influenced by past experience, with reef fishing generating lower economic returns compared to shark fishing (Ali, 2015). Acknowledging unequal distribution of impacts across stakeholder groups is important as most studies consider livelihood needs of fishing communities as one homogenous entity, primarily focusing on commercial fishers (Mizrahi *et al.*, 2020). Yet, as shown here perceptions of negative impacts were greater among small-scale reef fishers. At local scales failure to address inequitable impacts can be problematic leading to conflict among stakeholder groups (Bennett *et al.*, 2019). Thus, this study addresses an important evidence gap through increased understanding of perceptions among groups. Consideration of this data in fisheries management is needed and imperative to avoid further marginalisation of groups with less decision-making power.

Levels of support for each of the eight approaches listed varied at the fisheries level. Pelagic-PL fishers showed substantially higher support for the Maldives shark sanctuary relative to pelagic-HL and reef fishers. Support among pelagic-HL and reef fishers showed a clear trend with support decreasing as policies increased in severity. For example, target-based policies, which allow sustainable harvest (i.e. gear restrictions, finning bans, fishing quotas and species specific bans) received relatively high support while limit-based policies that ban exploitation (i.e. no-take MPAs and shark sanctuaries) received low support. The relatively low support for newer limit-based policies could be linked to the lack of awareness for the status of shark populations within the region and the belief that populations have increased post sanctuary implementation. This finding aligns with a study conducted by Shiffman and Hammerschlag (2016a) who found shark researchers also show higher support for target-based policy suggesting that sustainable fishers are preferred both among experts in the field and key resource users. Interestingly, reef fishers showed high support for spatial closures, particularly at dive locations (Respondent 33 “Ban in certain areas where people dive/ snorkel and let us fish in others”) implying they are aware of the value of reef shark populations for the tourism industry.

The analysis of individual characteristics and perceptions against levels of support for the Maldives shark sanctuary highlights specific variables that may be more important determinants of support – these include voice, shark depredation, age, economic dependence on the fishing sector, target fishery and whether respondents were former shark fishers. Findings have important implications for policy makers, future implementation of shark sanctuaries in other regions and ongoing management in the Maldives. Firstly, the results confirm the importance and value of understanding stakeholder perceptions (Bennett, 2016) in influencing context-specific management measures more likely to be supported by those most impacted. Secondly, monitoring perceptions and investigating how they influence support helps to identify management actions – including, increasing stakeholder participation and voice, mitigation of the costs associated with fisher-shark interactions and increasing transparency in decision making – that will improve positive perceptions around changing management and increase likelihood of support for the sanctuary. Third, variance in perceptions at the fishery level, particularly in relation to livelihood impacts, feelings of representation (voice) and sanctuary support suggest that managers need to be more attentive to concerns raised among reef and pelagic-HL fishers.

Younger fishers reported higher shark depredation rates indicating an issue with shifting baseline syndrome within the fishing community. Shifting baseline syndrome (SBS) describes changing perceptions of biological conditions due to a loss of historical knowledge and the discrepancy between an individual's perceived environmental baseline used to measure change, and the true environmental ‘starting point’ (Pauly, 1995). SBS presents a particular problem for the conservation of predatory species, especially when biological data on population trends are not available. Establishing historical baselines of species populations is important for contextualising present-day population trends (Collins *et al.*, 2020a) and in this example predator interactions and depredation events. Perceptions of relatively high depredation rates among younger fishers could be attributed to SBS and could indirectly influence support for sanctuary regulations if not addressed. In addition, perceptions of depredation were also influenced by fishers’ dependence on fishing; with fishers most reliant on fishing having more negative views. Previous studies have also found correlations between financial reliance of fisheries and support for species conservation (McClanahan *et al.*, 2008; Murphy *et al.*, 2015) suggesting that sources of alternative livelihood will be important to mitigate negative economic impacts and increase local support for conservation.

Increasing support through greater attention to the management actions suggested above may also improve ecological outcomes through increased compliance with regulations (Peterson and Stead, 2011; Rohe *et al.*, 2017). Illegal exploitation and trade of wildlife has been described as a primarily economic activity (Gallic and Cox, 2006) and economic incentives for illegal shark fisheries are well-documented (Carr *et al.*, 2013). Accordingly, high value of shark produce (Respondent 34: "shark meat and fins are a very good price now") was identified as the primary incentive for non-compliant behaviour in this study. Moreover, 37% (n = 38/ 103) of fishers reported illegal shark fishing and reports of illegal shark catch is increasing in the region with large consignments of shark produce marked for export seized by the Maldives customs (Oceanographic, 2021).

Interestingly, reports of illegal shark fishing were highest among pelagic-HL fishers despite support for sanctuary regulations being lowest among reef fishers. The proximity of human populated areas to fishing grounds, presence of local boats and vessel traffic from both fisheries and tourism sectors could deter illegal activity among reef fishers as likelihood of being seen/caught is greater. Thus, findings suggest that compliance may be linked to perceptions of risk and the consequence of enforcement (Gallic and Cox, 2006; Collins *et al.*, 2020b) in addition to support for conservation (Peterson and Stead, 2011; Turner *et al.*, 2019).

Improved enforcement was the most common response when fishers were asked 'how could compliance be improved'. However, the Maldives and other small-islands nations that have implemented shark sanctuaries have limited capacity, funding and resources will be available to increase enforcement capacity (Davidson, 2012; Vianna *et al.*, 2016). A focus on improved transparency relating to the need for the shark sanctuary and collection of data to establish current population trends within the context of historical baselines is therefore important to justify the ongoing need for sanctuary regulations and to encourage support. Our results are likely to be of relevance to other small island states that have declared shark sanctuaries in both the tropical Pacific and Caribbean regions and highlight important socio-economic aspects and perceptions that should be considered and monitored for the long-term sustainability of shark sanctuaries.

5.6. Conclusion

From a socio-economic perspective, findings raise sensitive questions regarding the equitability of livelihood consequences resulting from conservation policies and highlight negative perceptions of governance. This case study demonstrates the complexity and diverging responses to the Maldives shark sanctuary, driven by fishery and socio-economic context and previous management decisions which marginalised certain groups. By revealing factors that influence fisher perceptions of and support for shark sanctuaries findings highlight the need for greater consideration of stakeholder views and mitigation of negative economic impacts through improved livelihood opportunities during sanctuary implementation and ongoing management.

Chapter 6 Fisher-shark conflict: perceptions of shark interaction and depredation in reef and pelagic fisheries

6.1. Abstract

Global targets for protecting species of high biodiversity value often fail to consider the human costs of conservation. Human-wildlife conflicts can be intensified following conservation action and present a major challenge to development of ecological and socioeconomic sustainability. Using semi-structured interviews (n = 103), fisher-shark conflict was quantified in one of the world's first established shark sanctuaries – the Maldives. Seventy-three percent of fishers interviewed believe conflict increased post sanctuary implementation. Perceived depredation rate (loss of catch and fishing gear) and the associated economic impact was significantly higher in reef (21.2% of vessel earnings) versus pelagic fisheries (pelagic-handline: 2%, pelagic-pole-and-line: 0.2% of vessel earnings). Participatory mapping identified areas of high conflict potential and suggests that disproportionately high rates of depredation reported by reef fishers could be attributed to extensive spatial overlap (55- 78%) between shark hot spots and fishing activity with both competing for shared resources (prey). Findings also show a significant correlation between perceptions of depredation and support for conservation, highlighting potential for unmitigated conflict to undermine management goals. This chapter raises concerns for the potential impacts of shark conservation on local livelihood and highlights the need to integrate predator conservation with local fisheries management to both reduce conflict and support sustainable reef fisheries in complex socio-ecological systems.

6.2. Introduction

Hunting and widespread habitat modification has depleted predator populations throughout the world's ecosystems (Estes *et al.*, 2011), placing them at the forefront of conservation efforts. While recovery is the intent of conservation policy, population increase can lead to challenges for natural resource managers, particularly related to human responses (Treves and Karanth, 2003; Marshall *et al.*, 2016). For example, species recovery can increase competition for habitats and resources exacerbating conflicts between humans and wildlife (Carlson *et al.*, 2019; Guerra, 2019).

Human-wildlife conflicts (HWC) occur when the actions of people or wildlife have an adverse effect on the other, or represent threats (actual or perceived) to livelihood, property, security, recreation or safety (Nyhus, 2016). Such conflicts encompass a diverse range of species and situations and are well documented across both marine (Peterson and Carothers, 2013; Peterson *et al.*, 2013; Guerra, 2019) and terrestrial systems (Hanley *et al.*, 2018; Merson *et al.*, 2019). Conflicts where predators feed on resources captured, grown or raised by humans are among the most widespread HWC (Tixier *et al.*, 2020b). This behaviour, termed depredation, results in substantial socio-economic costs for humans and poses a threat to public safety (Nyhus, 2016). For predators, depredation can increase the risk of death or injury associated with equipment and/ or retaliatory killing from humans (McManus *et al.*, 2015; Merson *et al.*, 2019; Ontiri *et al.*, 2019). Unmitigated conflicts surrounding depredation can also reduce local support for conservation due to negative alteration of public perceptions (Artelle *et al.*, 2016; Khan *et al.*, 2018; Guerra, 2019) threatening species survival and the long-term sustainability of conservation measures (Carlson *et al.*, 2019)

In terrestrial systems, predator depredation as a side effect of successful conservation and population recovery has received substantial scientific and management attention (Guerra, 2019). An iconic case is the reintroduction and recovery of grey wolves (*Canis lupus*) in Yellowstone National Park which led to substantial livestock losses and decades of conflict between wolves and ranchers (Muhly and Musiani, 2009). While the same conflict exists in the ocean, it is not yet considered a global issue (Marshall *et al.*, 2016; Guerra, 2019) despite its potential to disrupt food security and the socio-economic viability of fisheries in complex socio-ecological systems (Bearzi *et al.*, 2019; Tixier *et al.*, 2020b). Given global conservation efforts to recover shark populations and shifts from target-based measures which focus on sustainable exploitation (i.e. fishing quotas, permits, species-specific restrictions) to limit-based measures (i.e. shark sanctuaries) that ban exploitation (Shiffman and Hammerschlag, 2016b) there is a need to address potential negative consequences of HWC as shark population recovery occurs (Carlson *et al.*, 2019).

Anecdotal and media reports of shark depredation within shark sanctuaries are increasing (Ali and Sinan, 2014; McKenzie, 2020; Chapman *et al.*, 2021; UW360, 2021). This has led to discussions to lift sanctuary regulations in both the Bahamas and the Maldives (McKenzie, 2020; Chapman *et al.*, 2021; UW360, 2021) suggesting that internal support for sanctuaries may decline as shark populations recover (Carlson *et al.*, 2019; Chapman *et al.*, 2021). This is concerning given the status of the worlds shark populations, with 31% of all species at risk of extinction (Dulvy *et al.*, 2021). Moreover, shark sanctuaries have typically been declared in small island nations, including the tropical Pacific, Caribbean and Republic of Maldives (Ward-

Paige, 2017), all of which have high dependence on the marine environment for fisheries and tourism (Selig *et al.*, 2019) and limited capacity for enforcement (Vianna *et al.*, 2016). Understanding and resolving shark depredation is therefore a major societal and environmental challenge (Tixier *et al.*, 2020a) and is critical for effective predator conservation in multi-use ecosystems (Dickman, 2010; Esmaeili *et al.*, 2019). Yet, compared to other fisheries issues, shark depredation has received little research attention (Mitchell *et al.*, 2018). Existing research has focused on shark depredation in commercial pelagic longline fisheries, with studies reporting reductions in catch by up to 28% (Gilman, 2007; Gilman *et al.*, 2008; MacNeil *et al.*, 2009; Mitchell *et al.*, 2018), while studies in small-scale fisheries (SSFs) or nearshore ecosystems are limited (Mitchell *et al.*, 2018). Further, no study has been conducted to investigate fisher-shark interaction and conflict (real or perceived) within shark sanctuaries.

A context-specific understanding of local concerns regarding shark depredation are required to mitigate conflict and support sustainable fisheries within a multi-level governance context (Stead, 2018). To address the evidence gap semi-structured interviews were utilised to compare the following across reef and pelagic fisheries: 1) perceptions of shark interaction, 2) fisher reported depredation rate, and 3) the relationship between depredation and support for shark sanctuary regulations. Overlap between reef fishing activity and shark hotspots, documented during participatory mapping exercises, was also investigated to identify areas with high conflict potential.

6.3. Methods

6.3.1. Study site

The Maldives is a small island nation composed of about 1,200 islands and located in the central Indian Ocean (Figure 6.1A). Fieldwork was conducted at landing sites in North Malé Atoll (Hulhuemalé, Malé, Thulusdhoo, Figure 6.1B) and Dhaalu Atoll (Bandidhoo, Kudahuvadhoo, Maaenboodhoo, Meedhoo, and Rinbudhoo, Figure 6.1C).

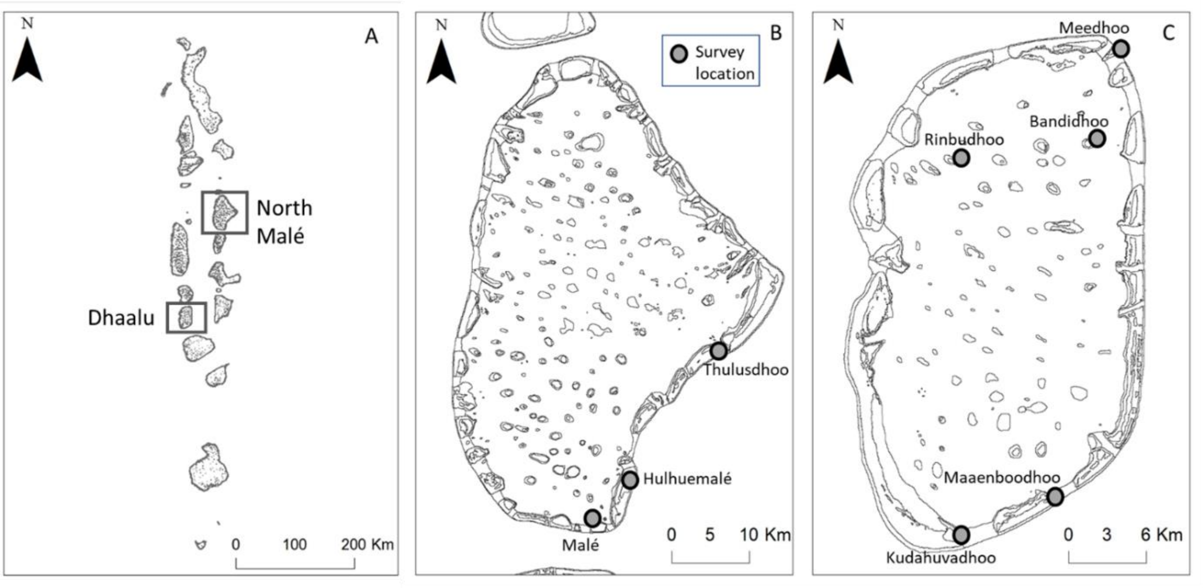

Figure 6.1. Study location. A) The Maldives is an archipelago of 26 natural atolls, consisting of 1190 coral reef islands in the Indian Ocean. North Malé Atoll is located on the eastern side (4.4167° N, 73.5000° E) and Dhaalu Atoll the west (2.8469° N, 72.9461° E) of the archipelago, B) interview locations in North Malé Atoll and C) interview locations in Dhaalu Atoll.

For the purpose of this study, fishing activities have been grouped into three subcategories: 1) industrial pole-and-line fishery (herein referred to as pelagic-PL); 2) industrial handline fishery (herein referred to as pelagic-HL) and 3) small-scale reef fishery. The pelagic-PL fishery primarily targets skipjack tuna (although yellow-fin is caught as a secondary species) and is the most commercially valuable fishery in the Maldives, accounting for 65% of total reported national tuna landings (FAO, 2017). The pelagic-HL fishery primarily targets yellow-fin tuna (Ahusan *et al.*, 2016) and accounts for 33% of total tuna landings (FAO, 2017). Both of these fisheries operate offshore however, livebait is first caught in nearshore waters using a lift net deployed from vessels (Yadav *et al.*, 2019). In the pelagic-PL fishery livebait is thrown overboard and water sprayed at the surface to attract tuna schools. Multiple fishers then use a single pole, line and barbless hook to haul catch one-by-one from the sea (Miller *et al.*, 2017).

In the pelagic-HL fishery, individual fishers typically deploy a single line and hook from a stationary vessel. When a fish bites, the fisher will then haul the catch onto the vessel (Adam, 2006). The small-scale reef fishery operates in nearshore waters both inside atolls and along atoll edges. The main gear used in reef fishing is a simple, single hook hand line. Historically exploited at low levels, the reef fishery has expanded in recent decades for commercial purposes with reef fishing now conducted in all atolls, with catch sold to island families, tourist resorts or exported (Sattar, 2014). Combined fishery products account for >80% of total exports (FAO, 2012) valued at ~160 million USD per year.

There are approximately 677 licenced commercial pole-and-line vessels employing 7,981 registered fishers in the Maldives (Edwards *et al.*, 2020). Demographic data for the number or registered vessels or fishers is not available for the pelagic-HL or reef fishery.

6.3.2. Interviews

A mixed-method approach was used in the interview process, including both semi-structured interview questions and participatory-mapping methods (Turner *et al.*, 2015; Noble *et al.*, 2020). Semi-structured interview questions were used to ensure all participants were asked the same questions but allowed individuals to add detail to responses and provided a more flexible conversation during the mapping component. In total, 103 interviews were conducted with reef and tuna (herein referred to as pelagic) fishermen from January - April 2019. Informants were targeted using opportunistic and snowball sampling with interviews conducted on local islands in North Malé and Dhaalu Atoll or at Malé fish market (Figure 6.1). Interviews included sections on fishing experience, depredation, demographics and a mapping exercise (Table A10). Interview questions were piloted with fishers outside of the target population to determine suitable wording and approximate interview time frame.

Participatory mapping was used to elicit reef fishers' spatial knowledge and to assess the level of overlap between core fishing grounds and shark distribution. The approach taken followed previous studies (Hall and Close, 2007; Hall *et al.*, 2009; Turner *et al.*, 2015) and methods outlined in Chapter 2. Reef fishers were prompted to draw polygons to outline their common fishing grounds and then on separate maps outline areas where they frequently encounter/ sight sharks. No restrictions were placed on participants regarding the number, shape or spatial extent of the polygons. Maps were obtained from 57 reef fishers (31 in North Malé and 26 in Dhaalu Atoll). Individual maps were photographed or scanned and georeferenced in ArcGIS using a minimum of three ground control points (Oniga *et al.*, 2018). Polygons drawn by fishers were digitized to closely reflect the areas drawn by each participant.

6.3.3. Ethics statement

Participants were informed of both the survey motivation and the intended use of the data collected and subsequently verbal consent was sought before the survey was undertaken. Participant's names were not recorded and anonymity of their responses was assured. Further, participants were informed of their right to decline any question with which they were unwilling or unsure about answering and, that should they so wish, the interview could be ended at any time. Interviews were not facilitated with either monetary or material motivation. Ethical approval for the survey was sought from and granted by the ethics review board at Newcastle University and research conducted under permits from the Maldives Ministry of Fisheries and Agriculture (MoFA).

6.3.4. Data analysis

To obtain comparable values for the economic cost associated with catch and gear depredation, the reported monetary loss was converted into the percentage of daily vessel earnings lost (estimated from average daily catch value). Kruskal-Wallis tests were used to examine differences in reported depredation (loss of catch and gear) and associated economic costs between each fishery.

Structural equation models conducted in Chapter five found a direct correlation between perceptions of depredation and fisher support for the shark sanctuary. To expand on this, correlations between both perceptions of catch lost and gear damage on support at the fishery level were assessed. Ordinal regression models were developed for each target fishery (pelagic-PL, pelagic -HL and reef) to predict support for shark sanctuaries as an ordinal outcome (strongly oppose, oppose, support, strongly support) with loss of catch (%) and damage to fishing gear (%) as predictors. Models were adjusted for individual socioeconomic characteristics (age, education, number of years fishing) and measures of individuals' dependence on fishing (proportion of income from fishing). Model fit was tested using both Hosmer–Lemeshow and Lipsitz tests. All analyses were carried out using R Studio version R version 3.5.3 (R Core Team, 2019).

Three stages of spatial analysis were undertaken:

1) Displaying digitised polygons on maps of Dhaalu and North Malé Atoll.
2) Analysing overlapping polygons to produce hotspot maps for common fishing grounds (A) and areas fishers reported frequent shark encounters (B).
3) Overlaying the results of 2 to highlight areas of potential conflict between fishing activity and shark distribution.

Hotspot maps were generated for common fishing grounds and areas of frequent shark encounters by calculating how frequently different respondents selected the same area during interviews. Individual polygons were each given an equal weighting of one and overlaid with overlapping areas summed. A frequency counting table counting overlapping polygons allowed cartographic representation of hotspots as outputs ranging from low to high and enabled me to calculate the percentage of respondents that selected each area. These steps were repeated separately for polygons of common fishing grounds and shark encounters creating two separate hotspot maps. Maps were then converted to raster layers (100 m x 100 m grid cell).

Maps created in step two were overlaid using the raster overlay tool. Conflict potential scores were calculated for each grid cell by mathematically combining values calculated for overlapping polygons in each map (i.e. fishing grounds + shark encounters). Outputs were visualised using hotspot maps with high values representing locations with high conflict potential (high percentage of fishers reported fishing in this area and frequent shark encounters) and vice versa.

The total area mapped for common fishing grounds (A) and areas of frequent shark encounters (B) was calculated and the area of which the two data sets coincided was expressed as a percentage of the total area mapped in B. Map processing was completed in ArcMap 10.6.1 (ArcGIS, 10.6.1).

6.4. Results

6.4.1. Fisher characteristics

In total, 103 fishers were interviewed face-to-face in North Malé (n = 66) and Dhaalu Atolls (n = 37), Maldives. Interviewees were exclusively male with an average age of 46.0 ± 10.9 (SD) and had 23.6 ± 13.2 (SD) years of fishing experience. Fifty-six percent (n = 57) were reef fishers, 26% pelagic pole-and-line fishers (n = 27) and 18% pelagic handline fishers (n = 19). Fishing was the only occupation for 81% of fishers and the majority (67%) stated that 75 - 100% of their household income came from fishing.

6.4.2. Fishing Activity—Reported Changes in Catch

Eighty percent of fishers who had been active for more than 10 years (n = 84) reported changes in their catch compared to 10 years ago (Figure 6.2).

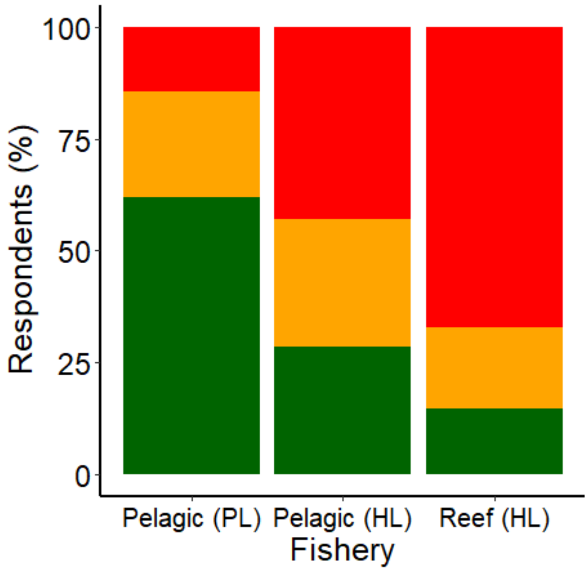

Figure 6.2. Fisher perception of change in fish catch compared with 10 years ago. Green: increase, orange: no change, red: decrease.

Pelagic-PL fishers reporting an increase in catch (61%, n = 17) attributed this to favourable ocean currents (n = 7), technological advances in fishing vessels meaning they could travel further (n = 6), climate change (n = 2) and an increase in bait fish (n = 1). Those reporting a decrease in catch (14%, n = 4) attributed it to an increase in the number of fishers and vessels (n = 4). Similarly, the majority (n = 4) of pelagic-HL fishers reporting an increase in catch (28%, n = 5) attributed this to technological advances. While those reporting decreased catch (42%, n = 8) attributed it to an increase in fishers and vessels (n = 6). Reef fishers reporting a decrease in catch (67%, n = 38) attributed this to shark disturbance (n = 18) and an increase in fishers and vessels (n = 15). Restrictions to fishing area linked to resort development (n = 2) and environmental damage linked to climate change (n = 2) and development (n = 1) were also listed. Reef fishers reporting increased catch (8%, n = 5) attributed this to vessel and gear advances (n = 3), an increase in bait fish (n = 1) and climate change (n = 1).

6.4.3. Perceptions of shark-fishery interaction

Overall, 97% of reef fishers and 55% of pelagic fishers using handlines (HL) reported negative shark interactions when fishing for target species. These interactions were primarily reported as catch depredation (partial or complete consumption of fish caught) and gear loss or damage (specifically hooks, lines and jigs). Conversely, 78% of pelagic fishers using pole-and-line (PL) reported positive shark interactions, because fishers believe sharks maintain tuna (specifically skipjack tuna, *Katsuwonus pelamis*) closer to the surface and improve catch success. Pole-and-line fishers (57%) only reported negative shark interactions during live-bait fishing.

The majority (73%) of respondents reporting negative interactions and actively fishing for over 10 years (n = 84) also reported an increase in shark depredation in the last 5-10 years. This included 93% of reef, 60% of pelagic-HL and 38% of pelagic-PL fishers. Increases in depredation were attributed to increased shark abundance following implementation of the shark sanctuary (100% of respondents).

The shark species individual fishermen described interacting with most frequently was significantly correlated with target fishery (Pearson's Chi-squared test, $\chi2 = 25.268$, df = 2, p-value = < 0.001). Reef fishers interacted with reef-associated species, primarily grey reef (*Carcharhinus amblyrhynchos),* whitetip reef *(Triaenodon obesus)* and blacktip reef sharks (*Carcharhinus melanopterus)*. Pelagic handline fishers reported interaction with reef-transients including tiger (*Galeocerdo cuvier)*, oceanic whitetip (*Carcharhinus longimanus)* and shortfin mako sharks (*Isurus oxyrinchus).* Pelagic pole and line fishers reported frequent sightings of silky sharks *(Carcharhinus falciformis),* but this species was not linked to catch or gear depredation. Blacktip reef sharks were perceived to be the greatest disturbance for pelagic fishers when livebait fishing. Seventy-four percent of reef fishers reported changing fishing practise to avoid shark depredation. The most common measure implemented was to change fishing location (91%), fishers also reported changing bait (17%), killing the shark (12%) or stopping fishing entirely for that day (2%).

6.4.5. Shark depredation rates

Perceived loss of catch and gear damage varied significantly depending on target fishery and gear type (Figure 6.3). For reef fisheries, reported loss of catch (43.1%, 95% CI [37.3, 48.5]) and gear (35.5%, 95% CI [30.2, 40.8]) was substantially higher than pelagic-HL (catch: 6.9%, 95% CI [4.1, 9.7], gear: 9.4%, 95% CI [6.4, 12.3]) and pelagic-PL fisheries (catch: 1.2%, 95% CI [4.1, 9.7], gear: 1.5%, 95% CI [0.66, 2.4]).

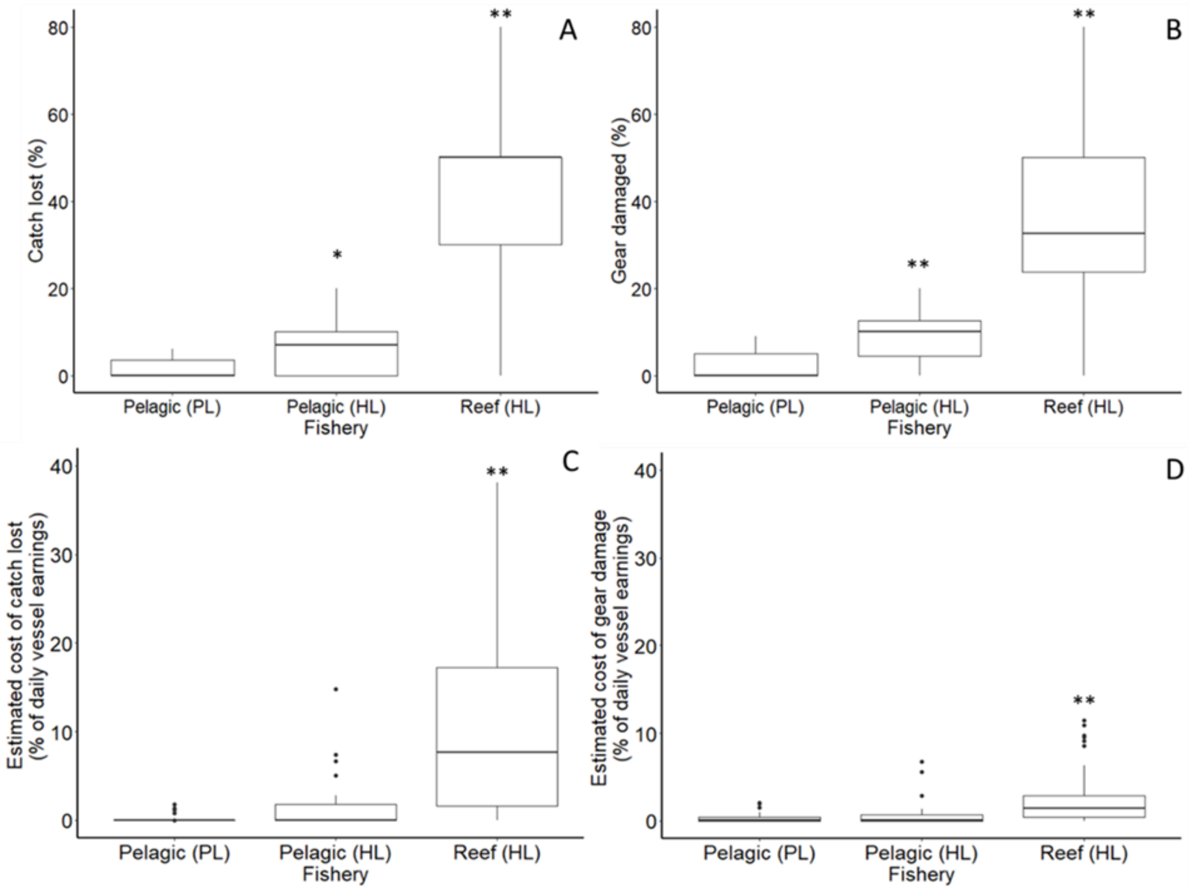

Figure 6.3. Fisher reported shark depredation and economic loss. (A) catch and (B) gear loss per vessel per day in pelagic pole-and-line (PL), pelagic handline (HL) and reef handline (HL) fisheries. Estimated economic loss (presented as % daily vessel earnings) associated with catch (C) and gear (D) depredation. Significant differences are marked (Kruskal-Wallis, p=<0.01* and p=<001**).

Economically, losses of catch in the reef fishery equated to a loss of 21.2% (95% CI, [9.3, 33.1]) of daily earnings. This was significantly higher than the relative economic loss reported in both pelagic-HL (2.0%, 95% CI, [0.2, 3.8]) and pelagic-PL fisheries (0.2%, 95% CI, [0.01, 0.4]) fisheries (Figure 6.2C).

The economic cost of gear losses was significantly higher in reef fisheries (4.1% of daily earnings, 95% CI, [1.0, 7.2]), when compared to pelagic-HL (1.0%, 95% CI, [0.1, 1.9) and pelagic-PL fisheries (0.4%, 95% CI, [0.1, 0.7]) fisheries (Figure 6.3D).

6.4.6. How does depredation influence support for conservation?

Overall, pelagic-PL fishers were mostly supportive of shark sanctuary regulations, reef fishers expressed opposition and support varied among pelagic-HL fishers (see Chapter 5, Figure 5.4). All fishers, regardless of fishery and method, exhibited reduced support as reported gear losses increased (Table 6.1). Reduced support from reef fishers was also significantly linked to catch losses.

Table 6.1. Ordinal regression models for levels of support for shark sanctuary regulations (dependent) as predicted by fisher reported catch and gear depredation.

		Dependent variable: Level of support for the shark sanctuary				
Fishery		**Odds Ratio[1]**	**95% CI**	**Std Error**	**t-value**	**p-value**
Pelagic -PL	Catch lost (%)	0.96	0.63, 1.47	0.23	-2.66	0.847
	Gear lost (%)	0.54	0.30, 0.79	0.21	-0.19	0.008
Pelagic-HL	Catch lost (%)	0.85	0.63, 1.04	0.12	-1.36	0.173
	Gear lost (%)	0.76	0.58, 0.92	0.11	-2.39	0.012
Reef-HL	Catch lost (%)	0.92	0.87, 0.96	0.02	-3.44	<0.001
	Gear lost (%)	0.94	0.89, 0.97	0.02	-2.92	0.003

[1]All models adjusted for respondents' age (continuous), years fishing (continuous), education (categorical) and dependence on fishing as a source of income (categorical). There was no evidence of lack of model fit (See table A11) using Hosmer–Lemeshow tests. Pseudo-R^2 (McFadden's) were 0.20 (pelagic-PL), 0.32 (pelagic-HL), and 0.34 (Reef).

6.4.7. Mapping conflict potential in reef fisheries

Participatory mapping suggested that fishing activity was concentrated on outer reef slopes (Figure 6.4A and 6.5A), while shark hotspots (delineated as areas marked by >50% of respondents) were concentrated in atoll channels in Dhaalu Atoll (Figure 6.4B) and outer reefs in North Malé (Figure 6.5B).

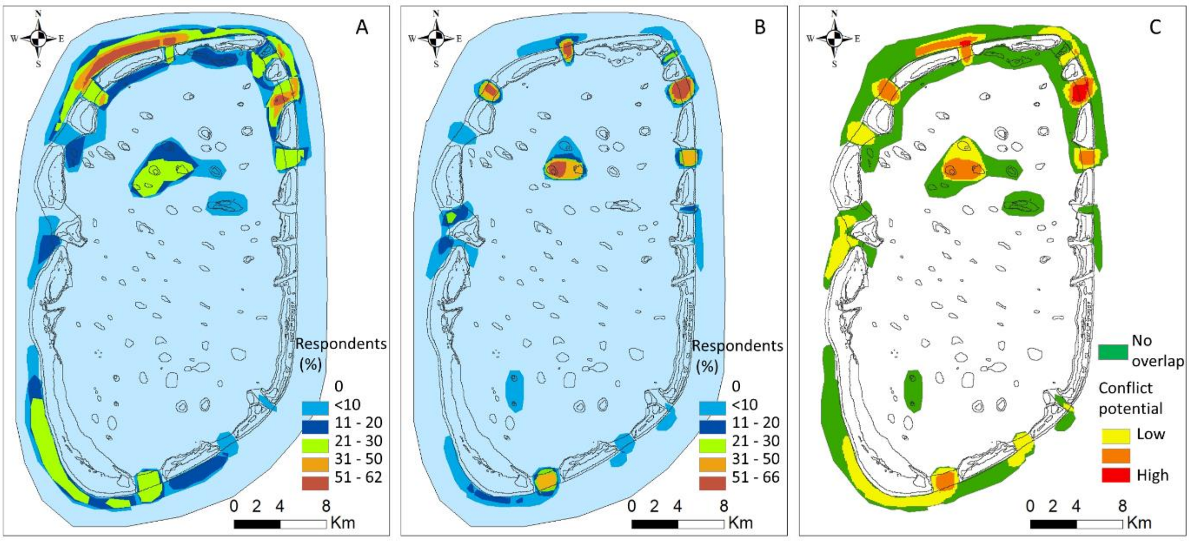

Figure 6.4. Hotspot maps of conflict potential. Reef fishers (n = 26) were asked to mark their core fishing grounds (A) and areas of high shark abundance (B) during interviews in Dhaalu Atoll. Panel (C) represents the overlap between reef fishing grounds and shark distribution.

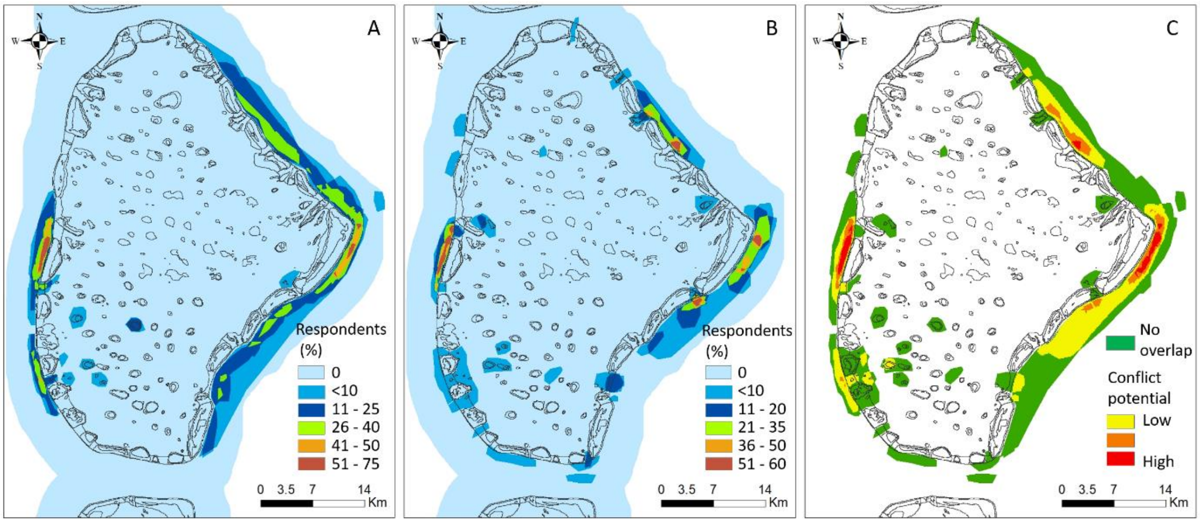

Figure 6.5. Hotspot maps of conflict potential. Reef fishers (n = 31) were asked to mark their core fishing grounds (A) and areas of high shark abundance (B) during interviews in North Malé Atoll. Panel (C) represents the overlap between reef fishing grounds and shark distribution.

Hotspot maps of shark abundance and fishing activity were overlaid to identify areas of potential conflict (Figure 6.4C and 6.5C). Spatially, 78% (63 km^2) of the total area perceived to have high frequency of shark encounters overlapped with reef fishing grounds in Dhaalu Atoll and 55% (128 km^2) in North Malé (Table 6.2).

Table 6.2. Summary of polygons drawn by fishers during participatory mapping exercises and estimates of area overlap between areas of frequent shark encounters and core fishing activity.

	Measurement	**Atoll**	
		Dhaalu	North Malé
Areas of high shark abundance	Total polygons	76.0	88.0
	Total area (km^2)	79.9	234.8
	Number of hotspots	4.0	4.0
	Total Hotspot area (km^2)	5.2	6.2
Core fishing grounds	Total polygons	51.0	73.0
	Total area (km^2)	175.3	276.2
Spatial Overlap	Area of total overlap (km^2)	62.7	128.0
	Total overlap (% of shark total area)	78.0	54.5

6.5. Discussion

The present study explores perceptions of fisher-shark conflict within one of the world's first established shark sanctuaries and represents the first empirical study of shark depredation in both commercial and small-scale reef fisheries for the Indian Ocean. Prior to this study, limited information was available regarding encounters between sharks and Maldivian fisheries, despite high shark diversity (Sinan *et al.*, 2011), local dependence on fishing (Yadav *et al.*, 2019) and anecdotal reports of shark-fisher conflict (Ali and Sinan, 2014). Perceived shark depredation rates and associated economic cost were disproportionately high for reef fishers equating to economic losses of 21% of daily vessel earnings. Consequently, reef fishers showed significantly reduced support for shark sanctuary regulations highlighting the need to sensitively address perceptions of depredation to avoid negative implications for shark conservation and recovery.

Findings provide critical insight into how local communities perceive the magnitude of fisher-shark conflict associated with fisheries depredation. Importantly, findings show that the majority of fishers believe depredation increased post-sanctuary implementation due to increasing shark populations. However, ecological studies conducted in the region show no sign of population recovery (Chapter 3) and suggest that reef shark populations remained stable between 2016-2020. While no data exists for pelagic shark species in the Maldives, global analysis show continued declines in across the Indian Ocean (Pacoureau *et al.*, 2021). Further, given the k-selected life history traits of sharks including slow growth, late sexual maturity, long lifespans and small brood sizes (Smith *et al.*, 1999), population recovery is inherently slow and would be unlikely given the relatively short timeframe since sanctuary implementation. Perceived increases in fisher-shark conflict are more likely to be due to one or a combination of factors including shark habituation (Mitchell *et al.*, 2020), fisheries exploitation (Sattar, 2014) and shifting perceptions (Dickman, 2010).

Shark habituation and associative learning (where sharks associate vessel presence with the availability of easily accessible food) around fishing activity may account for differences in fisher perceptions of shark abundance and ecological evidence. Field studies have documented faster shark arrival times, changes in habitat-use and site fidelity in areas subject to regular provisioning (Fitzpatrick *et al.*, 2011; Gallagher *et al.*, 2015) or fishing pressure (Mitchell *et al.*, 2020). Thus, interactions between fishers and sharks could be increasing despite populations remaining stable. The chance of behavioural associations forming is likely to be increased if fishing activity overlaps with the small home ranges and high site fidelity of certain shark species (Mitchell *et al.*, 2020), such as blacktip reef, whitetip reef and grey reef sharks (Barnett *et al.*, 2012; Vianna *et al.*, 2013), which were identified in this study as the main species depredating on reef fishers catch.

Our findings suggest that high levels of fisher-shark conflict in nearshore reef fisheries may also be driven by competition for resources. Findings show high spatial overlap between sharks and reef fishing activity with both favouring outer reef habitats that sustain high densities of teleost fish (Stewart *et al.*, 2011; Tickler *et al.*, 2017). Historically a subsistence fishery, extraction of Maldivian reef resources has increased in the last few decades (Sattar, 2014), driven by domestic markets and growing demand for reef fish from tourists (MoT, 2018). In line with evidence that suggests the Maldives reef fishery is approaching maximum sustainable yield (Sattar, 2014) the majority of reef fishers in this study reported declines in fish catch. Findings suggest that reef fisheries exploitation coupled with localised fishing effort in areas of high shark abundance may be intensifying competition and/ or associative foraging behaviours (e.g.(Newman *et al.*, 2010) leading to increased shark interaction with fishing vessels (Powell and Wells, 2011; Schifiliti, 2014).

While the validation of fisher's spatial knowledge was not an explicit goal of this study, BRUVs deployed in Chapter 2 confirm that areas in which fishers report frequent shark encounters "hot spots" have both high shark occurrence rates and abundance relative to other locations within the atoll. Moreover, comparison of observed abundance at hotspots was substantially greater (>8x) than regional and global averages. Ecological data therefore supports the theory that high rates of depredation reported in reef fisheries is linked to overlap between sharks and fishing activity, likely driven by the availability of prey (Chapter 4). However, it is important to note that spatial data will be influenced by sample coverage and that hotspot maps likely did not encompass all areas of high shark abundance and common fishing grounds within Dhaalu and North Malé Atolls.

Reports of increasing depredation are also likely to be marked by a shift in how fishers view sharks from a valuable resource to exploit to competitors for marine resources. Shaped by social and cultural beliefs, economic pressures, and past interactions (Dickman, 2010) perceptions of depredation rate are widely considered to overestimate reality (Muir, 2010; Verschueren *et al.*, 2020) and thus may require more mitigation than actual conflict (Guerra, 2019). Cultural traditions associated with sharks vary between regions, for example sharks retain a spiritual importance in numerous cultures in the Pacific where they were traditionally subjected to ritual killings (Techera, 2019). In the Indian Ocean however, there is little evidence of cultural tradition associated with shark fishing with fisheries driven by economic gain rather than cultural value (Techera, 2019). Given the economic incentive behind the

Maldives shark fishery, negative economic impacts associated with shark conservation could shape perceptions of depredation impact and as shown in this study motivate opposition for sanctuary regulations. This may be exemplified in small-scale fisheries (SSFs) as the economic cost of depredation has direct impacts for individuals rather than operations (Smith *et al.*, 2021). Thus, even relatively small losses to shark depredation may be perceived to have a proportionally large impact on fisher livelihood, leading to economic distress and prompting fishers to complain more about depredation (Gonzalvo *et al.*, 2015). Additionally, events that are rare (e.g. unusually poor fishing conditions or high shark depredation) may be more easily recalled by fishers and may be overrepresented relative to more common events (Temple *et al.*, 2020). If not addressed the emotive nature of fisher-shark conflict coupled with discussion among fishers and media attention as seen in the Maldives (MoFA, 2019) could propogate negative perceptions across fisheries and communities.

In the absence of demographic data for the Maldivian reef fishery (i.e. number of fishers and vessels) quantifying the impact of depredation on local livelihood is difficult. Additionally, shark depredation is unlikely to have severe consequences for food security as the fishery is largely for commercial purpose rather than subsidence (Sattar, 2014; Yadav *et al.*, 2019). However, our finding that perceived depredation rates were disproportionately high for reef fisheries, could have broader implications for SSFs operating within shark sanctuaries globally. To date, sanctuaries have been enacted in coastal nations (Ward-Paige, 2017) where SSF are of fundamental importance for local livelihood, revenue, employment and development (Bell *et al.*, 2013; Albert *et al.*, 2015; McConney, 2015). Typically operating in nearshore ecosystems, SSFs support large numbers of fishers compared with industrial fisheries (Smith *et al.*, 2021). In the Pacific Islands the majority of the population is engaged in coastal fishing activities and most of the fish consumed in the region is harvested from coral reefs (Hanich *et al.*, 2018). Similarly, SSF are one of the main sources of livelihood and food security for Caribbean coastal communities (McConney, 2015). Thus, given the global importance of SSF (Davis *et al.*, 2020), and high conflict potential in areas that they operate, more studies assessing fisher-shark interaction and associated socio-economic costs are needed.

Reported depredation rates in the pelagic pole-and-line fishery were low and economic impact negligible, aligning with data collected in Maldives by fishery observers (Miller *et al.*, 2016; Miller *et al.*, 2017). Low rates of depredation in the pelagic-PL fishery is attributed to the highly selective nature of this fishing method with previous studies noting that the fishery exhibits extremely low rates of bycatch, discards and interactions with endangered, threatened and protected species (Ford and Zelasney, 2020). Comparatively, the selectivity of the handline fishing method has been described as low (Peñaherrera and Hearn, 2008). Moreover, lines are left underwater for extended periods increasing the potential of intercaction with marine predators (Zimmerhackel *et al.*, 2015) as seen in this study. While our sample coverage is reflective of the three main fisheries in Maldives it is important to note that surveys were only conducted in two atolls and are therefore not representative of the full fishing community across the Maldives. Nonetheless, the diverging perceptions surrounding shark interaction emphasize the need to differentiate between fishery and gear types when making management decisions and in conflict mitigation strategies (Baynham-Herd et al., 2020).

Regardless of fishery type, fishers reporting higher rates of gear depredation showed significantly reduced support for shark sanctuary regaulations, while level of support among reef fishers was also significantly influenced by perceptions of catch lost. The strong correlation between gear depredation and support could be because gear loss and/or damage is a visible impact that incurs direct replacement cost (Tixier *et al.*, 2020b) while catch lost is unrealised loss of income. Findings suggest that perceptions of fisher-shark conflict could pose a challenge to shark conservation efficacy if not mitigated. Adverse ecological outcomes may result when stakeholders actively oppose conservation due to low compliance (Ward-Paige, 2017) and engagement in negative behaviours (e.g. poaching) (Lute *et al.*, 2016). For example, retaliatory killing to reduce conflict is prevalent in terrestrial systems (Jędrzejewski *et al.*, 2017; Kissui *et al.*, 2019) and recognised as an important factor causing worldwide declines of predators (Maheshwari and Sathyakumar, 2019). While only 12% of fishers in this study reported killing sharks to reduce conflict, illegal shark fishing is increasing within the Maldives sanctuary (Oceanographic, 2021) thus, failure to consider negative perceptions of fisher-shark conflict could have negative implications for shark conservation and recovery (Dulvy and Yan, 2020; MacNeil *et al.*, 2020).

Fisher-shark conflict is likely to escalate in coming decades as human pressures on resources increases and sanctuaries make progress towards ecological targets. Findings therefore have relevance to other nations where the recovery (real or perceived) of historically exploited predators intensifies existing conflict. Depredation is a long established conflict in terrestrial systems, however studies on depredation in fisheries has substantially increased over the last

40 years indicating an emerging issue (Guerra, 2019). Formal consideration of stakeholders' perceptions of conflict and quantification of associated economic losses can bring greater transparency to this controversial issue (König *et al.*, 2020). Findings suggest that fishers' perceptions of shark interactions and support for the shark sanctuary are strongly linked with the impact of sharks on earnings, both negatively through depredation and positively through increased catch success for target species.

Sustainable solutions to mitigate conflict must be specific to local contexts and include participatory and stakeholder-inclusive approaches (König *et al.*, 2020). While our hotspot maps provide a cost-effective initial underpinning for the identification of areas with high conflict potential, detailed assessments of fishing effort and shark distribution patterns are needed. Given that most shark sanctuaries have been implemented in developing nations (Ward-Paige, 2017), restrictions to capacity and technical expertise are likely to hinder data collection, however some simple changes to existing processes such as census collection data could provide the much need disaggregated data on local dependence on fish stocks and fishing effort. Based on the findings of this study the following recommendations are advised:

- Co-development and implementation of a standardised system for reporting depredation in the region (i.e. log books). This would facilitate a systemic evaluation of damage caused so that perceived and actual damage can be differentiated and trends in conflict assessed on available evidence.
- Increased awareness and education among fishing communities, particularly in relation to shark population status as perceptions of increasing depredation are attributed to population recovery.
- Collation of landings data for the reef fishery and consideration of ways to alleviate further pressure on reef resources to ensure long-term fisheries sustainability and reduce conflict.

6.6. Conclusion

Given reports of increasing shark depredation in many regions and recent discussions to lift shark sanctuary regulations in two countries (the Maldives and the Bahamas) this study provides valuable context to the issue of co-developing effective management to tackle fisher-shark conflict. Findings have implications for current and future shark conservation efficacy and highlight the need to consider how fishers will interact and potentially compete with shark populations, if and when they recover. Findings also raise concern for the livelihood costs of depredation for small-scale reef fisheries and the need to integrate predator conservation with local fisheries management. The findings have implications for future conservation and fisheries management action in the Maldives and beyond.

Chapter 7 General discussion

7.1. Overview

This thesis provided a unique interdisciplinary perspective on shark conservation, advancing our knowledge of contemporary population trends and distribution, and fisher perceptions of shark sanctuary impact. One of the strengths of this research has been the integration and triangulation of multiple knowledge sources spanning both social and ecological disciplines, which allowed greater insight into the complex interactions between sharks and resource dependent communities while identifying cost-effective approaches to monitor elusive marine predators in data poor regions. Baited remote underwater videos (BRUVs) and citizen science data established a contemporary population baseline against which future changes can be quantified, while fisher Local Ecological Knowledge (LEK) provided valuable historical context (**aim one**). Underwater Visual Census (UVC) and BRUVs identified key drivers of reef shark abundance and spatial distribution aiding identification of critical shark habitat (**aim two**). Interviews with fishers advanced our understating of local perceptions, drivers of support for shark sanctuary regulations and brought greater transparency to perceptions of fisher-shark conflict (**aim three**). This chapter draws together and integrates key findings to discuss the local and wider implications for shark conservation and marine management from an interdisciplinary perspective.

7.2. Evaluating the efficacy of a shark sanctuary

In recent decades there has been a rapid growth in the diversity, abundance and spatial extent of environmental conservation initiatives designed to protect biodiversity and foster sustainable development (Adams, 2004; Rands *et al.*, 2010; Mascia *et al.*, 2017), yet biodiversity continues to decline (Maxwell *et al.*, 2016; IPBES, 2019). If any progress is to be made towards stemming the global decline of biodiversity and achieving the UN SGDs, the field of conservation policy must adopt evaluation methods to determine what works and when (Ferraro and Pattanayak, 2006). As we enter the UN Decade of Ocean Science for Sustainable Development (2021-2030) a concerted effort will be required to develop strategies to “Conserve and sustainably use the oceans, seas and resources for natural sustainable development” (SDG 14, UN, 2015). This will require an innovative and transdisciplinary approach (Moallemi *et al.*, 2020) yet, for many marine populations, research and management continues to neglect socio-economic factors, focusing on biological knowledge (Booth *et al.*, 2019).

This thesis highlights the utility and importance of an interdisciplinary approach to conservation research and addressed a number of critical knowledge gaps outlined in the Maldives NPOA-sharks (Ali and Sinan, 2015) and in other existing studies (Ward-Paige, 2017). Shark sanctuaries have been rapidly implemented in tropical coastal nations to conserve shark populations. However, the impacts of this approach are poorly understood (Ward-Paige, 2017). Concerns about the ecological and social effectiveness of shark sanctuaries and whether or not they are equitably managed (Davidson, 2012; Chapman *et al.*, 2021) have led to growing interest in conducting management evaluations (Ward-Paige and Worm, 2017). Yet, for most shark sanctuaries there is a lack of baseline data that can be used to evaluate the efficacy of this approach (Ward-Paige, 2017). In the Maldives reef shark populations have stabilised suggesting that sanctuary regulations have been effective in stopping shark abundance decline (Chapter 3). Moreover, shark abundance was relatively healthy when compared to other regions and substantially higher than the average reef shark abundance for the Indian Ocean (MacNeil *et al.*, 2020). This implies that, from an ecological perspective, shark sanctuaries could be an effective conservation approach to maintain and recover vulnerable shark populations. However, when considered alongside data from Chapter 4, 5 and 6, findings show that if implemented without consideration of human dimensions, shark sanctuary regulations are unlikely to be sufficient for the protection and recovery of shark populations long-term. Findings echo statements from global studies that have evaluated shark populations across protected and unprotected regions (Ward-Paige and Worm, 2017; MacNeil *et al.*, 2020). Specifically, this thesis identifies two threats to the long-term sustainability of the Maldives shark sanctuary: 1) lack of support for the sanctuary among fisher communities and 2) reef fisheries exploitation and its components of fisher-shark conflict and prey depletion.

Conflicts surrounding conservation governance were identified during interviews with fishers; most fishers in reef and pelagic-HL fisheries did not believe their opinions were considered (voice) leading to inequality in management decision-making which affords benefits to pelagic-fishers and leads to disproportionate livelihood costs for reef fishers. Perceptions of voice was identified as the strongest predictor of support for the Maldives shark sanctuary suggesting that employing good governance principles is crucial to the success of conservation initiatives (Bennett *et al.*, 2019). Inclusive governance processes should include steps that actively include marginalised stakeholders (Lockwood *et al.*, 2010), however the diversity in perceptions across each of the three fisheries here suggests this may not be the case. A strong theme throughout this thesis is that negative perceptions were strongly associated with reef fishers. This may result from a number of factors, including: the high proportion of former shark fishers that moved to the reef fishery post sanctuary implementation (direct economic loss); historical marginalisation of this group in management decisions relating to sharks (Sinan *et al.*, 2011) and perceived economic loss associated with depredation (Chapter 6).

Depredation conflict was also identified as a major threat to the long-term sustainability of the Maldives shark sanctuary. Fishers and sharks are in competition for a shared resource (prey) with participatory maps showing extensive spatial overlap between reef fishing activity and ecologically validated shark hotspots (Chapter 6). Given that recent (April 2021) discussions to amend the total ban on shark fishing in Maldivian waters was linked to concerns surrounding shark depredation, areas of high conflict potential (where reef fishing activity overlaps with shark hotspots) identified during participatory mapping with fishers will be key to the development of potential mitigation. Studies have shown an increase in depredation on livestock and fisheries catch in areas where wild prey is overexploited and scarce (Sharma *et al.*, 2015; Nelson *et al.*, 2016) thus as reef fishing pressure continues to increase both locally in the Maldives (Sattar, 2014) and globally (Eddy *et al.*, 2021) fisher-shark conflict is likely to intensify. Increasing pressure on reef resources could also have indirect implications on shark populations due to declines in prey availability, with a significant positive correlation found between key prey groups and shark abundance (Chapter 4). Annual reef fishery catch has increased substantially in the last decade due to growing demand for reef fish from tourists (Sattar, 2014; MoT, 2018) and although the Maldives was classified as one of the most underexploited fisheries in the Indian Ocean (MacNeil *et al.*, 2015) estimates suggest the fishery is approaching the limits of its maximum sustainable yield (Sattar, 2014). Moreover, global catches of reef-associated fishes has been in decline since its peak in 2002 despite increased fishing effort with a 60% decline in catch-per-unit effort since 1950 (Eddy *et al.*, 2021). While not an immediate threat in the Maldives, this raises uncertainty over the long-term efficacy of the shark sanctuaries, which still permit catch of other commercially important species including reef fishes and thus could lead to on-going depletion of prey. Prey-depletion hypothesis have been linked to changes in the density of predator populations in both marine and terrestrial ecosystems (Bearzi *et al.*, 2006; Ripple *et al.*, 2014). In the Mediterranean, overfishing of anchovies and sardines was thought to be responsible for declines in near-shore encounters with dolphins, tuna and billfish (Bearzi *et al.*, 2006). Similarly, depletion of prey is a key threat to large carnivores at global scales (Wolf and Ripple, 2016).

Findings also raise concerns for SSFs operating within shark sanctuaries that ban both artisanal and commercial catch, whereby SSFs incur negative and disproportionate impacts, yet limited data (Pauly and Charles, 2015) and low commercial value restricts their representation in conservation planning (Cohen *et al.*, 2019; Kockel *et al.*, 2020). Negative impacts on SSFs also has implications for poverty alleviation (SDG 1) and food security (SDG 2) with SSFs estimated to harvest half of the world's fish and generate 90% of all fishing-related jobs (FAO, 2018). Although the tuna fishery retains a place of prominence in Maldivian diet and culture, local reef fish consumption has increased in recent decades (Yadav *et al.*, 2021) and thus the importance of this fishery for local food security may also be increasing. However, this finding has broader implications for shark conservation and sustainable fisheries policy in other regions that have enacted sanctuaries and are critically dependent on SSFs.

While BRUVs and citizen science data suggest that reef shark populations are stable within the Maldives shark sanctuary and thus provide evidence that sanctuaries could be an effective conservation tool, a key question arising from this thesis is can this be maintained long-term in light of the threats discussed herein? Specifically, how can negative perceptions and inequality in impacts be addressed in sustainable marine resource management interventions? Can fisher-shark conflicts be mitigated? Are ecosystem level rather than species-specific conservation measures needed to support shark recovery? Currently definitive answers to these questions are lacking. However, to address ecological and socio-economic problems and avoid generating new conflicts through singular approaches, robust fisheries management solutions should consider multi-pronged and integrated approaches to shark conservation (Booth *et al.*, 2020; Iwane *et al.*, 2021). This thesis highlights the need to improve participatory governance through effective engagement of key stakeholder groups representing all fisheries in decision-making processes of shark conservation management (Peterson and Stead, 2011; Gill *et al.*, 2017; Stead, 2018). Failure to address concerns raised and achieve greater participation and/ or platforms for reef fishers to voice opinions could create further divergence between stakeholders prioritising conservation goals and fishers prioritising livelihood needs (Stead, 2018). When conservation measures impact negatively on the sustainability of fisher livelihoods rule breaking is common (Peterson and Stead, 2011; Bergseth *et al.*, 2018).

A number of MPAs that directly involve local communities have been successfully implemented in Fiji and other areas of Oceania (Aswani, 2005; Christie and White, 2007; Sano, 2008). In such locations MPAs provide benefits to all involved stakeholders (fishers, local community, tourism sector, tourists) with user fee systems in place for divers. The Maldives did implement a series of compensation schemes that recompensed fishers for their loss in shark fishing rights and to support them to find alternative livelihoods, however 72% of former shark fishers interviewed here did not believe that assistance and support was provided to access alternative livelihoods. Moreover, former shark fishers state that their income has decreased following sanctuary implementation (Chapter 5). Given the value of shark-diving tourism and its potential to contribute to local and national economies in many countries (Vianna *et al.*, 2012; Huveneers *et al.*, 2017; Vianna *et al.*, 2018; Zimmerhackel *et al.*, 2019), one option to compensate fishers for direct (income) and indirect (depredation) economic loss could be additional fees on this type of tourism. A study conducted in the Maldives found that increasing shark abundance can increase dive trip demand by 15%, generating economic gains of over US$6 million for the local dive tourism industry and of almost US$24 million for the broader local tourism industry (Zimmerhackel *et al.*, 2018). Could this revenue help support fisher communities and improve local livelihoods? This has been shown to be achievable in Fiji and Malaysia (Brunnschweiler, 2010; Vianna *et al.*, 2018). However revenues of the shark-diving industry are not always retained locally (Haas *et al.*, 2017) and future research should focus on developing mechanisms to support fair distribution of economic benefits among all relevant stakeholders including assessing willingness of fishers to consider alterative or supplementary livelihood options such as tourism.

Although research into shark depredation is increasing (Mitchell *et al.*, 2018), studies exploring potential mitigation have focused on modification to fishing gear (Carmody *et al.*, 2021). This study suggests a combination of concentrated fishing effort and behavioural associations by sharks linked to fishing vessel activity is leading to an increase in depredation in reef fisheries. Reducing fishing activity in heavily fished locations and areas of high shark abundance could therefore decrease depredation. Interviews with both reef and pelagic fishers are recommended to discuss potential mitigation measures and to identify areas of conflict across a larger spatial scale. Moreover, in recognising that conservation action itself can lead to human-wildlife conflicts (Redpath *et al.*, 2013; Simpfendorfer *et al.*, 2021), addressing negative costs and perceptions associated with sanctuary implementation and management could help mitigate conflict.

Existing studies suggest that strict management measures (i.e. no entry and no take MPAs) may be needed to adequately protect sharks (Robbins *et al.*, 2006; Frisch and Rizzari, 2019). However, such measures would entail prohibitive economic costs to reef fishers and thus implementation would be challenging given that shark sanctuaries have been enacted in tropical coastal nations (Ward-Paige, 2017) where reef fisheries are important for local livelihood, revenue, employment and food security (Bell et al., 2013, Albert et al., 2015, McConney, 2015). Spatial closures of critical shark habitat and areas of overlap with fishing activity could be a way forward that promotes shark conservation while accounting for the livelihood needs and reducing fisher-shark conflict. The identification of important variables influencing shark abundance (Chapter 4) and hot spot maps to identify areas of high conflict potential (Chapter 6) are therefore a first, but essential, underpinning for the basis for future spatial planning and could facilitate the identification of critical areas for stricter management. Effective engagement and ongoing consultation with fishers, including the incorporation of LEK in spatial planning is recommended to increase participation and transparency in decision-making processes.

Findings also point to an urgent need to monitor socio-economic dependence on reef fisheries and their status in the Maldives. Catch data that distinguishes between target fisheries and fine-scale data on fishing activity are needed to both promote the transparency for good governance (Pauly and Charles, 2015) and inform future management plans for any MPA including shark sanctuaries. Reducing the socio-economic dependence on coral reef fisheries while sustaining the well-being of coastal communities is also an important consideration for the future sustainability of sharks and reef fisheries. In contrast to other island nations in the tropics, where reef fishing has played a prominent role in society and been practised for millennia, reef fisheries in the Maldives remains of lower importance compared to pelagic fisheries. Demand for reef fishes is primarily driven by the tourist sector; reef fishes now comprise 83% of fish consumed by tourists (Hemmings *et al.*, 2014) with resorts demanding ~500 kg of reef fish daily (Yadav *et al.*, 2021), thus regulating tourism sales and/ or demand could be one way to offset pressure on reef resources (Lewis *et al.*, 2020).

7.3. Building a robust evidence base in data poor regions

Shark species are disproportionately threatened in low-income countries throughout tropical and subtropical waters with more than 75% of species threatened with extinction (Dulvy *et al.*, 2021). In such locations financial and logistical constraints to data acquisition for marine predators are acute and a major barrier to evidence-based management (McQuatters-Gollop *et al.*, 2019). Novel and cost-effective approaches to collect data on shark abundance and distribution are therefore urgently required. This thesis triangulated data from a number of knowledge sources to address fundamental knowledge gaps: establishing new population baselines and identifying important shark habitat. The cost-efficiency of methods used is discussed below, and recommendations made for the long-term monitoring of shark populations within the region.

In marine systems there is considerable interest in combining local and scientific knowledge to achieve management objectives with the use of LEK to meet SDGs identified as a major governance priority (Borja *et al*. 2020). However, few studies have examined the merits and caveats of LEK to document spatial data or shown how combining both knowledge systems could benefit conservation (Hamilton *et al.*, 2012; Berkström *et al.*, 2019). Spatial or temporal overlap of ecological and social data-collection efforts is rare (Mascia *et al.*, 2017) and a major benefit of this study was the ability to compare data from multiple knowledge sources at the same spatial and temporal scale. The validation of fisher identified shark hot spots with BRUVs highlights the value of stakeholder inclusive approaches to identify critical shark habitat either as a standalone approach or to identify areas where more targeted and intensive monitoring should be focused (Elliott *et al.*, 2018). The conversion of fishers knowledge into geo-spatial data (Chapter 2) could aid the design and implementation of resource management strategies in a cost-effective and participatory way, bridging gaps between local and scientific knowledge and representing a powerful approach to inform data gaps in data depauperate fisheries (Aswani and Lauer, 2006; Santos *et al.*, 2019).

While BRUVs and citizen science were primarily used to assess relative trends in abundance in this study a benefit of these approaches is the simultaneous collation of data on species distribution. Citizen science approaches allows data to be collected at much larger spatial and temporal scales than ecological surveys and the value of this approach in documenting shark distributions is well established (Vianna *et al.*, 2014; Ward-Paige *et al.*, 2018). However, understanding why sharks show preference for certain habitats or locations is a much more difficult task than simply describing distribution (Espinoza *et al.*, 2014). A combination of BRUVs and UVC surveys provided the resolution required to understand finer-scale ecological questions relating to shark distribution and habitat use (Chapter 4) addressing an important evidence gap in shark conservation research (Heupel *et al.*, 2019). Such data are critical to identify threats to reef shark populations and evaluate spatial management measures (Speed *et al.*, 2010; Espinoza *et al.*, 2014; Acuña-Marrero *et al.*, 2018).

A key output from this thesis is the establishment of a contemporary shark population baseline which will form the foundation for future long-term monitoring in the region. Both BRUVs and citizen science approaches led to broadly comparable data sets showing that reef shark populations were stable between 2016-2020 and relative abundance was similar (Chapter 3). BRUVs are a widely applied to assess population status, thus allowing comparison of relative abundance over time or between regions making the utility of this data high (Brooks *et al.*, 2011; Goetze *et al.*, 2018; MacNeil *et al.*, 2020). Although citizen science data was only collected across one atoll in this study, this approach shows high potential for the collection of data at much larger spatial scales (Amano *et al.*, 2016; Ward-Paige *et al.*, 2018).

Biodiversity monitoring and evaluations of conservation efficacy require ongoing investment with observations collected periodically, to quantify trends and detect abrupt or small changes in population abundance or distribution that could lead to significant ecological change over time (Estes *et al.*, 2021). On this basis of this thesis and considering the economic costs associated with both BRUV and citizen science data collection (Table 7.1), it is recommended that on-going monitoring of shark population abundance uses a combination of BRUVs (every 3 years) and citizen science surveys (data collection: continuous, analysis: annual). It is also recommended that LEK continues to be utilised to identify priority areas at greater spatial scales to inform ecological surveys and engage fishers. Replication of fine-scale BRUV and UVC surveys at larger spatial scales to increase understanding of shark habitat-use will be costly, however the identification of key variables that influence species abundance could facilitate the development of predictive models to up-scale data collection and model distribution in a changing environment. The spatial prediction of species distributions from survey data is recognised as a significant component of conservation planning (Buse et al., 2007, Guisan and Zimmermann, 2000, Guisan and Thuiller, 2005) and future research should focus on the accuracy of such models to assess risk and prioritise management efforts both regionally and globally. As part of this research predictive models were developed based on key variables identified in Chapter 4 and UVC data collected in Dhaalu Atoll. Initial predictions showed high potential identifying areas of high shark abundance (Robinson, personal observation) however validation of predictions using BRUVs was impacted by the COVID-19 pandemic.

In addition to ecological data collection, the collection of socio-economic data over-time is essential to measuring and evaluating the impacts of conservation and human behavioural changes (Estes *et al.*, 2021). Such outcomes and social changes in perceptions and support for conservation can improve conservation implementation, ongoing management and the long-term sustainability of conservation approaches. This thesis highlights the value of stakeholder interviews for increasing understanding of fisher perceptions and how these in turn influence local support for conservation. Moreover, this approach is cost-effective and provides a platform for marginalised groups to voice concerns, which should help ensure that conservation efforts meet societal needs specific to local contexts.

Table 7.1. Outline of the economic costs associated with Baited Remote Underwater Videos (BRUVs), citizen science and Local Ecological Knowledge (LEK) for the collection of data to document reef shark abundance and distribution.

	Unit	BRUVs	Citizen science	LEK
Consumables	US$*	4,042	n/a	414
Monitoring costs		4,900	n/a	n/a
Personnel (monitoring)	Staff	224	n/a	192
Personnel (data handling)	(hours)	200	48	103

*Costs are based on the deployment of 100 BRUV replicates, 103 interviews with fishers and the collation of monthly citizen science data records from North Malé Atoll.

7.4. Balancing conservation objectives with local fisheries policy

Successful conservation of predator populations in socio-ecological systems is complex and requires improved integration of conservation objectives with local fisheries policy. Results of this study highlight a disconnect between shark sanctuary objectives which seek to protect threatened shark populations and global policies to promote the welfare of small-scale fishers (SDG 14.b). Reports of increasing depredation and substantial livelihood losses heighten concerns for the potential impacts of shark interactions with SSFs, thus creating trade-offs between predator conservation and sustainable fisheries management (Roman *et al.*, 2015; Ohlberger *et al.*, 2019).

If the disconnects between the ecological goals of predator conservation and socio-economic impacts on human welfare are not resolved, then local fishers may continue to bear the costs of conservation, undermining support and ultimately jeopardizing conservation outcomes (Booth *et al.*, 2019; Guerra, 2019). Conservation policies should look to incorporate the different perceptions and needs of fishers in open dialogue to enable the development of solutions that protect the welfare of SSFs while protecting shark populations. This will allow local and global advances towards a post-2020 deal for nature and people – where progress towards one target does not undermine another.

7.5. Concluding remarks

This thesis represents the most comprehensive evaluation of shark sanctuary efficacy to date. Findings have important implications for the ongoing management of shark populations within the Maldives and recommendations for other regions that have implemented shark sanctuaries or plan to do so in the future. The implementation of shark sanctuaries as a precautionary approach is advisable for k-selective species which are highly vulnerable, and as shown in this study, sanctuary regulations have effectively reduced targeted shark fishing enough to maintain Maldivian reef shark populations. This is a positive early indicator that shark sanctuaries could be an effective conservation approach, however greater recognition of the human dimensions during the planning and implementation stages are needed for improved tailored management interventions that are context specific. A stronger focus on achieving social outcomes (e.g. increased participation, reduced conflict and livelihood benefits) may help drive local support, thus enhancing the potential for shark sanctuaries to improve ecological outcomes. Moreover, findings of this thesis indicate that evaluations of conservation success should consider a combination of objective indicators (e.g. shark abundance trends) which show tangible change and subjective indicators (e.g. fisher support and perceived equity) as local attitudes will ultimately influence compliance and thus socio-ecological sustainability.

Appendices

A.1 Appendix for Chapter 1

Table A1. The list of 174 pre-defined stop-words provided by the tm package (Feinerer et al. 2008) that were removed from articles during the cleaning of the corpus.

Stop-words removed from corpus								
A	About	Above	After	Again	Against	All	Am	An
And	Any	Are	Aren't	As	At	Be	Because	Been
Before	Being	Below	Between	Both	But	By	Can't	Cannot
Could	Couldn't	Did	Didn't	Do	Does	Doesn't	Doing	Don't
Down	During	Each	Few	For	From	Further	Had	Hadn't
Has	Hasn't	Have	Haven't	Having	He	He'd	He'll	He's
Her	Here	Here's	Hers	Herself	Him	Himself	His	How
How's	I	I'd	I'll	I'm	I've	If	In	Into
Is	Isn't	It	It's	Its	Itself	Let's	Me	More
Most	Mustn't	My	Myself	No	Nor	Not	Of	Off
On	Once	Only	Or	Other	Ought	Our	Ours	Ourselves
Out	Over	Own	Same	Shan't	She	She'd	She'll	She's
Should	Shouldn't	So	Some	Such	Than	That	That's	The
Their	Theirs	Them	Themselves	Then	There	There's	These	They
They'd	They'll	They're	They've	This	Those	Through	To	Too
Under	Until	Up	Very	Was	Wasn't	We	We'd	We'll
We're	We've	Were	Weren't	What	What's	When	When's	Where
Where's	Which	While	Who	Who's	Whom	Why	Why's	With
Won't	Would	Wouldn't	You	You'd	You'll	You're	You've	Your
Yours	Yourself	Yourselves						

Table A2. Topic name and the 20 highest weighted words.

Topic name	Top 20 words
Carcharhinus	speci, carcharhinus, bull, suggest, river, import, freshwat, estuari, specif, use, result, rang, blacktip, leauca, wherea, estuarin, although, howev, occur, present
Evidence-based	data, inform, provid, avail, result, data, infrom, provid, avail, result, analys, collect, seal, present, limit, poor, suggest, base, lack, conclus, overal, independ, relat, howev, one
Physiology	activ, tissu, high, concentr, muscl, acid, dogfish, determin, level, relat, blood, like, feed, similar, detect, found, plasma, organ, physiolog, liver
Bioenergetics	chang, bodi, condit, effect, increase, result, climat, response, energi, temperatur, howev, relat, correl, influenc, direct, effect, like, process, scenario, shape
NPOA	manag, develop, marin, nation, plan, implement, resourc, need, action, protect, improv, intern, communiti, impact, framework, exist, object, countri, govern, global

Movement	movemnet, tag, day, pattern, individu, track, time, rang, acoust, migrat, satelit, use, depth, site, move, behaviour, telemetri, water, within, detect
Hammerhead	land, fisheri, hammerhead, speci, sphyrna, lewini, commerci, report, total, valu, mustelus, scallop, manag, million, result, near, highest, pacif, smooth, fish
Reproduction	femal, size, male, matur, reproduct, length, sex, total, mate, year, observ, season, immatur, pup, base, month, individu, ratio, litter, period
Trophic role	predat, ecosystem, prey, trophic, ecolog, funtion, role, diet, top, communiti, import, marin, food, level, isotop, larg, feed, stabl, apex, suggest
Observation	whale, observ, aggreg, sight, year, feed, period, typus, individua, mean, event, first, report, swim, rhincodon, follow, encount, describ, known, total
Depth	speci, water, depth, small, deep, trawl, abund, show, shallow, high, demers, vulner, relat, larg, bottom, identifi, low, mean, assemblag, continent
Life history	estim, year, growth, age, rate, life, size, popul, histori, paramet, model, mortal, length, low, surviv, demograph, best, rang, time, band
Research area	research, biolog, ecolog, societi, review, knowledg, publish, focus, current, import, provid, recent, new, scienc, bristish, understand, futur, will, gap, key
MPA	reef, protect, marin, area, coral, reserv, effect, mpas, network, use, take, high, design, amblyrhncho, resid, ecolog, human
DNA barcoding	speci, water, depth, small, deep, molecular, morpholog, barcod, sampl, previous, within, specifi, use, present, import, phylogenet, four, deveop, genus, first
Ocean	ocean, atlant, region, pacif, wetsern, north, trophic, indian, distirbut, occur, pelag, global, west, high, larg, eastern, indo, east, rang, across
Species diversity	Speci7, ray, chondrichthyan, divers, group, skate, manta, famili, include, batoid, rich, taxa, relay, endem, descib, first, indonesia, examin, despit, taxonom
Stock assessment	fisheri, manag, exploit, stock, assess, sustain, inform, strategi, cathc, target, speci, histori, harvest, include, need, status, depend, potenti, vulner, limit
Fisher knowledge	fish, local, fisher, scale, interview, one, main, small, fishermen, mani, communiti, remain, food, even, base, artisan, high, caught
Region	area, water, region, coast, gulf, southern, mexico, coastal, locat, northern, along, california, florida, brazil, unit, level, throughout, known, caribbean, import
Bycatch	bycatch, release, net, mortal, captur, effect, reduce, fisheri, gear, surviv, closur, post, time, control, measur, increas, rate, improv, reduct, commerci
Genomics	gene, vertebr, sequenc, express, protein, function, genom, evolut, region, human, structur, cell, receptor, domain, cartilagin, famili, mammalian, jaw, evolutionari, amino
Abundance	island, survey, abund, site, time, observ, densiti, detect, system, underwat, per, monitor, remot, video, assess, cat, bait, visual, bay, bruv
Context	distribut, provid, common, use, term, suggest, sourc, open, attribut, speci, origin, access, highm result, fish, howev, indic, reproduct, articl, permit
Habitat-use	model, spatial, habitat, distribut, use, predict, variabl, environment, pattern, tempor, occur, high, area, suitabl, potenti, surfac, across, scale, dynam, temperatur
Dive tourism	tourism, dive, activ, dolphin, impact, oper, industri, econom, behaviour, interact, benefit, tourists, diver, valu, potenti, ecotour, wildlif, provis, site, effect
Population trends	popul, declin, increas, abund, trend, long, change, recent, recoveri, current, sever, decad, sinc, indic, effect, substanti, past, remov, pressur
Taxonomy	record, sea, mediterranean, collect, present, sever, specimen, inform, report, data, first, includ, repres, presenc, speci, histor, consid, import, squatina, current
Perceptions	public, support, human, toward, knowledge, polici, attitud, percept, find, attack, factor, media, educ, issu, report, understand, regard, scientist, focus, respond
Fin Trade	fin, trade, speci, product, market, intern, global, import, cite, illeg, part, meat, high, monito, countri, demand, identifi, dri, world, regul

Behaviour	anim, behaviour, natur, environ, group, interact, mani, social, understand, wild, issue, new, exhibit, need, work, success, field, human, associ, captiv
Juvenile habitat	habitat, area, juvenil, coastal, nursery, adult, use, import, bay, protect, year, lemon, suggest, site, within, young, life, earli, indic, stage
Pelagic fisheries	catch, fisheri, speci, longlin, tuna, hook, pelag, fish, rate, target, blue, bycatch, caught, set, captur, per, effort, thresher, total, discard
Megafauna	marin, sea, turtl, impact, include, seamount, mammal, megafauna, live, effort, larg, green, scale, high, found, ecosystem, affect, risk, mitig, seabird
Data	use, sampl, non, result, tiger, detremin, valu, examin, measur, obtain, compa, analysi, method, need, indic, collect, develop, inform, level, techniqu
Australia	white, australia, south, australian, carcharia, along, africa, nurs, number, grey, coast, taurus, east, southern, indic, occur, carcharodon, like, fin
Population genetics	popul, genet, structur, divers, connect, microsatelite, loci, marker, mitochondri, samp, analyss, differenti, gene, evid, haplotyp, dispers, control, investig, reveal, region
Conservation status	speci, threaten, extinct, list, assess, endang, risk, vulner, red, rang, iucn, status, global, union, particular, concern, mani, intern, critiic, natur
Identification	indivu, use, identifi, sawfish, mark, identif, pattern, natur, photograph, popul, match, techniqu, pristi, imag, recaptur, spot, requir, critic, captur, photo
Method	approach, use, base, method, model, analysi, generat, assess, case, applic, appli, tool, cost, perform, evalu, select, simul, design, uncertainti, requir

A.2 Appendix for Chapter 2

Table A3. Shark species most commonly reported by fishers during interviews, with an indication of the level of catch by fishery (Ali and Sinan, 2015; MRC, 2009).

English name	Scientific name	Fishery: Reef	Fishery: Pelagic
Silvertip	*Carcharhinus albimarginatus*	**	*
Grey reef	*Carcharhinus amblyrhynchos*	**	
Silky	*Carcharhinus falciformis*		***
Oceanic whitetip	*Carcharhinus longimanus*		**
Blacktip reef	*Carcharhinus melanopterus*	**	
Tiger	*Galeocerdo cuvier*	*	*
Tawny nurse	*Nebrius ferrugineus*	*	
Scalloped hammerhead	*Sphyrna leweni*	*	*
Whitetip reef	*Triaenodon obesus*	**	

*** major target species, ** regularly taken, *occasionally taken

Table A4. General costs and staff time budgets (hours) associated with Baited Remote Underwater Videos (BRUVs) and participatory mapping (LEK) interviews.

Baited Remote Underwater Videos		Participatory mapping (LEK)	
General logistics ($US)		***General logistics ($US)***	
Vessel costs (per day)	350[a]	Travel to local Islands (per day)	20[a]
BRUV system costs (total)	4,042	Equipment costs (total)	414
Pre-field (staff hours)		***Pre-field (staff hours)***	
Equipment calibration and processing	8	Questionnaire development (mapping component only)	20
Bait processing	8	Pilot study	5
In-field (staff hours)		***In-field (staff hours)***	
Data collection (total)	224[b]	Data collection (total)	192[b]
Video download (per video)	0.25	Interview storage (per interview)	0.1
Post-field (staff hours)		***Post-field (staff hours)***	
Video processing (per video)	2	Map digitisation and processing (per map)	1

[a] Large vessel carrying 2 crew and 2 staff; travel for 2 staff.
[b] BRUVs = 2 staff x 10 days x 8 hours; Interviews = 2 staff x 12 days x 8 hours.

Time and cost budgets were maintained for all activities associated with ecological surveys (BRUVs) and interviews (LEK). Time was expressed as the number of hours per person devoted to each activity (Galaiduk *et al.*, 2017). Direct costs associated with general logistics (e.g. equipment) were also calculated for each survey method. Time not directly associated with survey tasks (e.g. travel to and from survey sites) was excluded as it was similar for both methods. Budgets were divided into; pre-field time (e.g. equipment set-up), in-field time (e.g. data collection and download), and post-field time (e.g. analysis).

A.3 Appendix for Chapter 3

Table A5. Results of tests for overdispersion on Poisson Generalised Linear Models (GLMs) for Baited Remote Unwater Videos (BRUVs). Dispersion ratios larger than one indicate overdispersion. A p-value < 0.05 indicates over dispersion.

Model	p-value	Sample estimates: Dispersion
All ~ Year	0.55	0.98
BT ~ Year	1.00	0.81
WT ~ Year	0.99	0.85
NS ~ Year	0.23	1.22

Table A6. Results of tests for zero-inflation tests conducted on Poisson Generalised Linear Models (GLMs) for Baited Remote Underwater Videos (BRUVs).

Model	Observed zeros	Predicted zeros	Ratio
All ~ Year	205	211	1.03
BT ~ Year	304	314	1.03
WT ~ Year	346	351	1.01
NS ~ Year	338	336	0.99

Table A7. Results of tests for overdispersion on Poisson Generalised Linear Models (GLMs) for citizen science data. Dispersion ratios larger than one indicate overdispersion. A p-value < 0.05 indicates over dispersion.

Model	p-value	Sample estimates: Dispersion
Lankan Manta Point	0.002	3.44
Hulhangu Kandu	0.001	1.61
Okkobe Thila	0.007	1.37

Table A8. Results of tests for zero-inflation tests conducted on Negative Binomial Generalised Linear Models (GLMs) for citizen science data.

Model	Observed zeros	Predicted zeros	Ratio
Lankan Manta Point	21	22	1.04
Hulhangu Kandu	26	27	1.04
Okkobe Thila	89	89	1.00

A.4 Appendix for Chapter 4

Table A9. Fish were primarily recorded to genus but where feeding preference (trophic groupings) varied they were recorded at the species level.

Functional Group	**Feeding habits**	**Group/ family**	**English name or species**
Piscivores	Top-level predators, exert top-down control on lower trophic levels of fish, are vulnerable to overfishing and therefore are good indicators of the level of fishing on a reef.	*Serranidae* *Lutjanidae* *Carangidae*	All groupers *Aprion viriscens, Lutjanus bohar* All jack and trevally
Omnivores (omnivorous carnivores)	Second-level predators with highly mixed diets including small fish, invertebrates, and dead animals. Their abundance is a good indicator of fishing pressure.	*Haemulidae* *Lethrinidae* *Lutjanidae*	All sweetlip All emperor All snapper except *Aprion viriscens* & *Lutjanus bohar*
Corallivores	Obligate and facultative corallivores are a secondary indicator of coral community health.	*Chaetodontidae*	7 butterflyfish: *C. meyeri, C. melannotus,* *C. ornatissimus, C. trifascialis,* *C. trifasciatus, C. lineolatus,* *C. triangulum*
Invertivores	Feed on small invertebrates in the benthos and coral competitors such as soft coral and sponges.	*Balistidae* *Chaetodontidae* *Zanclidae*	Benthic triggerfish (e.g. Suffamen spp.) Non corallivore butterflyfish: all other *chaeotdontids* except *H. zoster* and *H. diphreutes*. Moorish Idol Filefish Goatfish
Planktivores	Resident of reefs but feed in the water column. Their presence may be related to water column conditions, suitable habitat for shelter or reef channels.	*Chaetodontidae* *Balistidae* *Acanthuridae* *Caesionidae* *Pomacentridae* *Holocentridae*	*H. zoster, Heniochus* spp. eg. *Melichthys spp., O. niger* *A. thompsoni, A. mata, N. vlamingii, N. brevirostris, N. hexacanthus* All Fusiliers *Chromis* spp., All soldier and squirrelfish
Herbivores/ detritivores	Feed onendolithic and epilithic algae, substratum, and macroalgae. Exert control on coral-algal dynamics, implicated in determining phase shifts from coral to algal dominance.		Surgeonfish Parrotfish Damsel fish

A.5 Appendix for Chapter 5

Table A10. Survey Questionnaire

Survey Questionnaire

Shark census data: Fisher Questionnaire

Date: Location: Interviewer: Ref:

Section 1: Fisheries information

1. How long have you been a fisher (years)?
2. Which atolls do you fish?

3. Do you primarily fish at…..Reef/near shore ☐ Oceanic/off shore ☐
4. What is your target species (list)?

5. Do you fish? Full-time ☐ part-time ☐ seasonally ☐ other:

6. What determines your decisions about your fishing activity? **Why, when, where** and **what** you fish? How important are these factors (1=very important, 2=important, 3=unimportant, 4=very unimportant) in your decision-making about your type of fishing activity?

Factors in decision-making about fishing activity	**Reasons listed**	**Importance** (1-4)
Why do you fish? (e.g. income, food, both or other reason?)		
When (e.g. everyday all seasons, depends on crew availability or ability to cover costs of fishing?)		
Where? (e.g. what determines where you fish?)		
What (e.g. why do you target certain sp. (value, abundance?))		

7. Compared with your catch 10 years ago*:*
   a. Would you say that the number of fish that you catch has?

Increased ☐ Decreased ☐ No change ☐ Unsure ☐

   b. Would you say that fish abundances in the area are?

Increased ☐ Decreased ☐ No change ☐ Unsure ☐

8. If you have noticed a change in catch/ fish abundance why do you think this is?

9. How much fish do you catch on a i) good day, ii) bad day iii) normal day

	Units	i) Good day	ii) Bad day	iii) Normal day
Catch (e.g. kg/ no. of fish)				

10. On average how much is the catch worth (ruffia/ dollar)?

11. Have you ever caught sharks by accident (bycatch)? Yes ☐ No ☐
12. Which species (rank in order of most commonly caught)?

13. Have you ever fished specifically for sharks? Yes ☐ No ☐

14. If Yes, how long were you a shark fishermen?
    0-5 years ☐ 5-10 years ☐ 10-20 years ☐ 20+ years ☐

15. Which species of shark did you target?

Section 2: Quantifying impact on fishers

16. Have you noticed a change in shark abundance compared with? (increase/ decrease/ no)
    a. 10 Years ago:
    b. When you started fishing:
17. What do you think is causing the change in the shark populations?

18. Please identify when saw you the highest number of sharks?
    1960's☐ 1970's☐ 1980's☐ 1990's☐ 2000☐ 2010 – now☐

19. In the last year (2018) have sharks impacted your work (fishing)?

How?

20. How does this compare to with
    a. 10 Years ago:
    b. When you started fishing:

21. What influence do you expect sharks to have in the future (in 10 years)?

22. Overall, how much of a threat do you think sharks are to the local fishery?
    A lot ☐ A little bit ☐ Not at all☐ Don't know/unsure

23. On average, what percentage of your daily catch is lost to sharks?
24. On average, what percentage of your gear is damaged by sharks daily?

25. On average what is the estimated cost (ruffia) of lost **catch** caused by sharks daily?

26. On average what is the estimated cost (ruffia) of damaged **gear** caused by sharks daily? (specify which gear)

27. What do you do when you have a problem with a shark?[get them to state the problem for accurate context]

28. Do particular species of shark cause you problems? Please list in order of highest disturbance [match shark with the problem].

29. Can you list any environmental factors associated with shark abundance/ encounters? (i.e. depth, season).

Section 3: Perceptions and compliance

30. On a scale of 1-4 (1 being very important – 4 not important) how important are sharks for?
    a. The marine environment
    b. Tourism
    c. Local communities

31. Do you think that sharks need to be protected?

32. What is the purpose of the shark fishing ban in Maldives?

33. Please indicate the degree to which you support the following shark-conservation policies:

	Strongly support	Support	Neutral	Somewhat in opposition	Strong Opposition
Time restricted area closures					
Gear restrictions					
Year-round closures in certain areas (hotspots, nurseries, dive sites)					
Shark finning bans					
Nationwide bans (shark sanctuaries)					
Fisheries quotas					
No-take marine protected areas					
Strict bans on threatened species					

34. Is the fishing ban effective in stopping shark fishing? Yes ☐ No ☐ Unsure ☐
35. If no, why not?

36. Does illegal shark fishing still take place?
37. If yes by whom?

38. Why do fishers still fish for sharks illegally?

39. Can you suggest ways to improve how well rules are followed?

40. Please indicate whether you agree or disagree with the following statements:

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree

Voice: The opinions of fishers were taken into account in sanctuary planning and management.					
Livelihood: Livelihood needs were recognised and acknowledged in sanctuary implementation and management.					
Transparency: Research and scientific information about the marine environment and status of fisheries is available.					
Transparency: Information about how and why conservation decisions are made are readily available.					
Inclusiveness: Fishers are able to participate in decision-making and management activities?					

41. Has the shark fishing ban effected your livelihood? If yes, how?

*If previously a shark fisher:

42. What was your average monthly income before the shark fishing ban?
43. What is it now?
44. Was/ is assistance and training available to access alternative livelihood opportunities?

Section 4: Contemporary shark sightings – NOW

Please look at this map of Maldives. Please draw to show……

45. Please draw on the map areas where you frequently fish (mark with CF)

46. A) **Hotspots: Areas where you frequently encounter sharks**

B) What is the highest number of sharks you see in this area? (Write number next to each circle).

C) What species do you see in this area? (Write 2-letter code next to each circle).

Section 5: Demographics

47. Age
48. At what age did you leave school?
49. Which atoll do you live in?
50. Is fishing your only source of income?
51. If no, what are your other occupations?
52. What proportion of your **total** household income is from fishing?

A.6 Appendix for Chapter 6

Table A11. Assessment of model fit using Hosmer–Lemeshow tests. p > 0.05 indicates that models are a good fit.

Model	X-squared	df	p-value
Pelagic-PL	15.6	11	0.155
Pelagic-HL	3.9	7	0.721
Reef-HL	7.9	11	0.721

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