Movement patterns and bycatch of pelagic sharks in Australian waters

by

Matthew Heard

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FRONTISPIECE

I dedicate this work to my parents, Anne and Ian, this would not have been possible without your continual love and support. Who would have thought a dead penguin hidden under my bed would lead to this!

Love, Matt

THESIS DECLARATION

I certify that this thesis does not incorporate, without acknowledgment, any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

Matthew Heard

Submitted for examination

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LIST OF ACRONYMS

AFMA Australian Fisheries Management Authority
AIC Akaike Information Criterion
BIC Bayesian Information Criterion
BPM Best Practice Methods
CA-DGN Californian Drift Gillnet Fishery
CDR Catch Disposal Record
CITES Convention on the International Trade in Endangered Species of Wild Fauna and Flora
CMS Convention on the Conservation of Migratory Species of Wild Animals
CPUE Catch Per Unit Effort
DIVA Data Interpolating Variational Analysis
DoE Australian Department of Environment
dbRDA Distance based Redundancy Analysis
DistLM Distance based Linear Model
DVM Diel Vertical Migration
EBFM Ecosystem Based Fisheries Management
EEZ Exclusive Economic Zone
EPBC Act *Environment Protection and Biodiversity Conservation Act 1999*
ETBF Eastern Tuna and Billfish Fishery
FAO Food and Agriculture Organisation of the United Nations
FL Fork Length
HPF Hooks per Float
IPOA-Sharks International Plan of Action for the Conservation and Management of Sharks
ISMP Integrated Scientific Monitoring Program
IUCN International Union for Conservation of Nature
MPA Marine Protected Area
MOU Memorandum of Understanding
PERMANOVA Permutational Multivariate Analysis Of Variance
PSAT Pop-up Satellite Archival Transmitter
REM Remote Electronic Monitoring `
RFMO Regional Fisheries Management Authority
SBT Southern Bluefin Tuna
SESSF Southern and Eastern Shark and Scalefish Fishery
SMW Split Moving Window
SST Sea Surface Temperature
TACC Total Allowable Commercial Catch
TL Total Length
WTBF Western Tuna and Billfish Fishery

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ABSTRACT

With the increase in global fishing effort and expansion of fishing fleets into the open ocean, large predatory fishes are under increasing threat of extinction. Understanding the impacts of open ocean fisheries on top predators, such as sharks, is critical to the management of these fisheries, particularly for species caught as bycatch. In the past decade, several species of pelagic sharks have been recognised as vulnerable migratory species and included on Appendix II of the List of Migratory Species on the Convention on the Conservation of Migratory Species of Wild Animals (CMS). As a signatory to the CMS, Australia is committed to progressing actions that will improve the management and conservation of these species.

The major objectives of this study were to investigate the levels of commercial and recreational catches of migratory pelagic shark species and to determine the factors that influence these catches in Australian waters. I used a permutational analysis of pop-up satellite telemetry data to define the vertical movement patterns of five blue sharks (*Prionace glauca*) and one common thresher shark (*Alopias vulpinus*). I conducted a survey of recreational game fishers to determine the level of catch of shortfin mako (*Isurus oxyrinchus*) and *A. vulpinus* within this fishery and to investigate fishers' behaviours and attitudes towards sharks. Generalised and distance based linear modelling techniques were used to investigate commercial catches of *A. vulpinus* in the Southern and Eastern Scalefish and Shark Fishery and *P. glauca*, *I. oxyrinchus, Lamna nasus* and *Alopias* spp. in the Eastern and Western Tuna and Billfish Fisheries.

The minimum horizontal displacement of satellite tagged sharks was variable, with the largest displacement exceeding 5 000 km and pop-up locations indicating the importance of highly

productive upwelling areas. Movement patterns included surface-oriented, reverse diel vertical, and normal diel vertical movements, with the latter being the most common pattern identified for both *P. glauca* and *A. vulpinus*. Catch and release of pelagic sharks was practised by over half of the recreational anglers that were surveyed at game fishing tournaments. The majority of anglers asserted that they attempt to release sharks in good condition, but there was a relatively low use of circle hooks, that have been shown to increase post-release survival. Season and depth were the most important explanatory variables for catch rates of *A. vulpinus* in gillnet fisheries operating in South-eastern Australia. Catch rates were higher in summer and there was an inverse relationship between catch rate and depth. In pelagic longline fisheries, sea surface temperature was the most important environmental variable that influenced catches of *P. glauca*, *I. oxyrinchus,* and *L. nasus,* while depth was the most important variable for *Alopias* spp.

It is important that measures implemented by managers are based on evidence of the level of threat that fisheries pose to these highly migratory pelagic shark species. For recreational anglers, an increased emphasis on tagging competitions at tournaments and promotion of catch and release, and associated best practices should improve the sustainability of tournament angling. The importance of diel movements, depth preference, season, and temperature are highlighted by the satellite telemetry and analysis of gillnet and longline data. A better understanding of these parameters provides critical information for assessing the encounterability and susceptibility of pelagic sharks to different gear types within Australian waters.

1

GENERAL INTRODUCTION

Exponential human growth, industrialisation, and technological advances have put pressure on the earth's natural resources and marine ecosystems (Ceballos *et al.*, 2015; Halpern *et al.*, 2008). In the case of marine fishes, industrialised fishing is considered the greatest threat to fish populations (Hutchings, 2000). Global fishing effort has increased since the 1970s and while the rate has slowed since 2010, many fish stocks remain overexploited (Anticamara *et al.*, 2011; Bell *et al.*, 2017). The increased capacity and range of commercial fishing fleets has contributed to a recent estimate that 31.4% of global commercial fish stocks are overfished (FAO, 2016). There is increasing concern over the sustainability of current levels of fishing and the potential impacts that this may have on targeted fish stocks, bycatch, and marine ecosystems (Pauly *et al.*, 2002; Watson *et al.*, 2013).

Population declines of large marine predators have been documented in many fisheries around the globe (Baum *et al.*, 2003; Ferretti *et al.*, 2010; Ward & Myers, 2005b). While the magnitude of these declines has been the subject of some debate (e.g. Burgess *et al.*, 2005a; Burgess *et al.*, 2005b; Polacheck, 2006), there is agreement that there have been declines of large marine predators in several regions and that the effects of removing such predators should not be ignored (Baum & Worm, 2009; Donohue *et al.*, 2017; Ferretti *et al.*, 2010). Marine predators such as sharks have been shown to directly influence the community structure of ecosystems through the consumption of prey and indirectly through predator and competitor induced behavioural changes (Heithaus *et al.*, 2008). These direct and indirect effects may impact the abundance and ecological function of species through to the lowest levels in the food web (Ruppert *et al.*, 2013). The wide ranging nature of many shark species also results in sharks frequenting multiple ecosystems, which plays an important role in coupling and stabilising disparate food webs (Rooney *et al.*, 2008). Ultimately, perturbation of the predator-prey interactions between large predators and lower trophic species may lead to important changes to marine ecosystem function, productivity, and socioeconomic value (Halpern *et al.*, 2008; Holmlund & Hammer, 1999).

VULNERABILITY OF PELAGIC SHARKS TO FISHERIES

Pelagic sharks have been identified as a group of particular conservation concern because they are susceptible to high levels of mortality as bycatch in high seas fisheries (Dulvy *et al.*, 2008; Gallagher *et al.*, 2014). The rise of industrialised fishing has increased the range and fundamentally changed the spatial dynamics of commercial fishing in the open ocean (Kroodsma *et al.*, 2018; Watson *et al.*, 2013). Overexploitation of large pelagic shark species is exacerbated by an increasing demand for their fins due to the rise of the middle class in China (Clarke *et al.*, 2006). While exposure to threatening processes, such as fishing mortality, is the ultimate cause of extinction, the biology of a species will largely determine how well it will be able to withstand the threats to which it is exposed (Cardillo *et al.*, 2004). Pelagic shark species, with few exceptions, have slow life history strategies leading to a low rate of population increase, which contribute to their vulnerability to exploitation and slow recovery when overfished (Dulvy *et al.*, 2008; Smith *et al.*, 1998; Yokoi *et al.*, 2017).

Despite not being the target species of most open ocean fisheries, the slow life histories of pelagic sharks leave them more sensitive to exploitation than the targeted teleost species with which they are caught (Schindler *et al.*, 2002). As non-target species, catches of pelagic sharks are poorly or not reported in many of the fisheries in which they are caught (Dulvy *et al.*, 2008; Dulvy *et al.*, 2004; Macbeth *et al.*, 2018; Maunder & Punt, 2004). Efforts to assess the vulnerability of pelagic sharks are often hindered by the paucity of data as well as uncertainty around release rates and the fate of released sharks in both commercial and recreational fisheries (Dapp *et al.*, 2016a; Ellis *et al.*, 2017; Huang & Liu, 2010; Maunder & Punt, 2004).

Recent analysis has also shown that extinction risk is correlated with the number of jurisdictions that a species range may cover (Dulvy *et al.*, 2017). As many pelagic sharks undertake large-scale migrations across the exclusive economic zones of multiple countries, these sharks are considered to be at increased risk of extinction because they can be subjected to a number of different and often poorly aligned or conflicting fisheries management regimes (Dulvy *et al.*, 2017; Techera & Klein, 2011). While cross-jurisdiction management and international cooperation is critical for the effective protection of these species, it is also important that international management regimes are implemented through regulation at a national and local level as weaknesses in the laws of one range state can undermine the effort of other states (Chin *et al.*, 2017; Techera & Klein, 2011).

GLOBAL PROTECTION AND MANAGEMENT OF PELAGIC SHARKS

International protection and conservation of sharks is primarily facilitated through mechanisms that are implemented by the United Nations (UN). Recognition of a species vulnerability is initially identified by organisations such as the International Union for the Conservation of Nature (IUCN) and through listing on UN treaties such as the Convention on the International Trade in Endangered Species and Wild Fauna and Flora (CITES) and the Convention on the Conservation of Migratory Species of Wild Animals (CMS). The International Plan of Action for the Conservation and Management of Sharks (IPOA-sharks) is another mechanism, developed by the Food and Agriculture Organization of the UN (FAO), to improve the conservation and management of sharks (FAO, 1999). The IPOA-sharks provides a comprehensive set of guidelines for the long-term sustainable use of chondrichthyan species (Davis & Worm, 2013; Techera & Klein, 2017). At a regional level, Regional Fishery Management Authorities (RFMOs) are responsible for managing certain fisheries that operate outside of national exclusive economic zones and across the jurisdictions of multiple nations (Meltzer, 2005). RFMOs provide an established institutional framework for implementing management strategies for migratory shark species (Brown, 2016; Shuter *et al.*, 2011). Member states of the CMS, CITES, and the various RFMOs and signatories to the IPOA-Sharks are committed to progress arrangements that conserve vulnerable shark species at a local, national, and regional level (Techera & Klein, 2017).

Australia is seen as a global leader in the sustainable fisheries management (Costello *et al.*, 2012; Scandol *et al.*, 2005). As a member state of the CMS, CITES, and the three tuna and billfish RFMOs that straddle Australian waters, Australia is an active participant in fisheries management on the global stage (Polacheck, 2012). Australia was one of the first nations to develop a National Plan of Action for the Conservation and Management of Sharks (Shark-plan 1) in 2004 and has since reviewed and updated this plan, releasing Shark-plan 2 in 2012 (DAWR, 2012). While Australia is not considered a major shark fishing state, a large number of sharks are caught as both target species and bycatch in Australian fisheries and the potential for the overfishing of shark stocks has been recognised since the 1950s (Davis & Worm, 2013; Roughley, 1951; Stevens & Wayte, 1999). In Australia, fisheries management is shared by state and commonwealth agencies and Shark-plan 2 highlighted the importance of a national approach for the management of migratory sharks. At a regional and international level, Shark-plan 2 stressed the importance of Australia's engagement in international treaty arrangements and the adoption of best practice methods by RFMOs as well as encouraging the effective management of harvest and bycatch of pelagic sharks species on the high seas (DAWR, 2012).

Australia's marine jurisdiction is the third largest globally and stretches over 16 million km^2 (*Australia's Oceans Policy*, 1998). Fisheries within this area are managed by eight jurisdictions including six states (Queensland, New South Wales, Victoria, South Australia, Tasmania and Western Australia), one territory (Northern Territory) and the Commonwealth through the Australian Fisheries Management Authority (AFMA) (*Fisheries Management Act 1991*). State and territories, in general, govern fisheries from the coast to a distance of three nautical miles while AFMA is responsible for fisheries between three and 200 nautical miles from the coast and also governs Australian flagged vessels on the high seas (*Fisheries Management Act 1991*). Pelagic sharks, as inhabitants of the oceanic zone, are far more likely to be caught in fisheries managed by AFMA, with the majority of catches coming from three fisheries: Eastern Tuna and Billfish Fishery (ETBF); Western Tuna and Billfish Fishery (WTBF); and Southern and Eastern Scalefish and Shark Fishery (SESSF) (Stevens & Wayte, 1999; Walker & Gason, 2007). Boundaries of these fisheries are defined in Figure 1.1.

Dulvy *et al.* (2008) identified 16 species of pelagic sharks that range widely in the oceans of the world of which 14 occur in Australian waters (Last & Stevens, 2009). Five of these species are common in the temperate waters off southern Australia: white shark (*Carcharodon carcharias*); blue shark (*Prionace glauca*); shortfin mako (*Isurus oxyrinchus*); common thresher shark (*Alopias vulpinus*) and; porbeagle (*Lamna nasus*) (Last & Stevens, 2009; Walker, 2007). *Carcharadon carcharias* is listed on Appendix I of the CMS and Appendix II of CITES, and is the only of these species that is fully protected in Australia under Commonwealth and state legislation (DSEWPaC, 2013). Conservation concerns for the remaining four species (*A. vulpinus*, *I. oxyrinchus*, *L. nasus*, and *P. glauca*) have led to listings under Appendix II of the CMS (Bonfil, 1994; CMS CMS, 2017). Australia currently has no comprehensive national plans of action for any of these species and, to date, an inconsistent approach has been taken towards their conservation by Australian authorities in response to their listings on the CMS.

The *Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act)* is the central piece of environmental legislation under which the Australian Government assesses the environmental performance of fisheries and commits to the protection of CMS listed migratory species (DoEE, 1999). Inclusion on Appendix I or II of the CMS triggers an assessment for listing on the migratory species list of the *EPBC Act.* In Commonwealth areas, it is an offence to injure, take, trade or keep species that are listed on the migratory species list of the *EPBC Act*. In 2010, *I. oxyrinchus* and *L. nasus* were both included on the migratory species list of the *EPBC Act*. However, this listing was amended to allow recreational anglers to continue to target these species following lobbying from the recreational fishing sector (DEWHA, 2010). A different approach was taken in response to the more recent listing of *A. vulpinus* on Appendix II of the CMS where the Australian government moved to take out a reservation to the listing of all three *Alopias* spp. signalling a belief that no further conservation measures were required to protect *Alopias* spp. within Australian waters (CMS Secretariat, 2015). The policy uncertainty around the requirements for the protection and management of these species contributes to the complexity of the multi-jurisdictional management of these highly migratory species (Flood *et al.*, 2016).

Current research and knowledge gaps for pelagic sharks in Australian waters

Since the start of the 21st century, satellite telemetry has been widely applied to study the movements and behaviours of pelagic sharks (Hammerschlag *et al.*, 2011). In comparison to other regions, very few studies have utilised satellite telemetry for pelagic shark species within Australian waters. Satellite telemetry studies have been conducted for *I. oxyrinchus* (Rogers *et al.*, 2015), *P. glacuca*, and *A. superciliosus* (Rogers *et al.*, 2016) within the Great Australian Bight. Stevens *et al.* (2010) investigated the vertical movement patterns and behaviour of *P. glauca, I. oxyrinchus*, and *Alopias* spp. off the eastern coast of Australia. Despite these studies, there remains a lack of knowledge on the vertical movement patterns of pelagic sharks in this region. Conventional tagging of sharks provides valuable insights into their life histories, movements and population structure (Kohler & Turner, 2001). There is a long history of research on the species composition and movement of sharks caught by recreational anglers in Australia (Pepperell, 1992). Since 1973 the NSW Department of Primary Industries has operated the largest recreational game fish tagging program globally (Pepperell, 2010). The majority of the tagging effort and recaptures for this program occurs on the East Coast of Australia with relatively little information available for the movements of pelagic sharks in the southeastern Indian Ocean.

Understanding the movements of pelagic sharks is critical to assess the impacts of fisheries on these species and is important for their long-term sustainable management (Barker & Schluessel, 2005; Bigelow & Maunder, 2007; Queiroz *et al.*, 2012). Movement patterns can affect the selectivity, encounterability of sharks to different gear types as well as indicate critical habitats that may overlap with fisheries (Byrne *et al.*, 2017; Queiroz *et al.*, 2016; Vaudo *et al.*, 2016). The encounterability of pelagic sharks can be largely dependent on daily operational patterns and the depth distribution of the gear that is being used (Ward & Myers, 2005a). Understanding the depth distribution and vertical movement patterns of different species provides further clarity on their susceptibility to different gear types and changes in fishing practices (Bigelow & Maunder, 2007; Cartamil *et al.*, 2010a; Cortes *et al.*, 2010). For example, one of the most common vertical movement patterns recorded for marine species is diel vertical movement (DVM), where a shallow depth range is utilised during the night followed by a highly variable or deep distribution during the day (Brierley, 2014). Shark species that follow a DVM pattern are far more susceptible to capture by shallow set gear during the night and deeper set gear during the day and, on this basis, management measures can be tailored to reduce the level of unwanted shark bycatch (Beverly *et* *al.*, 2009). Movement patterns and the environmental drivers of the depth distribution of *A. vulpinus* and *P. glauca* is investigated further in Chapter 2.

Prohibitions and restrictions on targeting and retaining live pelagic sharks by commercial fisheries (e.g. *I. oxyrinchus* in the ETBF (AFMA, 2018a)) combined with amendments to the *EPBC Act*, outlined above, place recreational anglers as significant stakeholders in the management of pelagic shark species in Australian waters. Historical research on the composition of catches by game fishing clubs shows that over half of the sharks caught by recreational fishers in New South Wales were pelagic species (Pepperell, 1992). In the most recent National Recreational and Indigenous Fishing Survey, recreational anglers reported catching 1.2 million sharks and rays annually in Australia, however, shark catches were not reported to a species level (Henry & Lyle, 2003). Sharks and rays had the highest release rate (80%) of all species or species group although, without species-specific data, uncertainty remains around the species composition and release rates of pelagic shark species at a national scale (Henry & Lyle, 2003). Recreational and game fisheries promote catch and release fishing for pelagic shark species and this practice is becoming more widely accepted in many countries, including in Australia (Gallagher *et al.*, 2017; Horodysky *et al.*, 2016b). While high rates of catch and release are reported for sharks in Australian recreational fisheries, very little is known about the fate of sharks that are released within these fisheries (French *et al.*, 2015; Henry & Lyle, 2003). Post-release survival of recreationally caught pelagic sharks has been investigated for species of interest to this study including, *I. oxyrinchus* (French *et al.*, 2015) and *A. vulpinus* (Sepulveda *et al.*, 2015). These studies have highlighted the importance of the use of best practice methods (BPM), such as reducing fight times and using circle hooks, to increase post-release survival. While BPM for catch and release have been developed for some pelagic shark species including *I. oxyrinchus* (Rogers & Bailleul, 2015) and *A. vulpinus* (VRFish, 2017), there remains a high degree of uncertainty around the acceptance of BPM within the recreational fishing community (Arlinghaus *et al.*, 2012a). This uncertainty extends to the level of use of BPM and the motivation for the use of BPM by recreational game fishers. This issue is investigated through a survey on the practices and attitudes of tournament anglers in Chapter 3.

The majority of the commercial fish stocks within Australian waters have been subject to stock assessments (Flood *et al.*, 2012). In southern Australia, stocks of the two largest shark fisheries have been the focus of regular and extensive stock assessments since the 1950s (Olsen, 1953; Punt *et al.*, 2000; Punt & Walker, 1998), with *Mustelus antarcticus* recently assessed as sustainable and *Galeorhinus galeus* as overfished (Flood *et al.*, 2012). In addition to these stock assessments, risk assessments have been conducted for some bycatch species (e.g. *Callorhinchus milli* (Braccini *et al.*, 2011) and *Squalus megalops* (Braccini *et al.*, 2006)). There has also been analysis of the historical longline catch data from the Japanese longline fleet which operated within Australian waters until the late 1990s (Campbell, 2012; Stevens & Wayte, 1999). To date, the bycatch of pelagic shark bycatch within the Australian commercial domestic longline and gillnet fleets, has been the subject of limited scientific research.

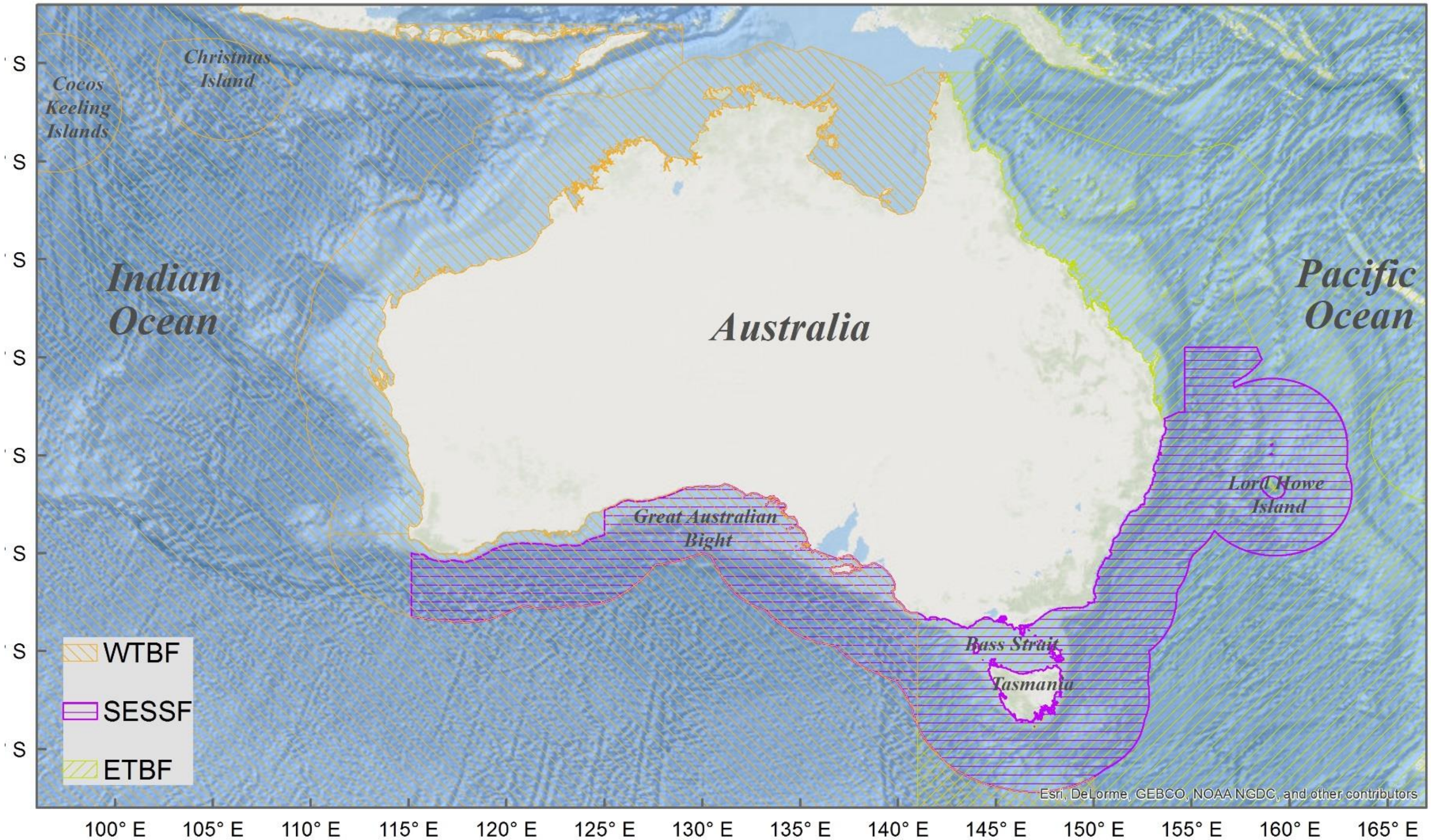

Fig. 1.1. Fisheries boundaries for: Western Tuna and Billfish Fishery (WTBF); Southern and Eastern Scalefish and Shark Fishery (SESSF) and; Eastern Tuna and Billfish Fishery (ETBF). Fishery boundary layers accessed from AFMA (2018b)

Thesis aims

Further information about the potential threats to migratory shark species within Australian waters are required to achieve the aims of Shark-plan 2 and meet Australia's obligations as a signatory to the CMS and CITES. To date, very few studies have been conducted on the susceptibility of *A. vulpinus*, *I. oxyrinchus*, *P. glauca*, and *L. nasus* to commercial and recreational fisheries in Australia. The overall objective of this thesis is to investigate the interactions between vulnerable pelagic sharks and fisheries in Australia using a combination of satellite telemetry and analysis of catch data from commercial and recreational fisheries that interact with these species. The aim was then to discuss practical solutions to improve the fisheries management of these species. To achieve this overall objective, I aim to:

1) Explore the behaviours and attitudes of recreational tournament anglers in relation to pelagic sharks and investigate the level of catch of pelagic sharks by commercial and recreational fisheries within Australian waters; and

2) Identify factors that influence catch susceptibility and encounterability of pelagic sharks within Australian fisheries.

To fulfil these aims, I have compiled four thesis chapters (excluding this general introduction [1] and a general discussion chapter [6]), each with specific goals that link to an aim. These can be visualised in Figure 1.

Thesis structure

Chapter 1 is a brief introduction providing background information on the major thesis themes and outlines the overall thesis objective and structure. The general introduction provides an overview of broader, contextual knowledge and background information that is directly relevant to the data chapters 2 to 5.

Chapter 2 describes depth distributions and diel movement patterns of five blue sharks (*Prionace glauca*) and one common thresher shark (*Alopias vulpinus*) in the southeastern Indian Ocean. Chapter 2 was published in *Fisheries Oceanography* (Appendix A).

In Chapter 3, I investigate the behaviours and attitudes of recreational tournament anglers towards to pelagic sharks in southeastern Australia. Acceptance of catch and release and the use of best practice methods were compared to practices used by game fishers surveyed across New South Wales, Victoria, and South Australia. Chapter 3 has been published in *Marine Policy* (Appendix A).

Chapter 4 uses catch and effort data of *A. vulpinus* from the gillnet sector of the Southern and Eastern Scalefish and Shark Fishery to investigate trends in catch rate from 2000 to 2015.

Chapter 5 investigates the influence of environmental and operational variables on the bycatch of *P. glauca*, *Isurus oxyrinchus*, *Lamna nasus* and *Alopias* spp. in Australian waters by the Western Tuna and Billfish Fishery and the Eastern Tuna and Billfish Fishery between 2000 and 2007.

Chapter 6 synthesises the results from Chapters 2–5 and discusses the implications of my findings. This chapter highlights the research gaps that have been addressed by my research and proposes future research that may further address national priorities for pelagic sharks

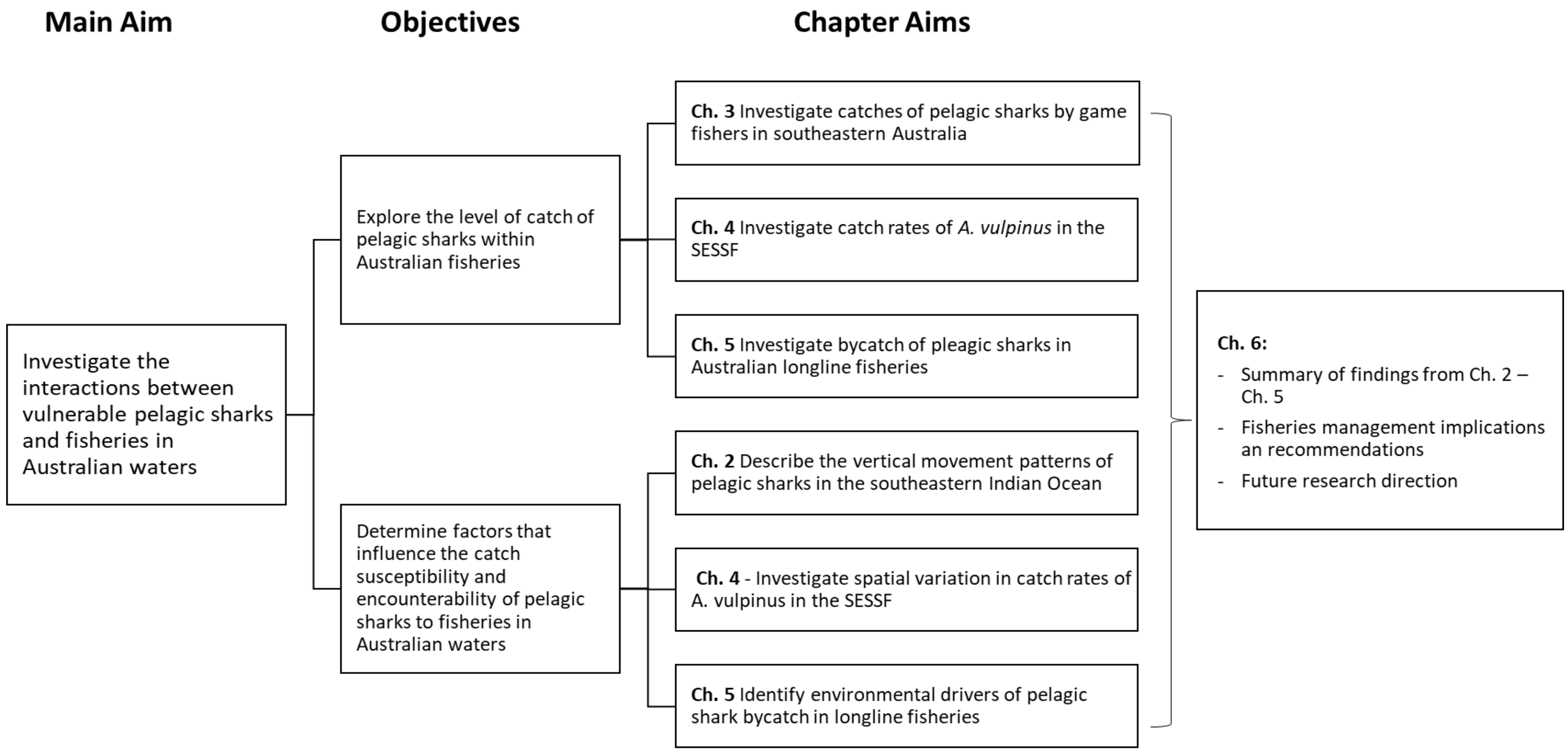

Fig. 1.2. Thesis structure with general objectives and specific chapter aims.

2

PLASTICITY IN THE DIEL VERTICAL MOVEMENT OF TWO PELAGIC PREDATORS (*PRIONACE GLAUCA* AND *ALOPIAS VULPINUS*) IN THE SOUTHEASTERN INDIAN OCEAN

This chapter is published as:

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See Appendix 1.

M.H, P.R and C.H. conceived the ideas, CH and MH obtained funding, M.H. and P.R deployed the satellite tags and M.H. and N.H. analysed the data. M.H. led the writing of the manuscript and all authors contributed to the drafts and gave final approval for publication.

ABSTRACT

Management and conservation of marine predator species relies on a fundamental knowledge of their movements and behaviours. Pop-up satellite archival tags were used to investigate the vertical movement patterns of five blue sharks (*Prionace glauca*) and one common thresher shark (*Alopias vulpinus*) within the southeastern Indian Ocean. Sections of similar depth distribution, identified using a split moving window analysis, were investigated in relation to the thermal structure of the water column and the sharks activity rates. Minimum horizontal displacement of between 66 km and 5 187 km for *P. glauca* and 16 km for *A. vulpinus* were recorded over 863 tracking days. Maximum depths ranged from 540 m to 807 m for *P. glauca* and 144 m for *A. vulpinus*. All sharks displayed plasticity in their depth distribution, with diel vertical movements and surface-oriented movements the two most common patterns. Behavioural responses to diel movement of prey is the most likely explanation for diel vertical movements of *A. vulpinus* and *P. glauca*. This study has improved our understanding of the vertical movement patterns of *P. glauca* and the relationship between their depth distribution, temperature, and activity. This information may be used to inform future fisheries management on the expected susceptibility of blue sharks to different gear types based on the extent vertical overlap.

INTRODUCTION

Characterising the movements and behaviour of animals in relation to their environment is a critical component of ecology (Bestley *et al.*, 2012; Jonsen *et al.*, 2003; Patterson *et al.*, 2009; Schlaff *et al.*, 2014). Research on the movement patterns of individuals provides a basis for understanding foraging ecology and habitat selection, and is vital in assessing population trends and species vulnerability (Austin *et al.*, 2006; Jonsen *et al.*, 2003; Patterson *et al.*, 2009; Schlaff *et al.*, 2014). For example, changes in the distribution and residency of apex predators, such as large sharks, can affect the structure and function of ecological communities through their interactions with prey species (Andrews *et al.*, 2009; Barnett *et al.*, 2011) and competition with other higher trophic level predators (Kitchell *et al.*, 1999; Kitchell *et al.*, 2002; Schindler *et al.*, 2002).

For many marine species, vertical movement patterns have received less attention than horizontal movement patterns. Investigation of the movement patterns of sharks are important in understanding their ecology, refining assessments of fisheries encounterability, and developing bycatch mitigation measures (Hobday *et al.*, 2011; Musyl *et al.*, 2011; Speed *et al.*, 2010; Vaudo *et al.*, 2014). Vertical movement patterns of marine species can vary over a range of temporal and spatial scales in response to different environmental conditions and behavioural cues (e.g. diel cycles, water temperature, and prey densities) (Brierley, 2014; Hays, 2003; Humphries *et al.*, 2010; Schlaff *et al.*, 2014). One of the most common vertical movement patterns observed in pelagic ecosystems is diel vertical movement (DVM), which is typically characterised by a shallow or surface-oriented depth distribution during the night followed by a highly variable or deep depth distribution during daylight hours (Brierley, 2014; Neilson & Perry, 1990). This movement pattern has been described in a broad range of marine species from plankton (Hays, 2003) and planktivores

(Brunnschweiler & Sims, 2011; Klevjer *et al.*, 2012; Sims *et al.*, 2005) to tertiary consumers (Bazzino *et al.*, 2010; Sims *et al.*, 2006) and large predators (Andrews *et al.*, 2009; Campana & Joyce, 2004; Cartamil *et al.*, 2010b; Queiroz *et al.*, 2010). Thermoregulation, oxygen limitation, predator avoidance, navigation during migrations, and foraging on diel migrating prey have all been suggested as drivers of DVM in pelagic predators (Campana *et al.*, 2011; Vaudo *et al.*, 2016).

The southeastern Indian Ocean is characterised by multiple oceanographic features that include the Sub-Tropical Front, Sub-Antarctic Front, Leeuwin Current, Flinders Current, and upwelling regions in the Great Australian Bight (Middleton & Bye, 2007). A seasonal coastal current facilitates the movement of warm Indian Ocean water from the Leeuwin Current eastwards into the South Australian basin (Hufford *et al.*, 1997; Middleton & Bye, 2007). The westward flowing Flinders Current along the shelf slope of southern Australia increases the ocean-shelf water exchange and raises the thermocline on the continental shelf which provides favourable conditions for cool water upwelling (Middleton & Bye, 2007; Middleton & Cirano, 2002; van Ruth *et al.*, 2010). The Bonney Coast in southeastern South Australia has the largest and most predictable upwelling events in the region, which support high primary productivity and abundant marine life (Nieblas *et al.*, 2009; Ward *et al.*, 2006). High primary productivity in this region drives aggregations of pelagic prey species (e.g., Australian sardine (*Sardinops sagax*), Australian anchovy (*Engraulis australis*) and arrow squid (*Nototodarus gouldi*)) and a diverse range of higher order predators, including the southern bluefin tuna (*Thunnus maccoyii*), pigmy blue whales (*Balaenoptera musculus*), long-nosed fur seals (*Arctocephalus forsteri*), and shortfin makos (*Isurus oxyrinchus*) (Baylis *et al.*, 2008; Bestley *et al.*, 2012; Gill *et al.*, 2011; Rogers *et al.*, 2015; Stark, 2008; Ward *et al.*, 2006). The southeastern Indian Ocean has also been identified as having high shark species richness and particularly high functional diversity due to the broad range of shark ecomorphotypes present in these waters (Lucifora *et al.*, 2011).

The blue shark (*Prionace glauca*) is an oceanic pelagic predator and is the most widely distributed elasmobranch globally (Last & Stevens, 2009; Nakano & Stevens, 2008). As a major component of the international fin trade and a bycatch species in many pelagic long-line fisheries, *P. glauca* are one of the most highly exploited elasmobranchs globally (Bonfil, 1994; Clarke *et al.*, 2006; Stevens *et al.*, 2000). Despite high levels of exploitation, *P. glauca* are listed globally only as Near Threatened by the IUCN, rather than Vulnerable or Endangered, due to their robust life history characteristics, in contrast to many other elasmobranchs (Stevens, 2009). The common thresher shark (*Alopias vulpinus*) has a cosmopolitan distribution in subtropical and temperate seas, is assessed as Vulnerable globally by the IUCN (Goldman *et al.*, 2009), and is listed in Appendix II of the Convention on the Conservation of Migratory Species (CMS). Both *P. glauca* and *A. vulpinus* are taken as bycatch in recreational and commercial fisheries throughout the southeastern Indian Ocean (Walker & Gason, 2007). The major fisheries in the region that take pelagic sharks as bycatch include the Southern and Eastern Shark and Scalefish Fishery (SESSF), the Eastern and Western Tuna and Billfish Fishery (ETBF and WTBF), and other high-seas tuna and billfish longline fisheries operating beyond Australia's exclusive economic zone (Stevens & Wayte, 2009). Better understanding of the movements and depth utilisation of *P. glauca* and *A. vulpinus* will clarify the susceptibility of these species to different fisheries and aid in developing strategies to reduce unwanted shark bycatch (Cartamil *et al.*, 2011; Hobday *et al.*, 2011).

The movement patterns of *P. glauca* and *A. vulpinus* have previously been investigated in the Atlantic (Campana *et al.*, 2011; Queiroz *et al.*, 2010; Vandeperre *et al.*, 2014; Vandeperre *et* *al.*, 2016) and Pacific Oceans (Cartamil *et al.*, 2010a; Cartamil *et al.*, 2010b; Cartamil *et al.*, 2016; Musyl *et al.*, 2011; Stevens *et al.*, 2010). Satellite tagging of *P. glauca* and *A. vulpinus* has also been conducted along the east coast of Australia where movements of sharks were largely restricted to the Tasman and Coral Seas (Stevens *et al.*, 2010). Limited data is available on the horizontal movements of *P. glauca* and *A. vulpinus* in the southeastern Indian Ocean (Pepperell, 2010; Rogers *et al.*, 2016), and very little is known about the vertical movement patterns and habitat use of these two species in this region. This study, therefore, aims to examine the vertical movement patterns of *P. glauca* and *A. vulpinus* in the southeastern Indian Ocean, and specifically to: (1) assess the plasticity of movement patterns within individual sharks; (2) identify common vertical movement patterns and; (3) examine the relationship between depth distributions, levels of activity and temperature.

METHODS

TAGGING

Capture and tagging was conducted between Port MacDonnell, South Australia and Lady Julia Percy Island, Victoria (Fig. 1). One *A. vulpinus* (hereafter T1) was tagged in December 2012 and five *P. glauca* (hereafter B1–B5) were tagged from May 2013 to April 2014 (Table 1). All sharks were caught using rod and line with heavy tackle and 37 kg test monofilament line to reduce the time between hooking and tag deployment. Sharks were caught for tagging using a trolled hard-bodied deep-diving lure on a monofilament trace (91 kg) (*A.* vulpinus) or using a baited circle hook (size 16/0) attached with a 2 m long plastic-coated wire trace (180 kg) (*P. glauca*). All sharks were brought alongside the vessel and restrained in an aluminium sling for the duration of the tagging procedure. The tagging procedure was < 3 minutes for all sharks. Water flow was maintained across the gill surface using either a water pump or flow through the sling. The eyes were covered using a soft wet cloth for the duration of the tagging procedure (AFMA & Reina, 2014). Fork length (*A. vulpinus*) or total length (*P. glauca*) was measured over the curvature of the body to the nearest cm and sex was determined from the presence of claspers in males.

Sharks were tagged with pop-up satellite archival transmitters (X-tag; Microwave Telemetry, Inc.; www.microwavetelemetry.com), hereafter referred to as tags. Pop-up locations were provided by Argos using a least squares analysis algorithm (Deibjerg *et al.*, 2003). Tags were attached to sharks using tethers consisting of 15 cm of 130 kg multiflex monofilament crimped to a Domeier plastic umbrella dart (www.marinecsi.org/umbrella-darts). Umbrella darts were inserted into the dorsal musculature perpendicular to the skin to a maximum depth of 10 cm. Tags were preprogramed to remain attached to the sharks for 180 days recording water temperature, pressure, and light intensity at two-minute intervals. At the end of the recording period, tags released from the sharks and transmitted data via the ARGOS satellite network. Transmitted data consisted of depth (range: 0 to 1296 m, resolution: 0.3–5.4 m) and temperature measurements (range: -4–40°C, resolution: 0.16–0.23°C) at 15-minute intervals although due to reduced transmission rates not all tags reported the entire track at this resolution. Two tags were physically retrieved which provided the full dataset at a resolution of two minutes.

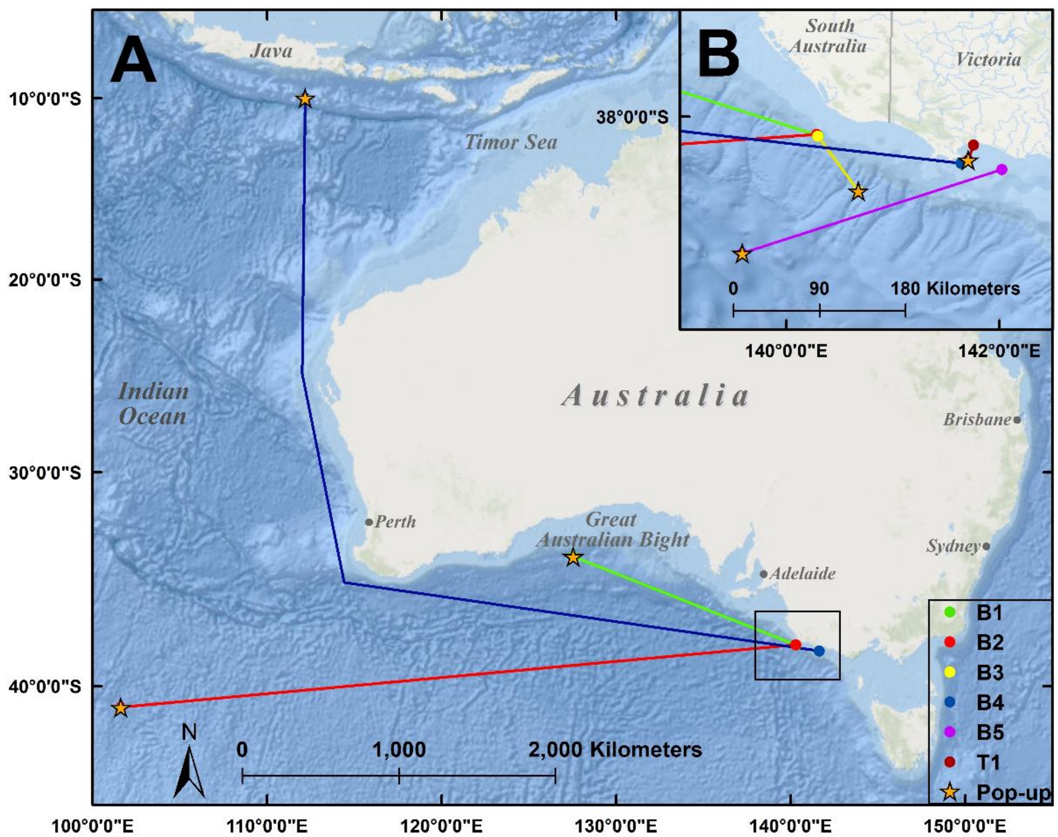

Figure 2.1. Tagging and pop-up locations with minimum distance travelled vectors for both large-scale **(A)** and small-scale **(B)** movements of tagged *P. glauca* (B1 – B5) and *A. vulpinus* (T1).

DATA SELECTION

Data from the first 24 hours were not included in the analysis to minimise any possible effects of capture stress and tagging procedure (Cartamil *et al.*, 2011; Skomal & Benrnal, 2010). As part of Microwave Telemetry© data compression techniques for transmitted ARGOS data, large changes in depth and temperature within a period of one hour may be identified as 'delta limited' and are potentially erroneous (Brunnschweiler, 2014). Delta limited depth values comprised 0.98% and delta limited temperature values only represented 0.47% of the total dataset and, therefore all delta limited values were included in the vertical movement analysis.

HORIZONTAL MOVEMENT

Minimum horizontal displacements of sharks were calculated using the recorded deployment location and the transmitted satellite location at pop-up (Fig. 2.1). Position estimation between release and pop-up were not used in further analysis due a low number of reliable position estimates based on light-based data. The deep diving diel behaviour of *P. glauca* with descents at dawn and ascents at dusk contributed to a large proportion of the inaccurate and erroneous position estimates in each track.

Table 2.1. Tag deployments and performance for five *P. glauca* and one *A. vulpinus*.

ID	Species	Sex	Length (cm)	Tagging Date	Pop-up date	Pop-up location	Min Distance (km)	Max Depth (m)	Days at liberty
B1	*Prionace glauca*	M	302 TL	7 May 13	7 Nov 13	34°5'S 127°32'E	1 230	560	184
B2	*Prionace glauca*	F	207 TL	7 May 13	7 Nov 13	40°55'S 101°36'E	3 305	586	184
B3*	*Prionace glauca*	F	178 TL	8 May 13	8 Nov 13	38°41'S 140°40'E	66	540	184
B4	*Prionace glauca*	F	216 TL	9 Jun 13	9 Dec 13	9°59'S 112°10'E	5 187	807	183
B5	*Prionace glauca*	F	159 TL	6 Apr 13	26 May 14	39°17'S 139°35'E	228	586	50
T1*	*Alopias vulpinus*	F	175 FL	15 Dec 12	3 Mar 13	38°24'S 141°42'E	16	144	78

*Tag recovered and archival data obtained. TL = total length; FL = fork length.

VERTICAL MOVEMENT ANALYSIS

Depth- and time-integrated thermal habitat profiles were created using the Data-Interpolating Variational Analysis (DIVA) gridding tools in OCEAN DATA VIEW© (Schlitzer, 2015). These profiles provided an overview of the vertical and thermal habitats of all sharks throughout the deployment period (Fig. 2.2).

PSATs record long and complex time-series of depth data which often encompasses a series of different movement patterns (Sims *et al.*, 2012). A split moving window (SMW) analysis was applied to objectively detect discontinuities in the dataset (Cornelius & Reynolds, 1991; Humphries *et al.*, 2010). Depth and time records were used to construct a time-at-depth matrix which consisted of 36-h time bins (as columns) and 20-m-depth bins (as rows) for *P. glauca* to represent the proportion of time spent at each depth within each time period. For T1, where the depth range was much smaller and changes in movement patterns occurred over a shorter time period, the time at depth matrix consisted of 24-h time bins and 5-m-depth bins. To perform the SMW analysis, a virtual window with a width of at least two columns (72 hours) was placed at the start of the matrix and the dissimilarity between the first and second half of the window was calculated. Significant dissimilarities ($p = 0.05$) were calculated using a Monte Carlo method where the calculation was repeated 1000 times with a random shift in the depth distribution. Dissimilarities were calculated for every possible position of the virtual window along the track for the two-column-width window. The process was repeated with the window width increased by two columns up to a window width of 16 columns (45 days) to identify dissimilarities over longer time scales. For presentation, positions of significant dissimilarities ($p = 0.05$) for each window width were plotted in black with narrow window widths stacked on top of wider windows (see supplementary information). Areas of consistent dissimilarity were identified as inverted triangles where the apex indicated the position in the time series where changes in depth utilisation occurred (Supplementary Fig. 2.S1-S6). This method has previously been used in analysis of PSAT data for *P. glauca* (Queiroz *et al.*, 2012) and other shark species (Sims *et al.*, 2012) and is described in more detail in Humphries et al (2010).

For each section, identified by the SMW analysis, depth use was estimated for day and night separately to assess diel variation in vertical habitat utilisation (Fig. 2.3–2.6). Sunrise and sunset times were based on the light data obtained from each tags light sensors. Anomalous sunrise and sunset data were removed by excluding readings where depth was more than 60 m at sunrise or sunset. Average monthly sunset and sunrise times for each shark were then calculated and categorised as 'Dawn' (sunrise ± 1 hour), 'Dusk' (sunset ± 1 hour), 'Day' (between dawn and dusk), and 'Night' (between dusk and dawn).

Permutational Multivariate Analysis Of Variance (PERMANOVA) was used to investigate differences in the depth distribution of sections between day and night and between sharks according to levels of activity and the thermal structure of the water column. Activity was computed as the change in depth between two depth records divided by the time between these records and represented rate of vertical movements (i.e. mean speed). Depth records at 15 minutes intervals were used to calculate activity for all tracks to allow comparisons between archival and transmitted records. Thermal structure of the water column was characterised by the mean, minimum, and maximum water temperature for each section. Permutational approaches have the advantage of not being constrained by many of the typical assumptions of parametric statistics (Legendre & Anderson, 1999). Distance matrices were calculated for day and night of each section identified by the SMW for both depth and temperature distributions. Bray-Curtis distance matrices were calculated using square-root transformed depth distributions to reduce the asymmetry of the depth distribution data. A Euclidean distance matrix was calculated for normalised behavioural (activity) and environmental (water temperature) variables. PERMANOVA for depth distributions was based on unrestricted permutations of raw data with 999 permutations using a Type III (Partial) sum of squares. Step-wise distance based linear models (DistLM) were used to investigate relationships between depth distributions and behavioural (activity) and environmental (water temperature) variables for day and night. Selection was based on Akaike's Information Criterion for small sample sizes (AIC*c*) to identify behavioural and environmental variables with significant relationships to the depth distribution data. Distance based redundancy analysis (dbRDA) plots were used to visualise the results of the step-wise DistLM analysis with significant environmental variables plotted as vectors (Fig. 2.7).

RESULTS

Five *P. glauca* (B1–B5, 159–302 cm TL) and one female *A. vulpinus* (T1, 175 cm FL) were tagged (Table 1). Based on known length-at-maturity, *P. glauca* included one mature male (B1), three sub-adult females (B2–B4), and one juvenile female (B5), while T1 was a mature female (Pratt, 1979; Smith *et al.*, 2008). Four of the six tags reached their 180 day pop-off dates, while two tags (B5 and T1) detached prematurely after 50 and 78 days, respectively. Two tags (B3 and T1) were recovered allowing the full archived datasets to be retrieved. Overall, *P. glauca* were tracked for a total of 785 days and covered an estimated horizontal displacement of 10 016 km (66–5 187 km; Fig. 2.1). The distance between deployment and pop-up location for T1 was 16 km over the 78-day deployment.

HORIZONTAL MOVEMENTS

Minimum horizontal displacement of *P. glauca* ranged from 66 km (B3) to 5 187 km (B4), with all large scale movements to the west or north-west (Fig. 2.1) The largest horizontal movements were made by two sub-adult females with tag releases recorded in the southern Indian Ocean (B2) and the Timor Sea (B4). The minimum horizontal displacement by B4 was 5 187 km over 183 days, which equates to an average horizontal displacement of 28.3 km.day^{-1}. The pop-up locations for the two smallest *P. glauca* (B3 and B5) and *A. vulpinus* (T1) were all within 230 km of their respective tagging locations (Fig. 2.1).

VERTICAL MOVEMENT PATTERNS

Prionace glauca demonstrated a wide vertical distribution, inhabiting depths from the surface to a maximum of 807 m (B4). Shark B4 also recorded the next four deepest dives (608–667 m) throughout the duration of the track. No other shark exceeded depths of 600 m, with the maximum depths for the other four *P. glauca* ranging between 540 and 586 m (Table 2.1). Water temperatures experienced by the *P. glauca* spanned a 24 °C range from 5.5 to 29.5 °C, with the maximum temperatures recorded by B4 during the last 50 days of the deployment and the minimum temperature recorded by the same shark on its deepest dive (Fig. 2.2).

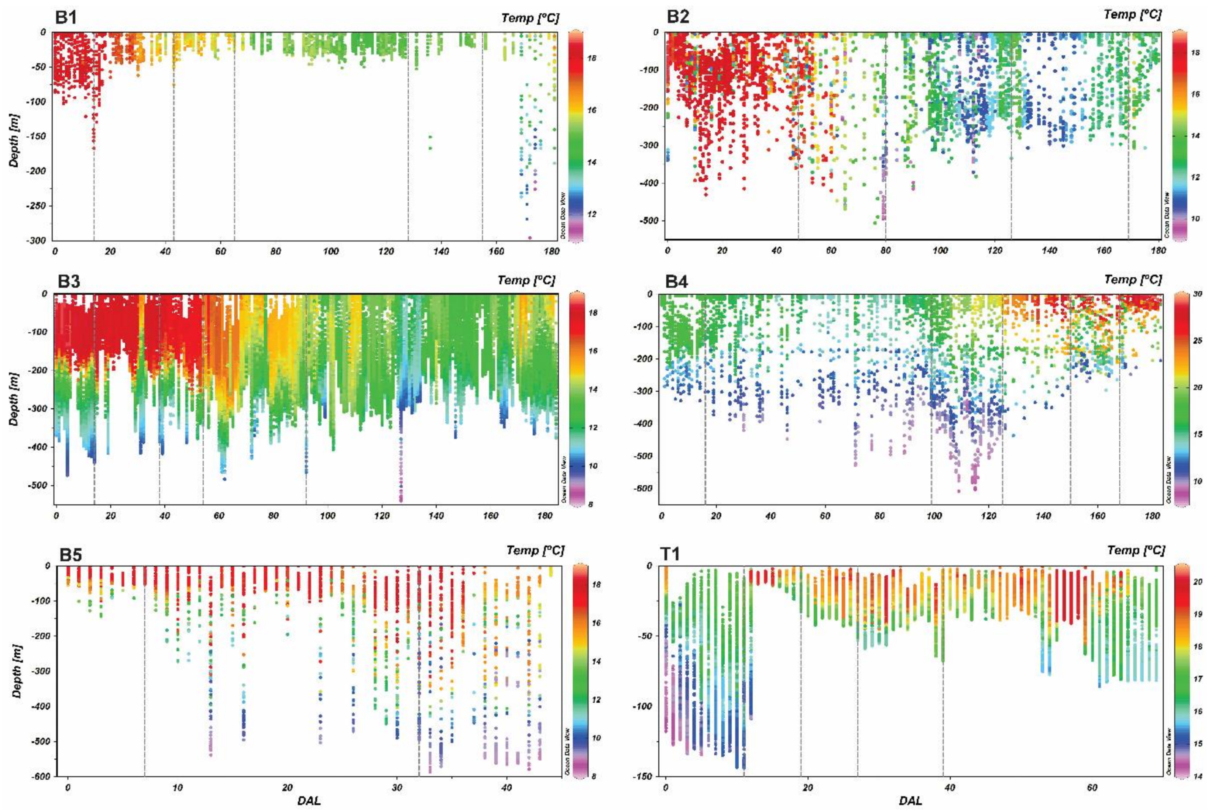

Figure 2.2. Depth and time integrated thermal habitat profiles for all sharks (B1 – B5 and T1) over total days at liberty (DAL). Grey dashed lines represent breaks between depth distributions identified by the split moving window analysis (Fig. S2.1 – S2.6).

Split moving window analysis revealed individual variation in the vertical depth distributions of all sharks with 2–5 changes in depth distribution resulting in 3–6 sections for each track (Fig. 2.2). Duration of sections ranged from 7 to 92 days (mean 27.6 ± 20.8 days). Vertical distributions for the majority of sections for *P. glauca* were characterised by oceanic phases (maximum daily depths >200 m), although B1 remained in the neritic/epipelagic zone (maximum daily depths <200 m) for three out of five sections and T1 remained in the neritic/epipelagic zone for the duration of the track. Diel patterns of vertical movement, where mean daytime depths were markedly deeper than mean night time depths, were common for all sharks but were more prominent in oceanic phases (Fig. 2.3–4).

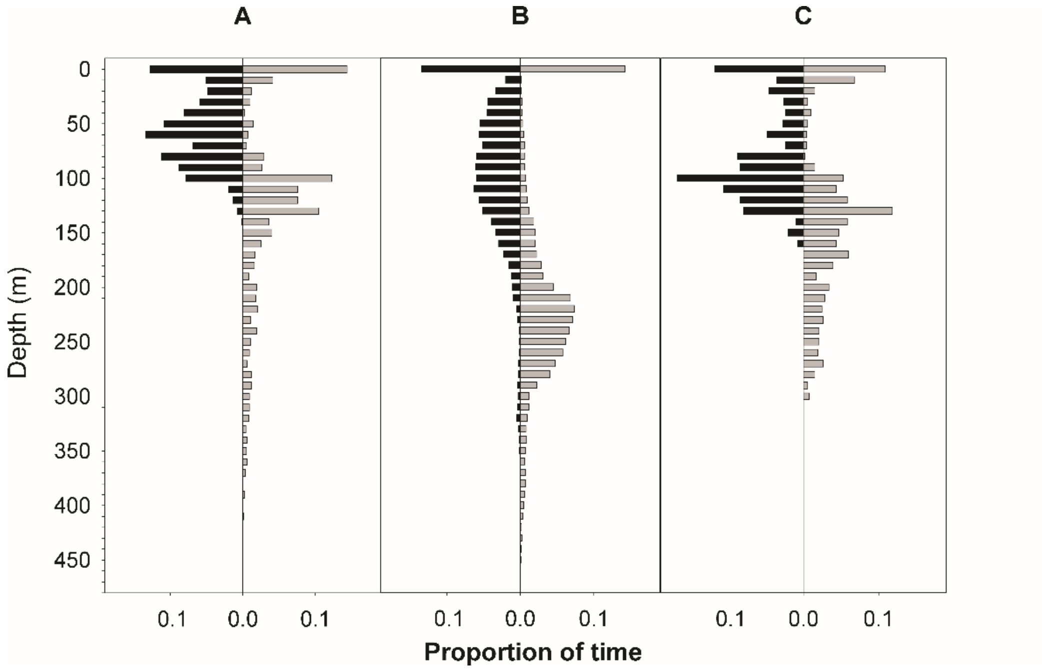

Figure 2.3. Frequency histograms for sections of Normal Diel Vertical Movement (nDVM) of *P. glauca* by night (black bars) and day (grey bars). Examples represented are: **(A)** B2 section 1; **(B)** B3 section 4; and **(C)** B4 section 1, as defined by the split moving window analysis (Fig. S2.1 – S2.6).

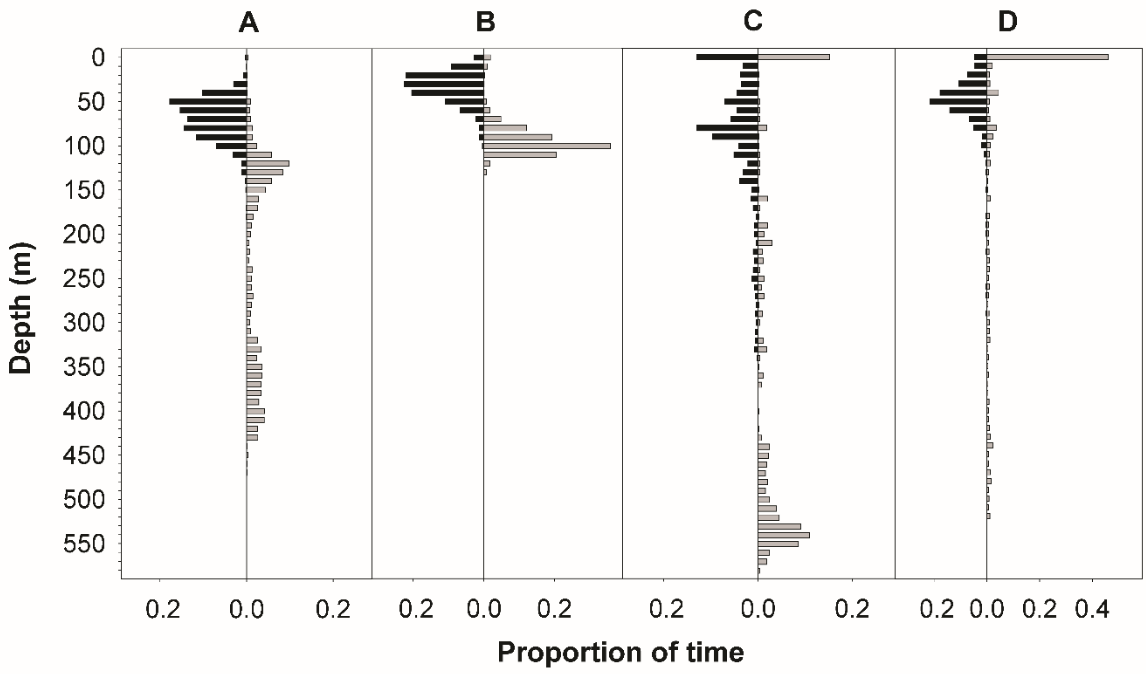

Figure 2.4. Frequency histograms for sections of other diel vertical movements of *P. glauca* and *A. vulpinus* by night (black bars) and day (grey bars). Normal diel vertical movement with very low surface occupancy as shown by B3 section 1 (**A**) and T1 section 1 (**B**); reverse diel vertical movement (rDVM) displayed by B5 section 2 (**C**); and deep diel vertical movement (dDVM) displayed by B5 section 3 (**D**), as defined by the split moving window analysis (Fig. S2.1 – S2.6).

Across all sharks a total of 29 sections of varying vertical movement patterns were identified (Fig. 2.2 and Supplementary Fig. S2.1–S2.6). Four different general vertical movement patterns were observed: normal diel vertical movements (nDVM, Fig. 2.3, Fig. 2.4A-C), reverse diel vertical movement (rDVM, Fig. 2.4D), surface-oriented behaviour (Fig. 2.5), and irregular shallow movements (Fig. 2.6). Normal DVM patterns can be further classified into three groups including nDVM with high levels of surface occupancy (Fig. 2.3), nDVM with low levels of surface occupancy (Fig 2.4A–B), and nDVM with deep (>400 m) day-time depth occupancy (Fig. 2.4C).

Normal DVM patterns accounted for 17 of the 29 sections defined by the SMW analysis and were observed in all sharks. Eleven of these sections included a combination of diel vertical movements and some surface occupancy throughout both day and night (Fig. 2.3). The majority of daytime depth occupancy for these sections was between 100 and 250 m. This movement pattern was displayed by four out of the five *P. glauca* (Fig. S2.1–S2.4). Sections of diel vertical movement with very little surface occupancy (0–5%) were observed in four sections including three from T1 and one from B5 (Fig. 2.4A-B). Deep nDVM patterns, which were characterised by the majority of daytime depth occupancy being deeper than 400 metres, were observed in sharks B4 and B5 (Fig. 2.4C). Reverse DVM patterns were also observed in these two sharks and were characterised by depth occupancy being deeper during the night compared to daytime (Fig. 2.4D).

Surface-oriented movements and irregular shallow movements each accounted for five of the remaining ten sections with multiple individual sharks displaying each of these movement patterns. Four *P. glauca* displayed surface-oriented movements, defined by a large proportion of time spent in the top 20 metres of the water column and occasional dives to greater depths (Fig. 2.5). Irregular shallow movement patterns were exhibited by two *P. glauca* (B1 and B5) as well as *A. vulpinus*. The depth distribution of these sections was largely confined to the upper 50 metres of the water column with little or no diel difference (Fig. 2.6).

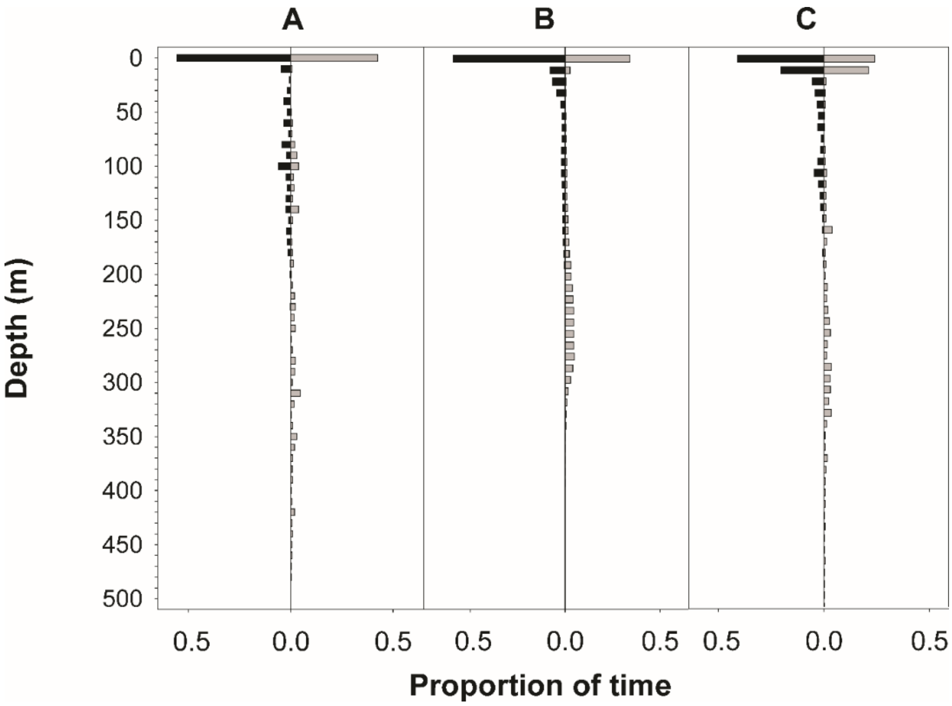

Figure 2.5. Frequency histograms for sections of surface-oriented movements of *P. glauca* by night (black bars) and day (grey bars). Examples represented are: **(A)** B2 section 2; **(B)** B3 section 5; and **(C)** B4 section 2, as defined by the split moving window analysis (Fig. S2.1 – S2.6).

Temperature at depth plots for shark B3 revealed the presence of distinct thermoclines in the first three sections of the track (Fig. S2.3). The thermocline ranged from 160–210 m (17.4–13.6°C) in section 1 to 180–250 m (16.2–12.6°C) in section 3. Night-time depth utilisation was concentrated above the thermocline throughout these sections. Surface temperatures in section 4 and section 5 were comparatively low (15.2°C and 13.5°C, respectively), with no distinct thermocline. The first four sections were characterised by nDVM movements both with surface occupancy (section 2–4) and without surface occupancy (section 1, Fig. 4A), while section 5 showed a much higher proportion of surface-oriented movement (Fig. S3).

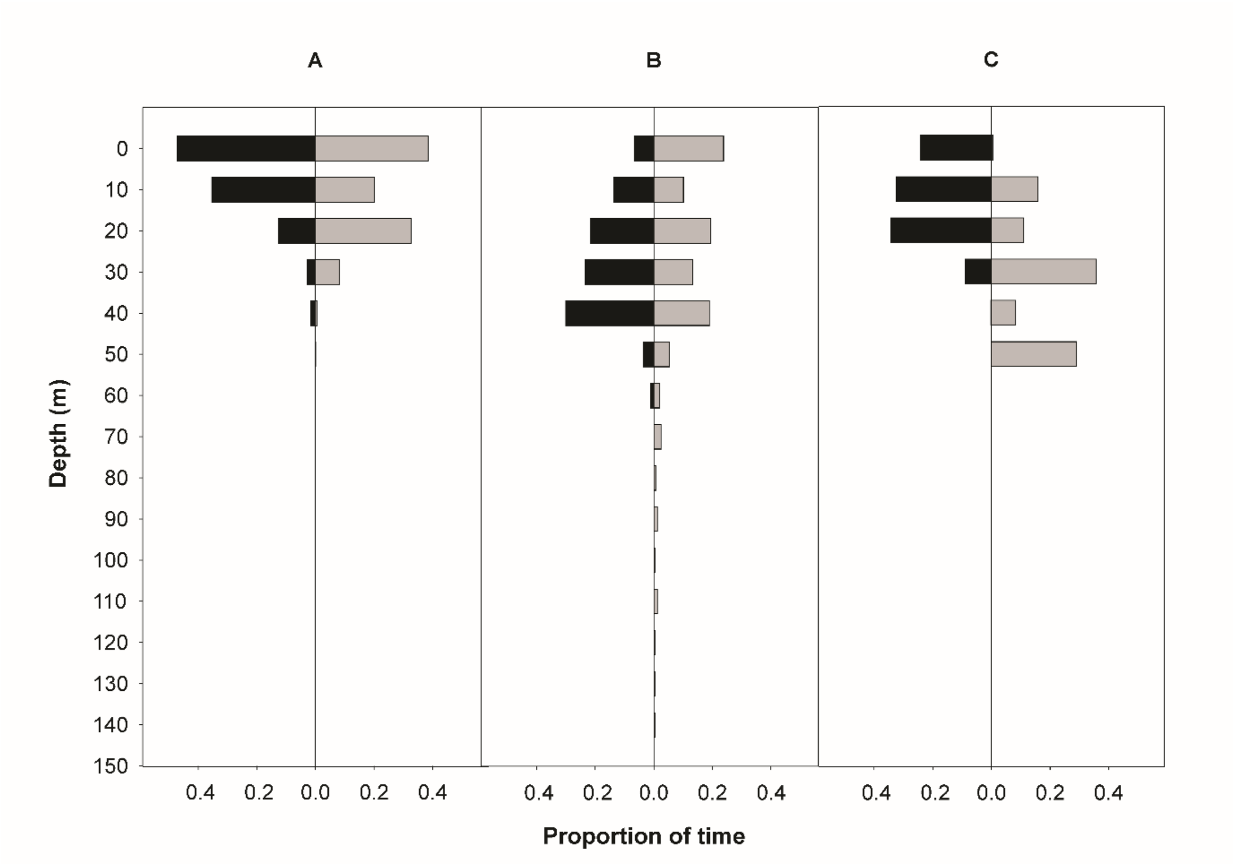

Figure 2.6. Frequency histograms for sections of shallow vertical movements of *P. glauca* and *A. vulpinus* by night (black bars) and day (grey bars). Panels represent: **(A)** B1 section 3; **(B)** B5 section 1; and **(C)** T1 section 4, as defined by the split moving window analysis (Fig. S2.1 – S2.6).

VERTICAL MOVEMENT CORRELATIONS

The two-way PERMANOVA of the depth distributions revealed significant differences between individual sharks (*Pseudo-F* = 3.41, P = 0.001) and between day and night (*Pseudo-F* = 5.43, P = 0.002). The interaction between sharks and day/night was, however, not significantly different (*Pseudo-F* = 0.63, P = 0.866). Step-wise DistLM for daytime depth distribution included minimum temperature (Day: *Pseudo-F* = 25.7, P = 0.001) and mean activity (*Pseudo-F* = 3.3, P = 0.012), and explained 54% of the variation in the data (AICc = 204.4, R^2 = 0.535). The DistLM for night-time distributions also included mean activity (*Pseudo-F* = 10.7, P = 0.001) and minimum temperature (*Pseudo-F* = 4.1, P = 0.014), but explained less of the variation (37%) in the depth distribution data (AICc = 192.9, R^2 = 0.371) (Fig. 2.7).

Distance based redundancy analysis plots (dbRDA) revealed that the daytime depth distributions of all T1 sections and the first five sections of B1 could be distinguished from the remainder of the *P. glauca* sections. Vectors reveal that this is largely explained by differences in minimum temperature. Shark B3 could also be differentiated from the other *P. glauca* largely based on differences in activity. Depth distribution across shark and section was more clustered during night-time than during the day. However, sections 2–5 of B3 and section 3 of B4 were distinguishable from the remainder of the sections. Mean activity (m/s) was the main explanatory variable differentiating between these night-time distributions (Fig. 2.7).

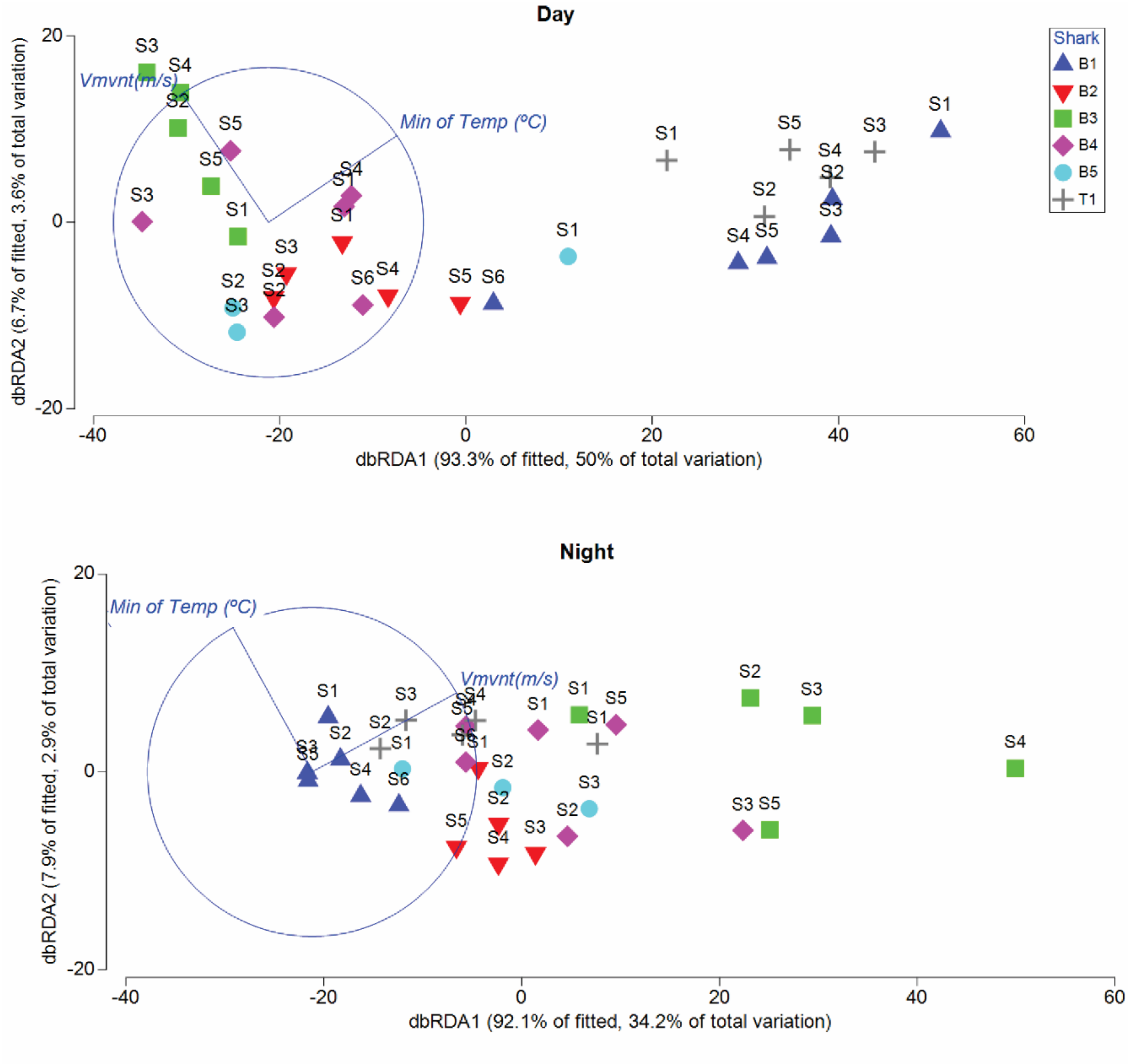

Figure 2.7. Distance based redundancy analysis (dbRDA) plots for split moving window analysis sections (S2.1 – S2.6) of all sharks for day (top) and night (bottom). Vectors inside blue circles represent the direction in which the environmental variables contributed to the DistLM across all sections.

DISCUSSION

This study provides the first investigation of the vertical movement patterns of *P. glauca* and *A. vulpinus* in the southeastern Indian Ocean. Using data collected during satellite tag deployments, we examined vertical movements in the context of behavioural plasticity and diel patterns. High levels of variability in depth distributions were observed within and between individual *P. glauca*. Normal diel vertical movement (nDVM), characterised by shallower night time depth distribution compared to daytime depth distribution, was the dominant movement pattern exhibited by all sharks. Other vertical movement patterns included reverse diel vertical movement (rDVM), surface-oriented movements, and irregular shallow movements. Overall, activity and minimum temperatures were driving changes in depth distributions between sections during both daytime and night-time.

HORIZONTAL MOVEMENTS

Minimal horizontal displacement of *P. glauca* was highly variable and encompassed a mix of short-distance movements and large-scale movements to the west and north-west. Minimum rates of horizontal displacement for *P. glauca* in the present study (mean ± SE = 11.85 ± 2.28 km.day^{-1}) were comparable to those recorded in the Northwest Atlantic (10.86 ± 1.2 km.day^{-1}) (Campana *et al.*, 2011). The longest migration recorded in the present study was made by a *P. glauca* (B4) that travelled up the west coast of Australia to the south of Java, Indonesia. Similar migrations have been recorded by two *P. glauca* tagged with conventional and smart position or temperature (SPOT) tags off southern Australia, migrating to the same region south of Java over a 10-month period (Rogers *et al.*, 2016; West *et al.*, 2004). This region is a productive frontal zone that experiences upwelling during the tropical monsoon and is an important spawning area for the southern bluefin tuna (*T. maccoyii*) (Nieblas *et al.*, 2014). In the present study, several of the *P. glauca* and the *A. vulpinus* remained within or retuned to the Bonney Upwelling region. This region is known for its high productivity driven by the strong and predictable upwelling of nutrient rich waters throughout the austral summer (Butler *et al.*, 2002). Highly productive areas within the North Atlantic have also previously been shown to be hotspots for *P. glauca* (Queiroz *et al.*, 2016). Upwelling systems are known to support aggregations of small pelagic teleosts (Pauly & Christensen, 1995) and oceanic squids (Anderson & Rodhouse, 2001), which are important prey of *P. glauca* and *A. vulpinus* (Preti *et al.*, 2012; Rogers *et al.*, 2012). Sharks returning to the Bonney Upwelling region and movement to the upwelling region south of Java, Indonesia, highlights the importance of these regions to pelagic predators and is likely to be linked to prey availability.

The diel diving behaviour, combined with extended periods of time spent in the mesopelagic zone, led to large numbers of erroneous location records and prevented the reconstruction of accurate horizontal tracks. The westward movements of *P. glauca* in this study may be aided by the Flinders Current which flows along the shelf slope. The lack of accurate location estimates, however, hinders our ability to confirm this. *Prionace glauca* have previously been shown to be an ideal candidate for fin-mounted SPOT tags (Stevens *et al.*, 2010) which would provide reliable location estimates. Future deployments of SPOT tags on *P. glauca* off southern Australia would provide further information on their horizontal movements and connection to the oceanographic features of the southeastern Indian Ocean. The extent of the horizontal movements of *P. glauca* confirms the need for their cross-jurisdictional management as a highly migratory species within the southeastern Indian Ocean.

VERTICAL MOVEMENT PATTERNS

All five *P. glauca* in this study recorded dives to depths greater than 500 m with a maximum dive depth of 807 m. The individual *A. vulpinus* primarily inhabited the epipelagic zone and waters over the continental shelf reaching a maximum depth of 144 m. The adult male *P. glauca* (B1) spent over four months in depths of less than 200 m suggesting that it was swimming over the continental shelf. This shark was unique among the sharks in this study, with all of the smaller female sharks inhabiting the shelf slope and waters beyond the continental shelf for the majority or entirety of their tracks. The relationship between the depth distributions of the large male *P. glauca* (B1) and *A. vulpinus* indicate that there may be overlap in the habitat use over the continental shelf for these two pelagic predators. Although small sample size prevents us from making inferences about sex- and size-based segregation, such spatial segregation has previously been observed and proposed to be linked to the species reproductive cycle or diet (Preti *et al.*, 2012; Vandeperre *et al.*, 2014; Vandeperre *et al.*, 2016). Subsequent tagging studies in this area should focus on male sharks and mature females to assess whether sexual or ontogenetic differences occur as suggested by our data.

All tagged sharks exhibited plasticity in their vertical movement with between two and five distinct changes in depth distributions identified for each individual. Queiroz *et al.* (2012) detected plasticity in the vertical movement patterns of only 60% of *P. glauca* in the northeastern Atlantic using a similar SMW analysis. The higher level of plasticity in the present study is likely due to the longer tag deployments (mean ± SD = 157 ± 54 days) compared to *P. glauca* tagged in the northeastern Atlantic (mean ± SD = 40 ± 21 days). There was a high level of variability in the length of time spent utilising different vertical movement patterns in the current study (range = 7–92 days, mean ± SD = 27.7 ± 20.8 days) and in the northeastern Atlantic (range =2–71 days, mean ± SD = 19.1 ± 16.4 days) (Queiroz *et al.*, 2012).

Normal DVM patterns were detected in the majority (83%) of behavioural sections in the present study. Diel vertical movement is common among large pelagic sharks and has been recorded in many species including *Cetorhinus maximus* (Shepard *et al.*, 2006), *Rhincodon typus* (Brunnschweiler & Sims, 2011), *Lamna nasus* (Francis *et al.*, 2015), *A. superciliosus* (Coelho *et al.*, 2015), *A. vulpinus* (Cartamil *et al.*, 2010a), and *P. glauca* (Campana *et al.*, 2011; Queiroz *et al.*, 2012). Diel vertical movement of *P. glauca* has been hypothesised to be related to foraging, thermoregulation, predator avoidance, or orientation (Campana *et al.*, 2011). Queiroz *et al.* (2012) identified five vertical movement patterns for *P. glauca* in the northeastern Atlantic: two distinct types of nDVM; rDVM; surface-oriented; and irregular. A similar range of movement patterns (three types of nDVM, rDVM, surface-oriented, and irregular) were exhibited by sharks in the present study, with nDVM patterns having greater variability in daytime depth distribution than those recorded in the northeastern Atlantic (Queiroz *et al.*, 2012).

Multivariate analysis revealed the importance of changes to activity and minimum temperature to depth distributions. Mean activity differed greatly between day and night and between different vertical movement patterns. Changes in daytime depth distribution were closely related to minimum temperatures, which is likely to be related to colder waters encountered during daytime deep diving behaviour. Temperature has previously provided explanation for changes in *P. glauca* depth distributions around the gulf stream in the northwestern Atlantic (Campana *et al.*, 2011). In waters with a distinct thermocline, the movements of *P. glauca* displayed nDVM patterns while in less stratified waters, we observed more surface-oriented movement patterns. This change in movement patterns may be associated with movements into well-mixed waters of the Bonney Upwelling as similar changes have been observed for *P. glauca* associated with upwelling regions in the northeastern Atlantic Ocean (Queiroz *et al.*, 2012). Daytime depth distributions were clustered around the depth of the thermocline, while depth occupancy at night was generally above the thermocline. This could be indicative of foraging on vertically migrating prey, such as oceanic cephalopods, which are known to aggregate around the thermocline during the day and move towards the surface to feed during the night (Roper & Young, 1975). Oceanic squid species have been shown to be a primary prey species for *P. glauca* in many areas of the globe (Hernández-Aguilar *et al.*, 2016; Kubodera *et al.*, 2007; Preti *et al.*, 2012). These squid species are a component of the deep scattering layer, which also follows a nDVM pattern, and foraging within this layer has previously been suggested based on *P. glauca* dietary data (Preti *et al.*, 2012). Arrow squid (*N. gouldi*) is the dominant squid species in southern Australian waters and are abundant in the Bonney Upwelling region throughout the year (Smith, 1983; Stark, 2008). Dietary analysis of *N. gouldi* has shown that they primarily feed during the night and follow a nDVM pattern (Stark, 2008).

Prionace glauca are known to prefer waters between 12°C –20°C and are thought to swim at greater depth in the tropics to seek colder water (Last & Stevens, 2009; Nakano & Stevens, 2008; Vandeperre *et al.*, 2016). In contrast, shark B4, which was the only individual to enter tropical waters, showed a preference for surface swimming during two of the three sections characterised as tropical waters (SST >25°C). Similar movement patterns have been recorded for *P. glauca* in warm surface waters off the east coast of Australia (Stevens *et al.*, 2010).

Alopias vulpinus had four distinct changes in depth distribution throughout its 78-day deployment with nDVM and irregular shallow movements being the dominant movement patterns. Normal DVM patterns have also been identified for *A. vulpinus* off the East Coast of Australia where the majority of daytime was spent between 200 and 300 m and the majority of night spent in the upper 50 m of the water column (Stevens *et al.*, 2010). Plasticity in the vertical movement pattern of the *A. vulpinus* in the present study may be related to depth constraints during inshore movements, however, juvenile *A. vulpinus* off the southern coast of California rarely recorded dives deeper than 100 m while remaining in waters of over 1000 m (Cartamil *et al.*, 2010a). *Alopias vulpinus* off the Californian coast showed two clear vertical movement patterns, identified as shallow and deep mode, which contained similar patterns to those we observed in the present study (Cartamil *et al.*, 2010a). Abrupt switches in daytime depth distribution for both juvenile and sub-adult *A. vulpinus* off the coast of California were attributed to changes in prey abundance (Cartamil *et al.*, 2016; Cartamil *et al.*, 2011). Shallow modes were thought to be related to abundant small pelagic teleosts near the surface while deep sections were thought to be related to areas of sparse prey abundance at the surface and the need to forage at depth during the day (Cartamil *et al.*, 2011). Foraging is also the most likely explanation for the diel movement patterns of the *A. vulpinus* tagged in the present study. The diet of *A. vulpinus* in waters off southern Australia is primarily composed of small pelagic teleost fishes of which, the Australian anchovy (*E. australis*) and the Australian sardine (*S. sagax*) are the most important prey items (Rogers *et al.*, 2012). Small pelagic teleosts are known to exhibit diel migrations and to move inshore during warmer months which coincides with the time of tagging for the *A. vulpinus* in the present study (Gutierez *et al.*, 2007; Stenevik *et al.*, 2007). Changes in the diet of *A. vulpinus* in the Eastern Pacific are associated with differing water temperature regimes (Preti *et al.*, 2004). Dietary comparisons of *A. vulpinus* from the U.S. Pacific Coast have also shown a widening of the dietary breadth during warm water periods with pacific squid becoming more important during cool water periods (Preti *et al.*, 2004). However, the tagging period of the *A. vulpinus* in the present study was restricted to summer months due to a premature release and therefore a possible seasonal change of habitat due to a shift in prey items could not be investigated. Further deployments of satellite tags would provide more information on the movements of *A. vulpinus* throughout the year.

MANAGEMENT IMPLICATIONS

The vertical movement patterns outlined in this study may be useful in developing methods to mitigate the bycatch of *A. vulpinus* and *P. glauca* in longline and gillnet fisheries that operate within the southeastern Indian Ocean. For example, the diel behaviour of *P. glauca* makes them more vulnerable to capture at night by shallow set longlines (< 100 m) typically used in the ETBF and WTBF fisheries (Campbell & Young, 2012). During the day, *P. glauca* inhabit depths that render them more susceptible to capture by Japanese longliners that generally set at depths between 100 and 300 m targeting bigeye tuna (*T. obesus*) and operate outside the exclusive economic zone of Australia (Hampton *et al.*, 1998). In 2007, gillnetting in the SESSF was excluded from waters shallower than 183 m (AFMA, 2014b). Recent restrictions have also limited the net drop (height the net extends from the sea floor) of demersal gillnets in the SESSF to reduce the bycatch of semi-pelagic shark species (AFMA, 2014b). Based on the diel behaviour of *A. vulpinus* in deeper waters, the restriction on the net drop is likely to be more effective at reducing bycatch during the night when sharks have a shallower depth distribution. The data obtained in this study will be useful in the development of risk assessments (e.g., Hobday *et al.*, 2011) of *P. glauca* and *A. vulpinus* susceptibility to the various fisheries that operate in the southeastern Indian Ocean. Understanding the potential effects of these fisheries on the conservation status of *P. glauca* and *A. vulpinus* in the region is crucial in determining the most efficient and effective management options for these species.

SUMMARY

Final pop-up locations of the satellite tags highlight the importance of upwelling regions to *P. glauca*, likely due to the high abundance of prey species associated with upwelling events. Plasticity was evident in the vertical movement patterns of all sharks indicating that *A. vulpinus* and *P. glauca* can change their habitat utilisation to make use of optimum conditions.

Due to the variability in movement patterns between individuals it is difficult to draw conclusions based on the single tag deployed on the *A. vulpinus* in this study. Further effort should be applied to tag additional individuals of this species to clarify these movement patterns in this region. All individuals consistently used nDVM, which was most likely related to the movement patterns of diel migrating prey species. Water temperature and level of activity explained much of the variability in the depth distribution of both species, providing a promising avenue for future investigations of pelagic shark habitat preference. This study provides valuable information on the vertical movement patterns of *P. glauca* which, combined with commercial fishery data, will aid in the assessment of the vulnerability of these species to commercial fishing in the southeastern Indian Ocean.

ACKNOWLEDGEMENTS

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SUPPLEMENTARY INFORMATION

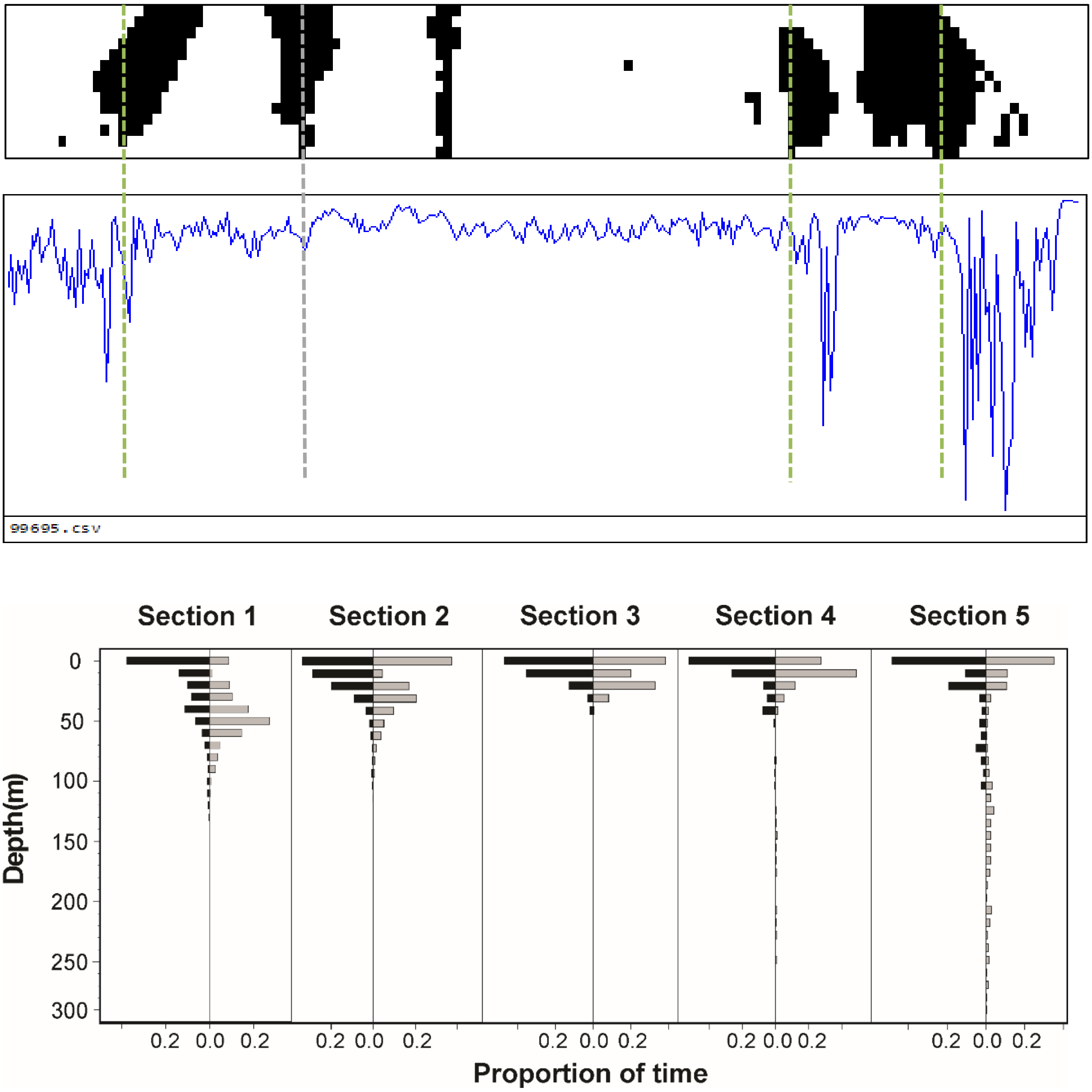
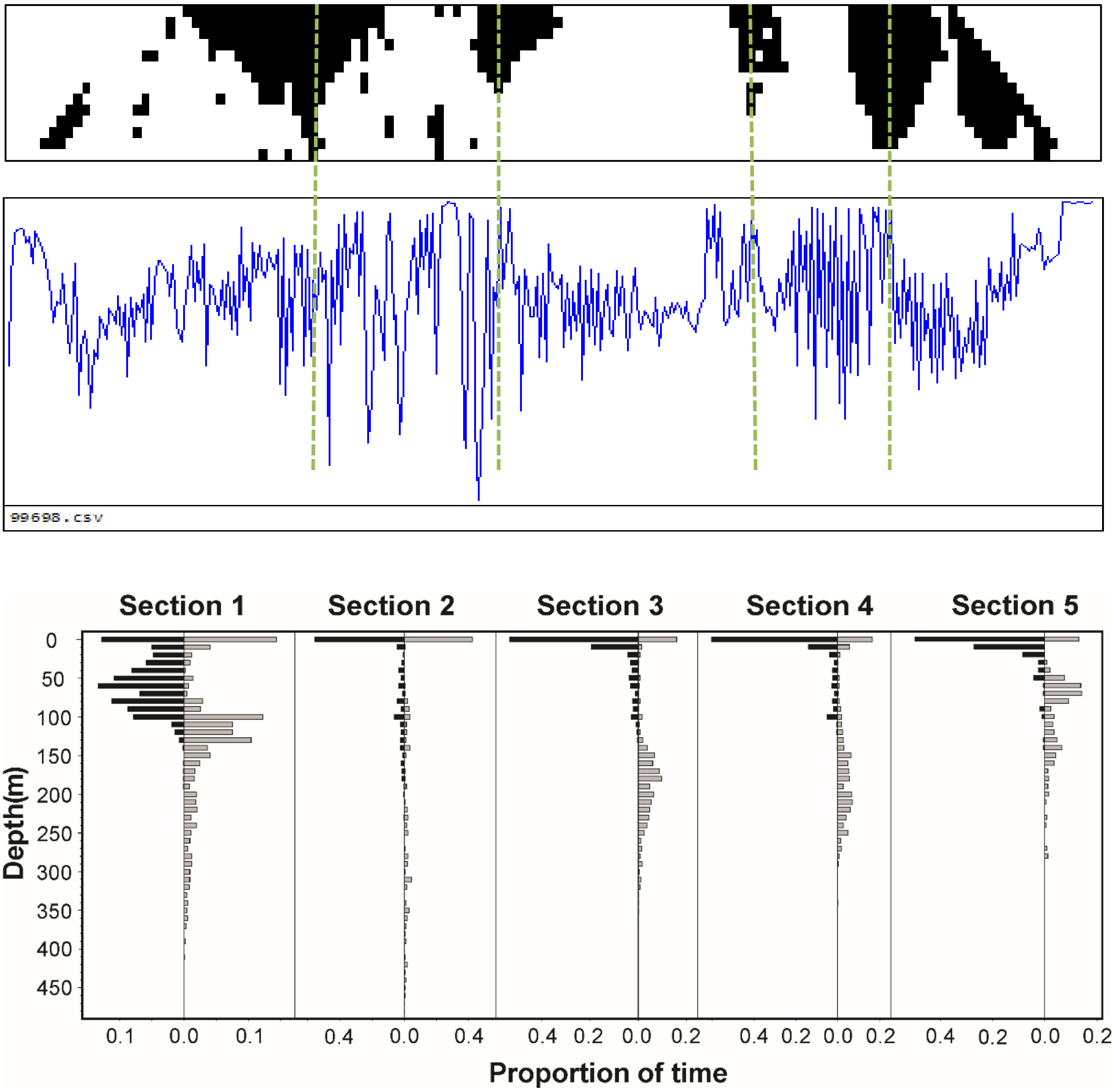


Figure S2.1. Split moving window (SMW) analysis for shark B1 (top panel) with significant dissimilarities (p = 0.05) for each window width shown in black with narrow window widths stacked on top of wider windows. Areas of consistent dissimilarity were identified as inverted triangles where the apex and grey dashed lines indicate the position in the time series where changes in depth utilisation occurred. Mean depth profile (middle panel) and frequency histograms for vertical movements of shark B1 by night (black bars) and day (grey bars) using sections defined by the SMW analysis.



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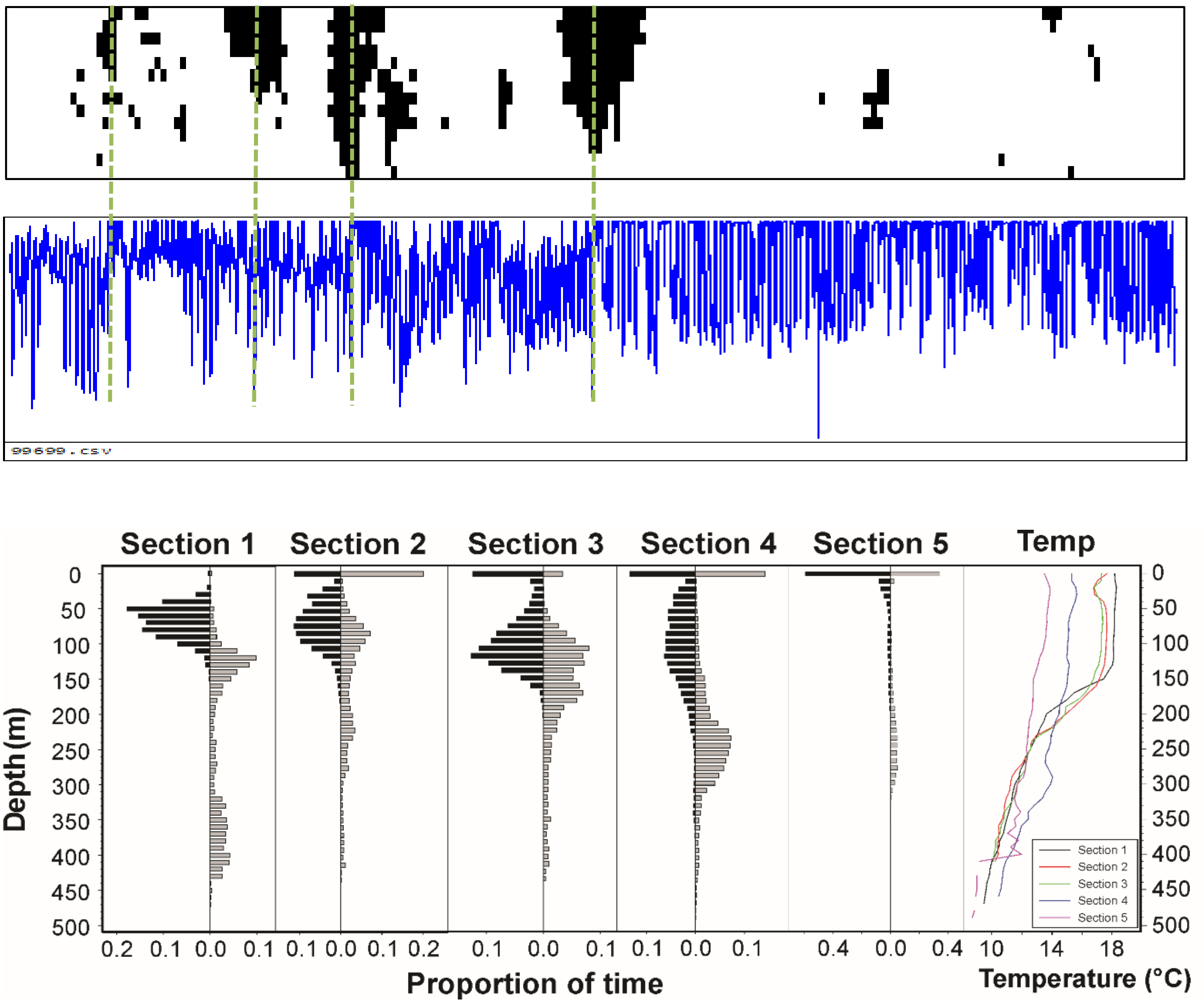

Figure S2.3. Split moving window (SMW) analysis for shark B3 (top panel) with significant dissimilarities (p = 0.05) for each window width shown in black with narrow window widths stacked on top of wider windows. Areas of consistent dissimilarity were identified as inverted triangles where the apex and grey dashed lines indicate the position in the time series where changes in depth utilisation occurred. Mean depth profile (middle panel) and frequency histograms for vertical movements of shark B3 by night (black bars) and day (grey bars) using sections defined by the SMW analysis.

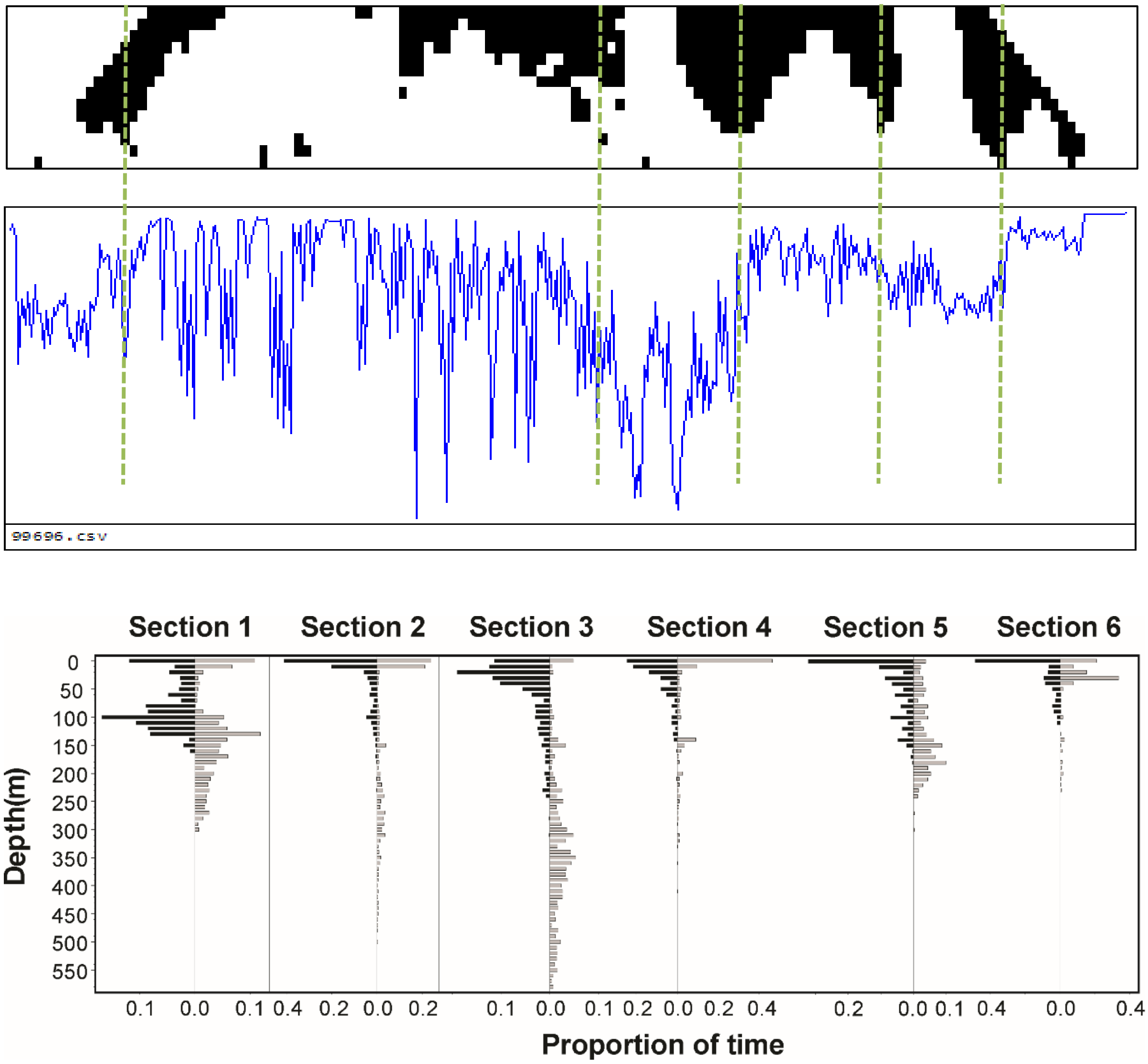

Figure S2.4. Split moving window (SMW) analysis for shark B4 (top panel) with significant dissimilarities (p = 0.05) for each window width shown in black with narrow window widths stacked on top of wider windows. Areas of consistent dissimilarity were identified as inverted triangles where the apex and grey dashed lines indicate the position in the time series where changes in depth utilisation occurred. Mean depth profile (middle panel) and frequency histograms for vertical movements of shark B4 by night (black bars) and day (grey bars) using sections defined by the SMW analysis.

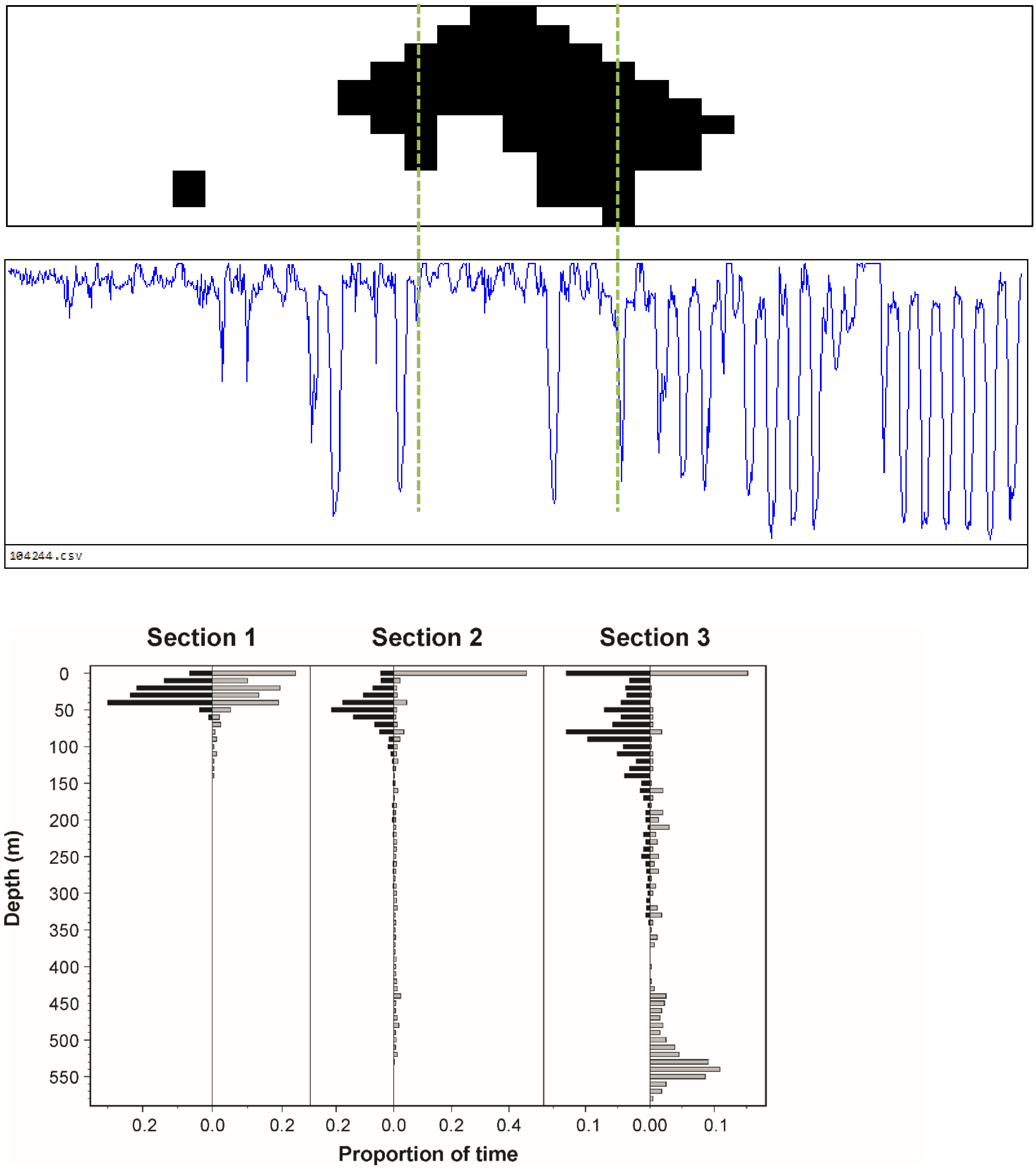

Figure S2.5. Split moving window (SMW) analysis for shark B5 (top panel) with significant dissimilarities ($p = 0.05$) for each window width shown in black with narrow window widths stacked on top of wider windows. Areas of consistent dissimilarity were identified as inverted triangles where the apex and grey dashed lines indicate the position in the time series where changes in depth utilisation occurred. Mean depth profile (middle panel) and frequency histograms for vertical movements of shark B5 by night (black bars) and day (grey bars) using sections defined by the SMW analysis.

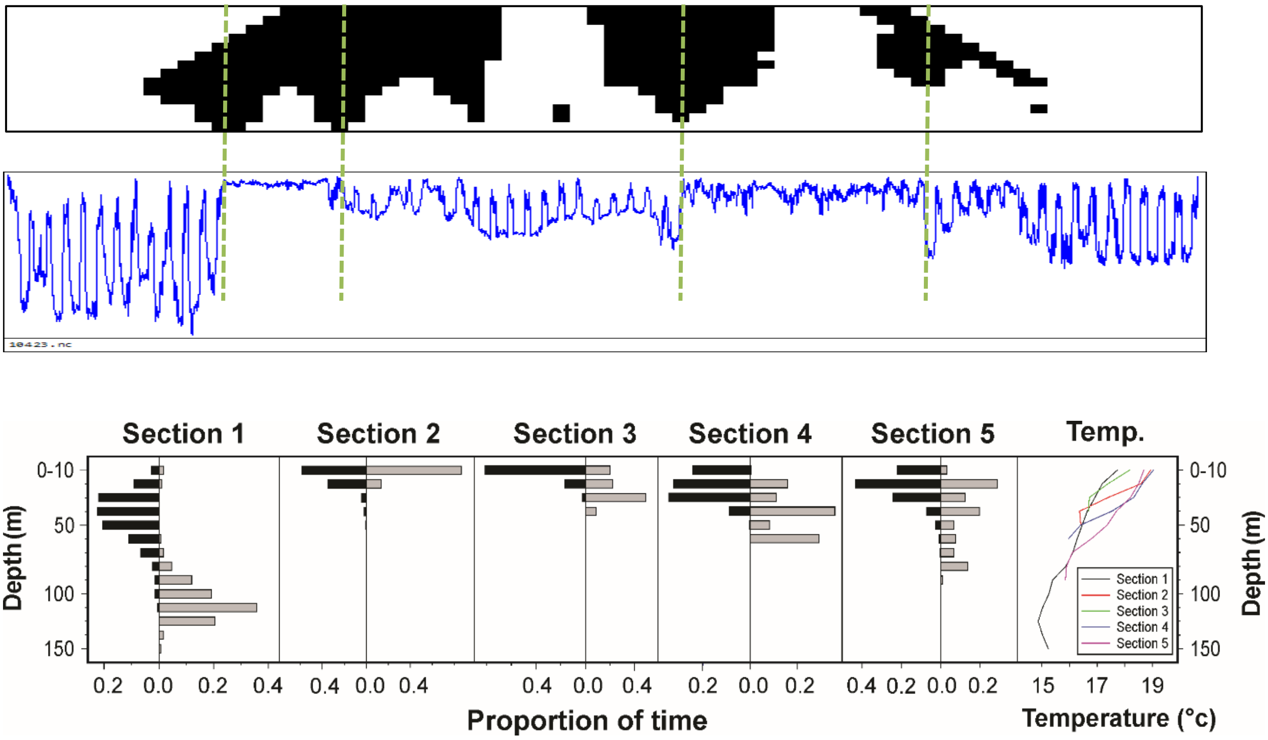

Figure S2.6. Split moving window (SMW) analysis for shark T1 (top panel) with significant dissimilarities (p = 0.05) for each window width shown in black with narrow window widths stacked on top of wider windows. Areas of consistent dissimilarity were identified as inverted triangles where the apex and grey dashed lines indicate the position in the time series where changes in depth utilisation occurred. Mean depth profile (middle panel) and frequency histograms for vertical movements of shark T1 by night (black bars) and day (grey bars) using sections defined by the SMW analysis.

3

ACTIONS SPEAK LOUDER THAN WORDS: TOURNAMENT ANGLING AS AN AVENUE TO PROMOTE BEST PRACTICE FOR PELAGIC SHARK FISHING

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See Appendix 2

M.H, P.R and C.H. conceived the ideas and, M.H. collected and analysed the data. M.H. led the writing of the manuscript and all authors contributed to the design of the survey, manuscript drafts and gave final approval for publication.

ABSTRACT

Social research can aid in understanding the behaviour of the general public or stakeholders towards natural resources. In the case of recreational fishing, social research aids in integrating anglers' knowledge and attitudes into management frameworks to increase the likelihood of the uptake of new management regulations. Tournament anglers were surveyed at game fishing competitions throughout New South Wales, Victoria, and South Australia between February 2012 and May 2013 to investigate their general beliefs around sharks and their behaviours when targeting pelagic sharks. Over half (55%) of the anglers interviewed practised catch and release of pelagic sharks. Of those, almost all (98%) asserted that they attempt to release sharks in good condition, but a large percentage of anglers (48%) did not use circle hooks that have been shown to increase post-release survival. Results showing some concordance between anglers' beliefs and behaviours when targeting pelagic sharks suggest that anglers are cognisant of the functional role of sharks in the ecosystem and would be open to recommendations ensuring the long-term sustainability of recreational fisheries targeting pelagic sharks.

INTRODUCTION

Recreational fisheries receive relatively little attention as a potential threat to fish populations compared to commercial fisheries, and the role of the recreational sector in driving stock declines remains largely unknown (Cooke & Cowx, 2006; Cooke *et al.*, 2016; Pauly *et al.*, 2003). Recreational catches have been estimated to account for ≈12% of total global catches of fish, but recreational catches can also far exceed commercial catches (Coleman *et al.*, 2004; Cooke & Cowx, 2004). For example, recreational catches from the United States account for 93% of red drum (*Sciaenops ocellatus*) catches in the South Atlantic, and 87% of bocaccio (*Sebastes paucispinus*) from the northeastern Pacific (Coleman *et al.*, 2004). The effect of recreational fishing on fish stocks is difficult to detect due to a lack of quantitative data, however, there is growing evidence that recreational angling can contribute to declines in fish populations, leading to the sustainability of recreational fisheries being increasingly questioned (Cooke & Cowx, 2004; Lewin *et al.*, 2006; McPhee *et al.*, 2002; Post *et al.*, 2002).

In Australia, estimates of recreational catches range from ≈ 13% (ABARE, 2005; Henry & Lyle, 2003) to 25% (Kearney, 1994) of total catches, with recreational catches exceeding commercial catches of some teleost species, e.g. King George whiting (*Sillaginodes punctatus*), mulloway (*Argyrosomus japonicus*), and snapper (*Pagrus auratus*) (Ferrell & Sumpton, 1997; Jones, 2009; Marshall & Moore, 2000). The most recent National Recreational and Indigenous Fishing Survey in Australia (Henry & Lyle, 2003) provides estimates of catches for commonly caught teleost species but provides no species-specific information about sharks and rays.

Pelagic sharks have been identified as a group of particular conservation concern because they are susceptible to high levels of mortality as targeted catch and bycatch in high seas fisheries (Dulvy *et al.*, 2008). Reported declines in the northern hemisphere (Baum *et al.*, 2003; Ferretti *et al.*, 2008) and concerns about the population status of several species of pelagic sharks prompted global assessments of the longfin mako (*Isurus paucus*), shortfin mako (*I. oxyrinchus*), porbeagle (*Lamna nasus*) and of three thresher shark species (*Alopias* spp.) as vulnerable on the International Union for the Conservation of Nature Red-list. Subsequent listings of these species under Appendix II of the Convention on the Conservation of Migratory Species of Wild Animals (CMS, of which Australia is a range state) triggered the requirement for legislative protection under the Australian governments Environmental Protection and Biodiversity Conservation (EPBC Act 1999). In addition, the Indian Ocean Tuna Commission (IOTC) passed a resolution to protect all three *Alopias* species in 2010. Following these listings and resolutions the mandatory release of live *Alopias* spp. (IOTC resolution 12/09) and of *I. oxyrinchus*, *I. paucus*, and *L. nasus* (*EPBC Act 1999*) is required by commercial fisheries within Australian waters. However, the same restrictions are not enforced (IOTC resolution 12/09) or have been directly amended (*EPBC Act amendment part 13*) to allow fishing for these species by recreational and tournament anglers.

In Australian waters, the prohibitions and restrictions on retaining these pelagic shark species by commercial fisheries has led to recreational anglers becoming important stakeholders in the management of *I. oxyrinchus, I. paucus, L. nasus,* and *Alopias* spp. stocks. While tournament anglers only make up a small proportion of recreational anglers in Australia (~5%), they tend to fish more frequently and invest more in vessels and gear than non-tournament anglers, therefore representing a disproportionately high percentage of fishing effort (Wilde *et al.*, 1998; Wright *et al.*, 2003). Tournament anglers are likely to account for a large proportion of recreational offshore fishing effort and pelagic shark catch as they are equipped to reach offshore areas and have additional incentives to target sharks through points bonuses and trophies during tournaments (Henry & Lyle, 2003; Lowry & Murphy, 2003). Catch and release angling is widely practised at game fishing tournaments in Australia with tagging of pelagic sharks playing an integral part of tournament angling (Lowry & Murphy, 2003). Best practice methods for catch and release fishing (e.g. the use of circle hooks) are promoted by organisations at all levels (e.g. United Nations Food and Agriculture Organisation, International Game Fishing Association, Australian National Sportsfishing Association and the NSW Department of Primary Industries Game Fish Tagging Program) although, it is unclear what percentage of anglers adopt these methods (ANSA, 2012; Arlinghaus *et al.*, 2012b; IGFA, 2015; NSW-DPI, 2013).

Recreational fisheries are inherently complex and management must consider the social and economic benefits of recreational fishing along with the effects that fishers have on both fish populations and the environment (Arlinghaus *et al.*, 2013). This is especially important if recreational fishers are targeting threatened or protected species (Arlinghaus *et al.*, 2010; Cooke *et al.,* 2016). Social research can aid understanding the behaviour of the general public or stakeholders towards natural resources (Heck *et al.*, 2015). In the case of recreational fishing, social research aims to integrate angler knowledge and attitudes into the management framework and increase the likelihood of the uptake of new management regulations (Arlinghaus *et al.*, 2013; Hunt *et al.*, 2013; Simpfendorfer *et al.*, 2011). There is a large body of evidence showing that individual's beliefs and attitude towards a behaviour will influence their intentions to perform that behaviour (see Armitage & Conner, 2001). Few previous studies have compared angler preferences and behavioural intent with their actual behaviour (Sutton & Ditton, 2001; Wallmo & Gentner, 2008). By better understanding anglers' beliefs and how they are linked to their behaviours, researchers are able to inform managers on the most appropriate methods to change angler behaviours (Wallmo & Gentner, 2008). Along with the choice to practise catch and release, the gear (e.g. circle or 'J' hooks) and methods that anglers choose to use when targeting pelagic sharks may also have an effect on the survival of line caught released sharks.

This study aims to investigate the beliefs of tournament anglers around sharks and the behaviours of anglers when targeting pelagic sharks. Specifically, the level of catch and release for pelagic sharks was quantified to gain an insight into anglers' fishing practices. Anglers' reasons behind retaining or releasing sharks was examined to better understand what is required to promote catch and release. This study also aimed to explore links between angler behaviours and their beliefs in relation to the value of catching a shark, the value of the existence of sharks to the ecosystem, and the importance of releasing sharks in a good condition. These aims were addressed by measuring the beliefs and behaviours of tournament anglers through surveys at game fishing tournaments in South Australia, Victoria, and New South Wales throughout 2012 and 2013.

Methods

Shortfin mako (I. *oxyrinchus*), longfin mako (*I. paucus*), thresher sharks (*Alopias* spp.) and porbeagle (*L. nasus*), henceforth referred to as 'pelagic sharks', were the primary interest of this research due to global conservation concerns relating to these species. The target population for this study was tournament anglers >18 years of age who fish in temperate Australian waters. Surveys were undertaken at game fishing tournaments throughout South Australia, Victoria, and New South Wales. A short 5–10 min questionnaire (Appendix 3.1) was provided to tournament anglers at boat ramps to collect data on anglers catch of pelagic sharks over the previous 12 months, release practices, gear preference, and beliefs about sharks. An interview based questionnaire was used due to their increased effectiveness at generating responses compared to mail surveys (Yu & Cooper, 1983). An opportunistic sampling approach was used as the angling population that we aimed to survey has previously been identified to be a minority of the recreational fishing community particularly hard to reach (Griffiths *et al.*, 2010).

Questionnaire design

Anglers were asked to provide details about their fishing catch and effort targeting pelagic sharks during the previous 12 months. Respondents that had caught or targeted pelagic sharks were provided with the full survey, while those that had not targeted pelagic sharks were only provided with the belief and demographic questions. We surveyed both anglers who targeted pelagic sharks and anglers that did not target pelagic sharks to allow comparisons between the beliefs of these two groups. The population demographics of tournament anglers was assessed, including; age, gender, and education level.

DEPENDENT VARIABLES: ANGLER BEHAVIOURS

Respondents were asked questions about their fishing effort (days fished) and catch of pelagic sharks over the previous 12 months. Capture of pelagic sharks is considered to be memorable due to both the rarity and seasonality of these captures and we would therefore expect minimal recall bias and telescoping in estimates over the previous 12 months (Zischke & Griffiths, 2014). Fishers who had fished for, or caught a pelagic shark in the previous 12 months were also asked about the release rate for each species and the reasons for retaining or releasing sharks. We investigated the gear type used by recreational fishers when targeting pelagic sharks by asking them specific questions regarding hook shape and material, and leader material.

INDEPENDENT VARIABLES: BELIEFS ABOUT SHARKS

Respondents' beliefs towards sharks were evaluated through questions asking anglers to rate their level of agreement to a series of statements about catching and releasing sharks. These questions pertain to different aspects of beliefs about sharks and were grouped to measure beliefs on three different domains: (1) importance of releasing sharks in a good condition; (2) value of catching sharks; and (3) conservation of sharks. Broad terms such as 'shark' and 'fish' were used in some survey questions (e.g. I prefer to catch fish than sharks) rather than 'elasmobranch' and 'teleost' to be more easily understood by respondents. Anglers responses to the belief questions were originally asked on a five point Likert scale from strongly agree to strongly disagree. Several negatively geared questions were included in the survey and results for these questions with the answers transposed for analysis. To produce discrete analysis, responses were subsequently collapsed into three categories (agree, neutral and disagree). Belief questions in each of the three domains were grouped and the mean calculated to create an index for each domain. Scores with a value over two represent a positive belief with higher mean scores (>3) indicating strong positive beliefs. Reliability of each question to add to the consistency of each domain was investigated using Cronbach's Alpha.

Binary logistic regression models were used to test the combined effects of anglers' beliefs (independent variables: importance of releasing a shark in good condition, personal value of catching a shark, and the existence values of sharks) on the various behaviours of anglers when fishing for pelagic sharks (dependent variables: choice to practise catch and release, and gear preference). Gear specific behaviours were aggregated into binary measures separating anglers who used best practice measures (e.g. circle hooks, non-stainless steel hooks and monofilament leader) and those who did not. For each logistic regression model, the model was simplified by using a backward-stepwise regression procedure that eliminated the non-significant variables. Odds ratios were used as a measure of effect size for each dependent variable and concordance statistics (measures the agreement between two variables) were used to assess the predictive ability of each model.

RESULTS

DESCRIPTION OF THE SAMPLE

We surveyed 201 individual tournament anglers, of which the vast majority (95%) were male. Respondents ranged in age from 18 to 74, with most in their thirties (39%) or forties (26%) and the remainder aged under 30 (20%), or 50 and over (19%). Forty-five percent of respondents had completed a trade or apprenticeship, 31% had completed high school or less, and 24% had attained a university degree. There was a fairly even split of respondents from each state, with 37% from South Australia, 32% from New South Wales, and the remaining 31% from Victoria. Comparison of these results with the 2003 national recreational fisheries survey (Henry & Lyle, 2003) indicates that our sample was biased towards males, but it is likely that this is a reflection of the higher participation rates of males in tournaments (Oh *et al.*, 2013). The overall response rate for this survey was 76% which is considered acceptable for a face to face survey (Fisher, 1996).

CATCH AND EFFORT DATA

Pelagic sharks were targeted by over half (58%) of the respondents to this survey. These anglers caught pelagic sharks at an average (± SD) of 4.45 ± 5.35 sharks in the year prior to being surveyed. Tournament anglers caught a total of 459 sharks, of which, 445 (97%) were *I. oxyrinchus* and 14 (3%) were *A. vulpinus*. No anglers reported catching porbeagles (*L. nasus*). Respondents reported releasing 282 (61%) of the captured sharks and tagged 106 (24%) prior to release. This accounts for 39% of the pelagic sharks tagged by tournament anglers in Australia over the period of this study based on a mean of 271 sharks tagged per year between 2011 and 2013 (*NSW DPI Game Fish Tagging Program Report 2011 -2012,* 2012; *NSW DPI Game Fish Tagging Program Report 2012 -2013,* 2013). Anglers that had targeted pelagic sharks in the 12 months prior to being surveyed fished an average of 44.8 days per year compared to 34.4 days for anglers who did not target pelagic sharks. Anglers who targeted pelagic sharks spent an average of 11.8 days per year specifically targeting sharks, which accounts for more than the difference between the two groups in total fishing days per year.

RELEASE OR RETENTION OF PELAGIC SHARKS

Of the anglers that targeted pelagic sharks, 33% released some while 32% released all of the sharks they had caught in the previous 12 months. In total, 70 respondents gave reasons for why they released some or all of the pelagic sharks that they caught. Approximately 30% of these respondents cited size (e.g. “too big” or “too small”) as a reason for releasing pelagic sharks. Tagging, either for research or for competition points was also cited by approximately 30% of the respondents that gave reasons for releasing sharks. Other reasons for releasing sharks were that anglers had no need to kill sharks (13%), or that they had reached their catch limit (6%).

The majority (68%) of tournament anglers that had caught sharks in the previous 12 months had retained some or all of the pelagic sharks that they had caught. Of these anglers, 51 gave reasons for retaining sharks. The most common reason for retaining sharks (69%) was for consumption, expressed as either “food” or “eating”. Reasons for retaining sharks for tournaments such as “trophy fish” or “capture for competition” accounted for 33% of the reasons cited.

*G*EAR PREFERENCE

Of the anglers that responded to gear specific questions (n=91), almost half (48%) reported using only J-hooks, while slightly less (36%) used only circle hooks, with the remainder (16%) using a combination of both styles when targeting sharks. Half of the respondents reported using non-stainless steel (i.e. degradable) hooks, with 40% using stainless steel hooks and the remaining 10% using both stainless and non-stainless hooks. The use of non-stainless steel hooks was correlated with the use of circle hooks and the practice of catch and release (Table 3.1).

Table 3.1. Correlation matrix for tournament angler behaviours when fishing for pelagic sharks.

	Hook Shape		Hook Material		Leader Type	
	φ	*p*	*φ*	*p*	*φ*	*p φ*
Catch and release	0.1	0.402	0.275	0.009	0.201	0.071
Hook shape	x		0.29	0.003	0.045	654
Hook material	x		x		0.232	0.12

Table 3.2. Descriptive statistics and reliability analysis for the variables used to measure the beliefs of tournament anglers about catching, releasing, and the existence value of sharks. Item wording is identical to the survey. Items were measured on a five-point scale with responses ranging from (0) strongly disagree to (4) strongly agree.

Belief dimensions and items	**Mean Score**	**SD**	**Item-total correlation**	**α if item deleted**
Importance of releasing a shark in a good condition (α = 0.732)	**3.69**			
I would be willing to use tackle and special handling practices that minimise damage to released sharks	3.55	0.703	0.615	0.603
I like to ensure that a shark is released in a good condition	3.73	0.517	0.559	0.649
It is important to me that all the fish that I release survive	3.78	0.486	0.546	0.670
Value of catching a shark (α = 0.817)	**2.78**			
Catching a shark adds to the enjoyment of my fishing trip	3.46	0.798	0.656	0.768
I prefer to catch fish than sharks**	1.61	1.087	0.565	0.814
I enjoy the challenge of catching a shark	3.49	0.701	0.724	0.755
I target sharks when I go fishing	2.55	1.125	0.705	0.742
Existence value of sharks (α = 0.624)	**3.36**			
It is important to have viable populations of sharks	3.23	0.786	0.491	0.447
It would be better if there were fewer sharks in the sea**	3.43	0.809	0.482	0.459
Sharks are a good sign of a healthy marine ecosystem	3.44	0.706	0.343	0.646
Individual items				
Sharks are good to eat	2.81	1.048		
More regulations are required for recreational fishing for sharks	1.48	1.163		
Commercial fishing is a threat to shark populations	3.31	0.846		
Recreational fishing is a threat to shark populations	1.10	0.954		
Sharks need to be protected	1.61	1.185		
Sharks should be conserved as they have a right to exist	2.99	0.932		

** Denotes survey questions that were negatively geared with answers transposed for analysis

Belief orientations

Anglers' beliefs about the importance of releasing a shark in a good condition, value of catching a shark, existence value of sharks, threats to sharks, and protection of sharks are presented in Table 3.2. The majority of anglers were of the perception that the numbers of pelagic sharks are stable (55%) or increasing (28%), while only a small proportion considered numbers to be decreasing (17%). Tournament anglers generally had positive beliefs surrounding the value of catching a shark, the importance of releasing a shark in a good condition, and the existence value of sharks. The highest score was recorded for questions about the importance of releasing sharks in good condition (mean scale score = 3.69 out of 4), which included the importance of releasing all fish in good condition so that they survive and the willingness of anglers to use tackle and handling practices to ensure this. Anglers had positive responses towards the value of catching a shark (mean scale score = 2.78 out of 4).

While most anglers did not prefer to catch sharks over fish, the majority targeted sharks when they went fishing (mean scale score = 2.55 out of 4), enjoyed the challenge of catching a shark (mean scale score = 3.49 out of 4), and believed it added to the enjoyment of their fishing trip (mean scale score = 3.46 out of 4). Respondents had positive beliefs towards the existence value of sharks (mean scale score = 3.36 out of 4), recognised the importance of having viable shark populations, and that sharks are a sign of a healthy ecosystem. Beliefs were very strong when considering the threats to shark populations with the majority of anglers agreeing that commercial fishing is a threat (mean score = 3.31 out of 4), but not recreational fishing (mean score = 1.1 out of 4). Most respondents also disagreed with the statements that 'more regulations are required for recreational fishing for sharks' (mean score = 1.48 out of 4) or that 'sharks need to be protected' (mean score = 1.61 out of 4).

Table 3.3. Binary logistic regression analysis testing the effect of tournament angler beliefs about catching, releasing and the existence value of sharks on their behaviours when fishing for pelagic sharks. (p values = * < 0.05, ** < 0.01, *** < 0.005 or ns)

Model	**Parameter**	**df**	**Estimate**	**SE**	**X^2**	**p**	**Odds ratio**
Target pelagic sharks	Value of catching a shark	1	-.521	0.198	6.895	**	0.594
	Constant	1	1.447	0.467	9.599	***	4.249
	Model X^2 = 7.255, df = 1, p = 0.007 Concordance 57%, n = 201 (target pelagic sharks = 84, do not target pelagic sharks = 112)						
Catch and release	Existence value of sharks	1	-1.319	0.448	7.291	**	0.268
	More regulations are required for the fishing of sharks*	1	-0.505	0.271	3.491	ns	0.603
	Constant	1	5.132	1.459	12.362	***	169.281
	Model X^2 = 13.784, df = 3, p = 0.003 Concordance 77%, n = 84 (retain all = 22, release all or some = 62)						
Hook Shape	Sharks need to be protected*	1	0.478	0.201	5.675	*	1.614
	Value of catching a shark	1	1.243	0.407	9.313	**	3.467
	Importance of releasing a shark in good condition	1	-0.841	0.494	2.897	ns	0.431
	Model X^2 = 12.961, df = 3, p = 0.005 Concordance 65%, n = 95 (Circle = 40, J-hook = 55)						
Leader Material	Existence value of sharks	1	-1.055	0.477	4.885	*	0.348
	Sharks need to be protected*	1	-0.403	0.183	4.861	*	0.668
	Constant	1	1.773	1.040	2.908	ns	5.887
	Model X^2 = 9.061, df = 2, p = 0.011 Concordance 76%, n = 106 (Wire = 86, Monofilament = 26)						

BELIEF ORIENTATIONS AND BEHAVIOUR

Logistic regression models revealed that anglers that placed a higher value on catching sharks were more likely to fish for pelagic sharks (Table 3.3). Tournament anglers' decision to practise catch and release was influenced by positive beliefs around existence value of sharks, while the question of whether more regulations were required for fishing of sharks was also included in the model (Table 3.3).

Anglers were more likely to use circle hooks if they placed greater value on catching sharks and had more positive beliefs around the protection of sharks (Table 3.3). The importance of releasing a shark in good condition was also included in the hook shape model (Table 3.3). Beliefs around existence value of sharks as well as the belief that sharks need to be protected led to an increased use of monofilament leader (Table 3.3). Model concordance statistics show that the predictive accuracy of the models was quite high for catch and release, hook shape, and leader material, while the model related to the targeting of pelagic sharks was weaker (Table 3.3).

DISCUSSION

Levels of fishing effort by tournament anglers in this survey (44.5 days/year) are much higher than the reported national average of 6.13 days/year for recreational fishers (Henry & Lyle, 2003). This is consistent with previous studies, which have found that tournament anglers spend more time fishing than non-tournament anglers (Arlinghaus *et al.*, 2007; Wilde *et al.*, 1998). Because fishing is more central to the lives of tournament anglers, as indicated by their greater frequency of fishing, it is reasonable to expect them to be better informed, more politically organised and active, and generally more supportive of management rules and programs (Ditton *et al.*, 1992). The sex bias represented in our sample (95% male) when compared to the national average (68% male) reported by (Henry & Lyle, 2003) is similar to bias reported between tournament and non-tournament black bass anglers (Wilde *et al.*, 1998) and saltwater anglers (Oh *et al.*, 2006) in Texas.

The catch of pelagic sharks reported by anglers in this study was dominated by *I. oxyrinchus*, with a small number of *A. vulpinus* accounting for the remaining of the catch. The number of *I. oxyrinchus* that anglers reported tagging in this study represents 39% of those tagged by tournament anglers nationwide during this period (*NSW DPI Game Fish Tagging Program Report 2011 -2012*, 2012; *NSW DPI Game Fish Tagging Program Report 2012 -2013*, 2013). Based on these numbers, the total annual catch by tournament anglers is likely to be more than double the 445 caught by respondents to this survey, with approximately 60% of these sharks being released. In comparison, annual recreational catches of *I. oxyrinchus* are estimated to be in the order of 1200–1500 individuals and therefore, tournament anglers should be considered as key stakeholders in the management and conservation of this species (Bruce, 2014). Pelagic sharks have been identified as particularly vulnerable to exploitation and the cumulative effects of commercial exploitation and recreational catch requires further investigation (Dulvy *et al.*, 2008).

This study found some concordance between general beliefs about sharks and anglers' specific behaviours. Unsurprisingly, anglers that placed a high value on catching a shark were more likely to target pelagic sharks and were more likely to use circle hooks. Anglers that valued the existence of sharks and the held the belief that sharks need to be protected also had higher usage of gear types that are recommended for the catch and release of sharks. However, almost all anglers had very strong beliefs around the value of releasing sharks in good condition, and we would therefore expect higher rates of gear use that is recommended to increase the chance of post release survival than we recorded in this study (Arlinghaus *et al.*, 2007; McLoughlin & Eliason, 2008).

Catch and release of pelagic sharks was common in this study with over half of the respondents releasing some or all of the sharks that they had caught. Despite the over a decade of education around the benefits of catch and release fishing, the release rate recorded for sharks in the present study (61%) was lower than the release rate (82 %) for sharks and rays reported by recreational anglers nationally in 2000-2002 (Henry & Lyle, 2003). This rate was also lower than the rate (96 %) reported for sharks and rays within the Great Barrier Reef Marine Park (Lynch *et al.*, 2010). Reasons for releasing sharks are also very different between anglers in the GBRMP, who released sharks because they believed that they were inedible, whereas most anglers in this study released pelagic sharks for competition or because they were either too big or too small. The differences in motivations to release sharks between these two studies can be explained by the fact that the majority of sharks caught by anglers in the GBRMP are incidental captures while pelagic sharks are more commonly caught through targeted fishing. In addition, pelagic sharks are considered more edible than many sharks and ray species captured in the GBRMP. This is confirmed by the prevalence of anglers in this study that retained sharks for consumption and the strength of anglers' beliefs that they would rather catch sharks than other fish and that they are good to eat. Considering the varied motivations for targeting and releasing sharks throughout Australia, future fisheries management research should investigate angler motivations and behaviours to comprehensively understand the threats posed to sharks by anglers.

Game fishing tournaments in Australia award prizes for both capture, where the fish is retained, and for tagging (catch and release), which is highly encouraged at many tournaments (Lowry & Murphy, 2003). Previous research on saltwater anglers (Oh *et al.*, 2006) and black bass tournament anglers in Texas (Wilde *et al.*, 1998) has shown a preference for the promotion of catch and release in tournaments. Competition points and records were cited as reasons for both releasing (30%) and retaining (33%) by tournament anglers in this study. Tagging for competition ranked as the equal most important reason given for releasing sharks, while retaining sharks for competition ranked second, only behind consumption (69%), as a reason for retaining pelagic sharks. The high rankings of competition-based responses emphasise the importance of the structure of tournaments to the catch and release behaviour of anglers and the potential for tournament organisers to promote catch and release by tournament anglers.

Relationships between anglers' beliefs and behaviours when targeting pelagic sharks provided an insight into the driving factors behind these behaviours. We acknowledge that there are limitations in the analysis of the effect of beliefs on behaviours in the current study. Firstly, respondents held generally positive views towards sharks making the test performed in this study a comparison of anglers who held positive views with those who held strongly positive views about sharks. Our survey also asked questions that ascertained anglers' general beliefs around sharks, but not their attitudes towards specific behaviours. To better understand the correlation between belief and behaviour, future research should measure beliefs that are specific to that catch and release behaviour of tournament anglers (Ajzen, 1991; Kollmuss & Agyeman, 2002; McLoughlin & Eliason, 2008). Anglers' response to belief statements may have been influenced by a desirability bias, where respondents answer inaccurately to represent themselves in the most socially correct or acceptable way (Nederhof, 1985). This bias could explain some of the disparity between the beliefs and behaviours that we recorded, however, we would expect this bias to also affect anglers' responses to behaviour questions. Future research could use indirect questioning methods to investigate this further (Thomas *et al.*, 2014). Finally, when considering the behaviours of tournament anglers we must also consider what effect perceived social norms will have on these behaviours (Madden *et al.*, 1992). For example, anglers may believe that the use of J-style hooks is widely accepted when targeting pelagic sharks and this may be influencing their hook choice despite a desire to release sharks in a good condition. Increases in the practice of catch and release and use of best practice may have a broader influence on the behaviours of tournament angler and the general recreational fishing population through changes to the perceived social norms around these behaviours. Game fishing clubs currently play a role in educating anglers, encouraging catch and release, and improving angling practices through promotion of best practice.

CONCLUSIONS

The results of this study indicate that an increase in advocacy for the existence of sharks should lead to higher rates of catch and release. Anglers that place greater value on catching sharks are more likely to target pelagic sharks but also have higher use of best practice methods. Increased emphasis on tagging competitions at tournaments, promotion of catch and release and development of best practice guides should improve the sustainability of tournament angling in relation to pelagic shark populations. The lack of relationship between tournament anglers' desires to release sharks in a good condition and the use of best practice requires further investigation. The positive attitudes towards sharks recorded by this study show that the tournament anglers will be accepting of measures that improve management of these species. Subsequent changes to the behaviours of tournament anglers may also have a broader influence on the behaviours of recreational anglers when targeting pelagic sharks and through changing perceived social norms.

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Pelagic shark survey

SECTION 1 – These questions focus on fishing for Pelagic Sharks (Mako, Thresher and Porbeagle)

In the past 12 months, how many days have you fished for pelagic sharks (Mako, Thresher and Porbeagle)?

……………………….

Approximately how much have you spent on your boat and tackle specifically to fish for pelagic sharks?

$....................

In the past 12 months, how many sharks have you caught?

Mako:………………… Thresher:………………. Porbeagle:……………………

How many (if any) of these sharks were released?

Mako:………………… Thresher:………………. Porbeagle:……………………

How many (if any) of these sharks were tagged prior to being released?

Mako:………………… Thresher:………………. Porbeagle:……………………

If sharks were released, what were your reasons for releasing them?

If sharks were retained, what were your reasons for retaining them?

What types of hooks do you use when fishing for pelagic sharks?

Hook Shape: Circle J Hook Other

Material: Stainless steel Non stainless steel

Leader type: Monofilament Wire Other

Do the fishing restrictions on sharks limit your fishing experience?

Yes No

What do you think is happening to the numbers of pelagic sharks?

Increasing Decreasing Stable

SECTION 2- General attitudes towards sharks

Please tick the box corresponding to your response to the statements provided.

Statement	Response				
	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
I like to ensure that a shark is released in a good condition					
I would be willing to use tackle and special handling practices that minimise damage to released sharks					
It is important to me that all the fish I release survive					
Catching a shark adds to the enjoyment of my fishing trip					
I prefer to catch fish rather than sharks					
Sharks are good to eat					
I enjoy the challenge of catching a shark					
I target sharks when I go fishing					
More regulations are required for recreational fishing of sharks					
Commercial fishing is a threat to shark populations					
Recreational fishing is a threat to shark populations					
Sharks need to be protected					
It is important to have viable sharks populations					
It would be better if there were fewer sharks in the sea					
Sharks are a sign of a healthy marine ecosystem					
Sharks should be conserved as they have a right to exist					

SECTION 3- General Demographic

Age: .... Sex: M F Postcode: ....

Education:

High school or less University degree or higher Trade or apprentice

How many years have you been fishing for?

…………………………..

How many days a have you spent fishing in the last 12months?

……………………..

On your last fishing trip how much did you spend on;

Fuel $................ Bait $................ Tackle $................ Ramp Fees $................

Other $................

4

SPATIAL AND TEMPORAL TRENDS IN GILLNET BYCATCH OF A THREATENED MIGRATORY SPECIES IN A COMPLEX MULTISPECIES FISHERY

ABSTRACT

Commercial fisheries are one of the major threats to populations of pelagic sharks globally. Analysis of catch rates and the factors that explain catches of pelagic sharks assists in the understanding of the impact a fishery may have on shark populations. Catch rates of non-target elasmobranchs within gillnet fisheries have received very little attention despite the threatened status of many of these species. This chapter presents 15 years of standardised catch rates for common thresher sharks (*Alopias vulpinus*) caught by gillnets within the Southern and Eastern Shark and Scalefish Fishery (SESSF). Data from 111,923 gillnet sets was analysed, with 97.4% of sets not recording catches of *A. vulpinus*. Zero-inflated generalised linear models were used to investigate variables contributing to changes in catch rates and to standardize estimates of catch-per-unit-of-effort (CPUE). While standardised CPUE peaked in 2010, no discernible trend was apparent between 2000 and 2015. Area closures and other management measures within South Australian waters, has coincided with a decrease in gillnet effort and catch of *A. vulpinus* throughout the fishery. While we recognise the limitations of fishery-dependent data and the use of effort measures for non-target species, this study provides support for the assertion that *A. vulpinus* catch rate is stable within the SESSF. Season and depth were the most important explanatory variables with high CPUE in summer and an inverse relationship between CPUE and depth. These findings provide further support for the use of spatial and seasonal management approaches to mitigate the bycatch of listed and protected large marine fauna and is consistent with findings for other gillnet fisheries.

Introduction

The threatened status and extinction risk of elasmobranchs (sharks, skates, and rays) have recently been the focus of many studies and reviews (e.g. Davidson *et al.*, 2015; Dulvy *et al.*, 2014; Field *et al.*, 2009). Increasing exploitation and trade in shark products, an expansion in the geographical range of fishing fleets and the under-management of shark bycatch all contribute to the challenge of conserving shark populations (Dulvy *et al.*, 2017). High exploitation rates of pelagic sharks and life history traits that result in a low intrinsic rate of population increase contribute to the high proportion of threatened species within this group (Dulvy *et al.*, 2008; García *et al.*, 2008). The threatened status, along with the recognition that many pelagic sharks are migratory species with large ranges that extend across multiple jurisdictions, has resulted in their listing, protection and management under international agreements such as the Bonn Convention on the Conservation of Migratory Species of Wild Animals (CMS) and resolutions by various regional fisheries management authorities (Compagno *et al.*, 2008; Lyster, 1989; Techera & Klein, 2014; Techera & Klein, 2017).

Prior to the adoption of ecosystem based fisheries management, far less consideration has been given to the management of bycatch species when compared to the management of target species (Barker & Schluessel, 2005; Dulvy *et al.*, 2008). The number of sharks caught as bycatch has also been more difficult to estimate (Braccini *et al.*, 2011; Dulvy *et al.*, 2017). Management of target catch and bycatch often relies on the analysis of fisheries-dependent datasets but these data are typically less rigorously collected and recorded in commercial logbooks for bycatch species and are often wrong (Macbeth *et al.*, 2018; Maunder & Punt, 2004). This provides significant challenges for standardizing catch rates for non-target species using fishery-dependent datasets (Braccini *et al.*, 2011; Braccini *et al.*, 2006; Maunder & Punt, 2004).While subjective data subsetting procedures can be used to refine fishery-dependent datasets to present standardised catch rates, applying these to infer an index of abundance for bycatch species is not recommended due to the inherent uncertainty around the definition of targeted effort for these species (Braccini *et al.*, 2011). The analysis of fishery- dependent datasets can be used to identify factors that lead to increased bycatch and to develop strategies that fisheries may minimise interactions with bycatch species. A better understanding of these factors is also crucial in assessing the vulnerability of non-target species and for their effective management at a national and regional level (Campana *et al.*, 2009; Maunder & Punt, 2004).

To date, longline and trawl fisheries remain the focus of the majority of the research on shark bycatch (Molina & Cooke, 2012). Relatively little attention is given to the potential impacts of bottom-set gillnet fisheries despite the increased mortality rates for obligate ram ventilators, such as pelagic sharks, when compared to other gear types (Dapp *et al.*, 2016b). The combination of the paucity of data and high mortality rates experienced by pelagic sharks in gillnet fisheries present significant challenges for the management and conservation of these species. While positive catches in logbooks are considered fairly accurate, it is often impossible to distinguish between the reasons for zero catches (Barreto *et al.*, 2015; Baum *et al.*, 2003).

The Southern and Eastern Scalefish and Shark Fishery (SESSF) is a multi-species and multi-gear type fishery considered to be the most important chondrichthyan fishery in Australian waters (Braccini *et al.*, 2011; Smith & Wayte, 2005) and was valued at AU$72.2 million in 2013–14 (AFMA, 2015a). The Shark Gillnet Sector of the SESSF extends from the South Australian/West Australian border eastwards to the Victorian/New South Wales border including the waters around Tasmania (Fig. 4.1). The fishery includes parts of the state waters of South Australia and Tasmania, while targeted shark fishing is prohibited within 3 nm of the

Victorian coast (AFMA, 2014c). Gillnets are restricted to waters shallower than 183 m and there are currently 117 vessels licenced in that fishery (AFMA, 2014b).

Changes in target species and fishing methods over time, including the introduction of new technologies, changes in gear specification, management measures and market demands all have effects on catch rates of bycatch and byproduct species within a fleet (Barreto *et al.*, 2015). In 2000, management of shark fishing was ceded to the Commonwealth with extensive closures of coastal waters of South Australia, Victoria, and Tasmania (SharkRAG, 2011; Stobutzki *et al.*, 2010). The SESSF has undergone many changes that may affect the catch rates of shark bycatch species, including gear changes, such as the implementation of 6–6.5 inch mesh throughout the gillnet fishery in 1997 to reduce catches of school sharks (*G. galeus*) in favour of the more productive gummy sharks (*M. antarcticus*), and the reduction of the net drop to a maximum number of 20 meshes in 2014 to reduce bycatch of semi-pelagic shark species by limiting the height of the net from the seabed (AFMA, 2014c; SharkRAG, 2011). Other management regulations that might have affected catch rates of pelagic sharks include: the exclusion of shark gillnets in waters deeper than 183 m introduced in 2007; exclusion zones around South Australian islands to reduce interactions with Australian Sea Lions (*Neophoca cinerea*) implemented between 2009 and 2010; the 2011 closure of the Cooorong Dolphin Zone; and the 2012 closure of Australian Sea Lion Management Zones and the subsequent increases in monitoring requirements (AFMA, 2010; AFMA, 2014a; AFMA, 2014b).

The common thresher shark (*Alopias vulpinus*), along with the bigeye thresher shark (*A. supercciliosus*) are circumglobally distributed while the pelagic thresher shark (*A. pelagicus*) is restricted to the Indian and Pacific Oceans (Compagno, 1984). All three species are present in Australian waters, although *A. vulpinus* is more frequently encountered in coastal and temperate waters and is the most commonly caught pelagic shark in the SESSF.

There is no targeted commercial fishery for *Alopias* spp. in Australian waters, but are targeted sporadically by recreational fishers and taken as bycatch in some commercial fisheries (Braccini *et al.*, 2012; Stevens & Wayte, 1999). Declines in *A. vulpinius* populations, based on reductions in longline catch rates, have been recorded in areas of the Mediterranean Sea, the northeastern Pacific Ocean, and northwestern Atlantic Ocean (Cortés *et al.*, 2007; Ferretti *et al.*, 2008; Hanan *et al.*, 1993; Maguire, 2006). *Alopias* spp. were listed as migratory species in Appendix II of the CMS in 2015 based largely on these declines (CMS, 2017). As a signatory to the CMS, Australia is committed to progress agreements covering the conservation and management of migratory species included in Appendix II. Following the listing of *Alopias* spp., the Australian government filed a reservation due to the listing being based on population declines in the northern hemisphere (Lyster, 1989; CMS Secretariat, 2015).

Given the recent listings of *Alopias* spp. on Appendix II of the CMS and the requirement to conserve these species, it is necessary to determine the level of catches of *A. vulpinus* within Australian waters. Despite the reservation by the Australian government on the listing of *Alopias* spp. on the CMS, information on these species currently remains inadequate to make an assessment of their vulnerability to specific fisheries in Australian waters. Our analysis focusses on *A. vulpinus* due to the paucity of data of this species in this region, the frequency of catches of this species within the SESSF, the recent conservation concerns raised by population declines in the northern hemisphere, and its internationally-recognised status as a threatened highly migratory species (HMS). The range of management changes to the gillnet fishery of the SESSF provides a unique challenge in investigating bycatch trends in this fishery. Our objective is to investigate spatial trends in the bycatch of *A. vulpinus* within the gillnet sector of the SESSF. We identify factors that have the greatest influence on catch rates of *A. vulpinus* in this fishery and provide recommendations to mitigate the bycatch of this species. We aim to understand these catch rates in the context of changes to the fishery over time, while recognising the limitations of fishery-dependent data for non-target species.

METHODS

Data for all vessels known to use demersal gillnets within the SESSF were sourced from the Australian Fisheries Management Authority (AFMA) database for the period between January 2000 and December 2015. Commercial vessels operating within the SESSF are required to record their catch in logbooks to provide a continuous record of fishing operations. Logbook records generally provide gear, vessel, effort, and the weight or number of the catch and bycatch. As a bycatch species, *A. vulpinus* catches are most commonly recorded as number of individuals (nominal catch) rather than as weight of catch. Effort data, most commonly recorded as metres of net set, also include location, date, time, and depth. Nominal catch of *A. vulpinus* as well as effort (km of net set) was calculated in a one degree grid with areas representing the operation of less than five vessels excluded due to the confidentiality of commercial catch data (Fig. 4.1).

Figure 4.1 has been removed due to confidentiality

Figure 4.1 (A) Nominal gillnet catch of *Alopias vulpinus* and **(B)** cumulative gillnet effort (km of net) for the SESSF in southeastern Australia, 2000–2015. Data combined over 1 degree with cells representing data from less than 5 boats excluded. Points over land represent effort in boxes directly adjacent to the coastline.

DATA SUBSETTING

Following an initial investigation of the data, a subsetting procedure was adopted to refine the dataset used to model *A. vulpinus* catch rates. Records that were incomplete or missing the information required for CPUE standardisation (no effort information, depth, gear type, or location) were removed from the dataset. Effort records beyond the range of the species (e.g. records on land) or the fishery (e.g. records deeper than 183 m) were eliminated by removing data records outside the geographical range of reported catch using a 1 degree^2 filter (Austin & Meyers, 1996). Due to the infrequency of *A. vulpinus* catches in the SESSF and following similar subsetting procedures to Braccini *et al.* (2011), catch and effort data were used for vessels that reported catches of *A. vulpinus* over a minimum of five years of the time period. This process removed vessels from the dataset that either, did not, or infrequently reported catches of *A. vulpinus*. Forty-seven vessels (29%) met this criteria over the 16 year period of the dataset, representing 82.6% of the catches of *A. vulpinus* and 90.7% of the positive sets from the full data extract (Table 4.1). Only retained catches were analysed in this study as released sharks represented a very small proportion of the reported catch (0.005%).

Table 4.1. Summary of original extract and data subset used to standardize *A. vulpinus* catch and effort data from the gillnet sector of the SESSF in 2000–2015

	Full data extract	**Data subset**	**% data used**
Total nominal catch (*A. vulpinus*)	5,744	4,747	82.6
Number of vessels	162	47	29.0
Total Effort (Km of Net)	595,714	444,615	74.6
Number of positive sets	3,122	2,833	90.7
Number of zero sets	157,810	109,090	69.1

VARIABLES AND MODELLING OF CPUE

The dataset contained a large number of sets with zero catches, which could be missing values, unreported catches, or true zero catches. Positive catches in logbooks are considered fairly accurate, but zero catches are problematic so we adopted a zero-inflated GLM approach to model the distributions of the catches (Barreto *et al.*, 2015; Baum *et al.*, 2003). The zero-inflated GLM approach adopted in this study used a two-stage process where the pattern of occurrence of positive catches (count model) and zero sets (zero-inflation model) are modelled separately (Campbell, 2015; Trenberth, 1983). All variables were used to build the initial model with logarithm of effort (length of net in metres) included as an offset to model catch rates while maintaining the probalistic nature of the response variable (Barreto *et al.*, 2015) (Table 4.2). Both zero inflated Poisson (ZIP) and zero inflated negative binomial (ZINB) GLMs were conducted using the full set of explanatory variables and Vuongs test was used to select the most appropriate error distribution (Minami *et al.*, 2007; Vuong, 1989). Residual analyses were also used for model validation (Hoyle *et al.*, 2014).

Nominal catch was selected as the response variable and year was modelled as a categorical variable to detect annual variability. Temporal variation throughout the year was also included in the model using seasons defined by the austral meteorological definition as summer (December–February), autumn (March–May), winter (June–August), and spring (September–November). Fishing ground was separated into three areas to represent their proximity to various state waters. These areas were defined by the following boundaries: Area 1 - west of 141°E; Area 2 - east of 141°E and north of 40°S; and Area 3 - east of 141°E and south of 40°S (Fig. 4.5) These areas are hereafter referred to as South Australia (Area 1), Victoria (Area 2), and Tasmania (Area 3). Vessel was included in the model as a fixed categorical variable and depth was included as a continuous variable (Table 2)

Table 4.2. Response variables used in generalised linear models – *A. Vulpinus* catch per set (number of animals per set)

Predictor	**Type**	**Description**
Year	Categorical	2000–2015
Season	Categorical	1–4
Vessel	Categorical	Vessel name
Area	Categorical	South Australian, Victorian, and Tasmanian waters
Depth	Continuous	Average depth of net (metres)
Effort (offset)	Continuous	Length of net (metres)

The full zero-inflated negative binomial GLM is as follows:

$$\text{Catch} \sim \text{as.factor(YEAR)} + \alpha_1\text{AREA} + \alpha_2\ \text{SEASON} + \alpha_3\text{VESSEL} + \text{DEPTH}$$

$$|\ \text{as.factor(YEAR)} + \alpha_2\text{SEASON, Offset} = \log(\text{EFFORT}), \text{Dist} = \text{"negbin"}$$

A stepwise variable selection approach using Akaike information criterion (Akaike, 1992) was used to select the best fitted group of variables for standardisation (Table 4.3). The reduction in AIC values was also used to determine the relative importance of explanatory variables that significantly contributed to changes in catch rates. Interactions terms were not considered due to the limitation of computer capacity caused by the complex modelling of large number of gillnet sets (111,923 sets).

Annual mean catch rates were obtained by fixing the explanatory variables at their median values and standardizing by km of net set (Barreto *et al.*, 2015). Lower and upper confidence intervals (95%) for the yearly changes in relative CPUE were estimated using bootstrapping with 1,000 non parametric replicates using the final best fit model. All statistical analyses were conducted using R 3.2.2 (www.r-project.org). Zero-inflated models were developed using the function ‘zeroinfl’, available in the *pscl* package (Jackman, 2015) and bootstrapping was conducted using the function ‘boot’ from the *BOOT* package (Canty & Ripley, 2017).

RESULTS

DATA SUBSET

From 2000 to 2015, 5,744 *A. vulpinus* were reported caught in gillnets within the SESSF. Total gillnet effort in this study was approximately 444,615 km of net set which represented 69.5% of the effort in the fishery throughout the time period. Following data subsetting procedures, 4,747 (82.6%) sharks were included in CPUE analysis (Table 4.1). Distribution of fishing effort was concentrated in Bass Strait and in the eastern Great Australian Bight (Fig. 4.1). Of the 162 vessels that reported gillnet effort over the time period, 47 vessels met inclusion criteria and were included in the final data subset for catch rate analysis. Positive sets represented a very small proportion (2.6%) of the total sets providing justification for the use of a zero-inflated GLM approach. Number of vessels was greatly reduced during data subsetting due to the removal of vessels that reported no catches of *A. vulpinus* (59 vessels), or reported catches in fewer than 5 years (56 vessels).

TEMPORAL PATTERNS AND MODEL SELECTION

Overall, nominal catches of *A. vulpinus* were lowest in 2005 (151 sharks) and peaked in 2010 (610 sharks) (Fig. 4.2, Table 4.2). Likelihood ratio tests provided overwhelming support for the ZINB model over the ZIP model for *A. vulpinus* catches (V = 6.040, $p < 0.001$). The full model (model 1) had the lowest AIC value (AIC = 31,103) and highest convergence value (*Theta* = 0.0821). Zero-inflated GLM detected significant differences in 2002, 2004, and 2010–2015 for the binomial model, and for all years except 2010 for the count model. Standardised CPUE showed a relatively stable trend in catches throughout the time period with a peak in 2010 (Fig. 4.3). The 95% confidence intervals of the best fitting model showed the highest variability in the upper range of CPUE with peaks in 2003, 2004 and 2010. The AIC and BIC values showed, the full model (ZINB) provided the best fit for the data (Table 4.3).

The effects of explanatory variables including year, season, area, and depth were statistically significant in the full model. Percent changes in AIC and BIC as the result of stepwise variable selection indicated that season and depth explained more variability in CPUE than area or vessel (Table 4.3).

Season was a significant explanatory variable in the final ZINB model and contributed 1.5% to the percentage change in AIC (Table 4.3). Effort varied little throughout the year, yet catches and nominal CPUE were markedly higher in summer compared to other seasons (Fig. 4.4A-C). Catches of *A. vulpinus* were higher in summer in all years (Mean = 143 ± 69 individuals, Fig. 4.4) while gillnet effort remained consistent throughout the year (Fig 4.4B).

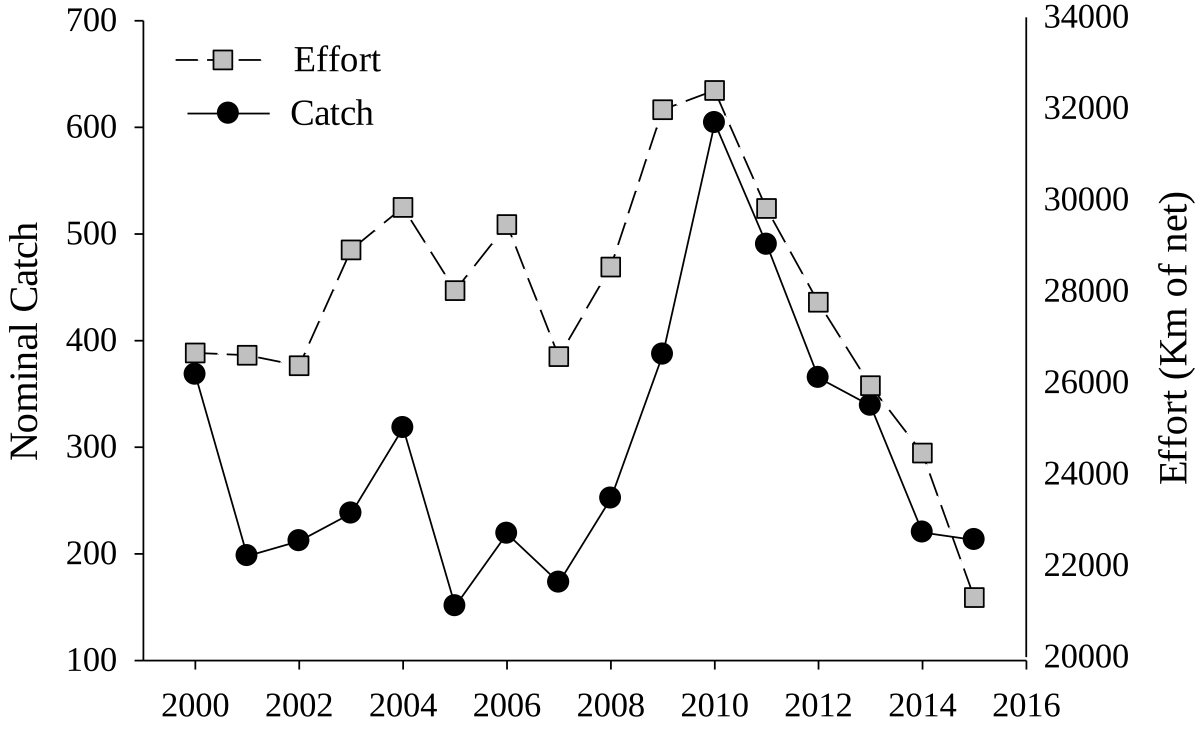


Figure 4.2. Nominal catch of *Alopias vulpinus* and effort for gillnets in the SESSF from 2000 to 2015.

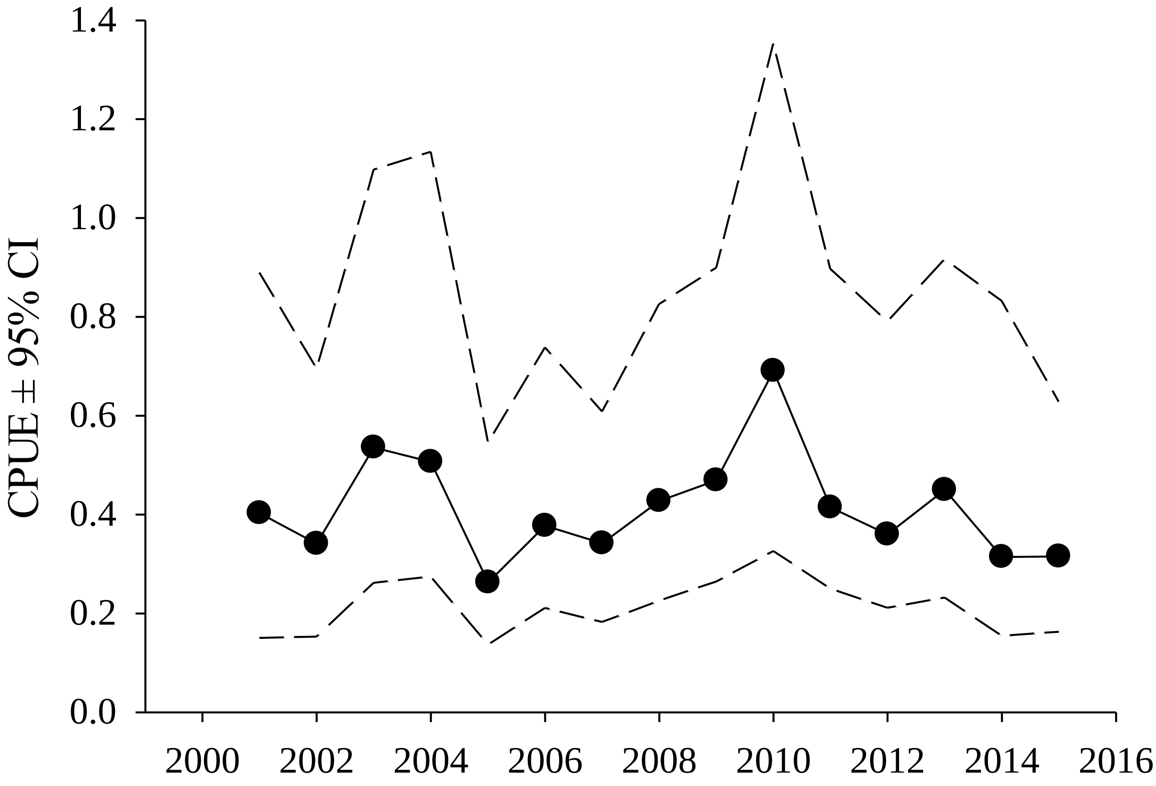


Figure 4.3. Estimated annual CPUE with 95% confidence intervals (dashed lines) for catches of *Alopias vulpinus* in gillnets within the SESSF based on bootstrapping of fixed variables of the zero-inflated negative binomial GLM.

Table 4.3. Model structure and changes in AIC and BIC among zero-inflated negative binomial GLM. Full model, in bold was selected for based on lowest AIC and highest convergence value (Theta).

Model	**Count Model**	**Zero inflated model**	**Theta**	**DF**	**AIC**	**Δ AIC**	**% AIC**	**BIC**	**Δ BIC**	**% BIC**
1	Year Season Area Vessel Depth	Year Season	0.0821	38	31103.7	-		31469.4	-	
2	Year Season Area Vessel Depth	Year	0.0644	37	31150.9	47.27	0.152	31507.1	37.64	0.120
3	Year Season Area Vessel	Year	0.0645	36	31619.8	468.85	1.505	31966.3	459.23	1.458
4	Year Season Area	Year	0.0666	35	31618.7	-1.1	-0.003	31955.6	-10.72	-0.034
5	Year Season	Year	0.0662	34	31619.4	0.75	0.002	31946.7	-8.88	-0.028
6	Year	Year	0.058	33	32104.8	485.34	1.535	32422.4	475.72	1.489

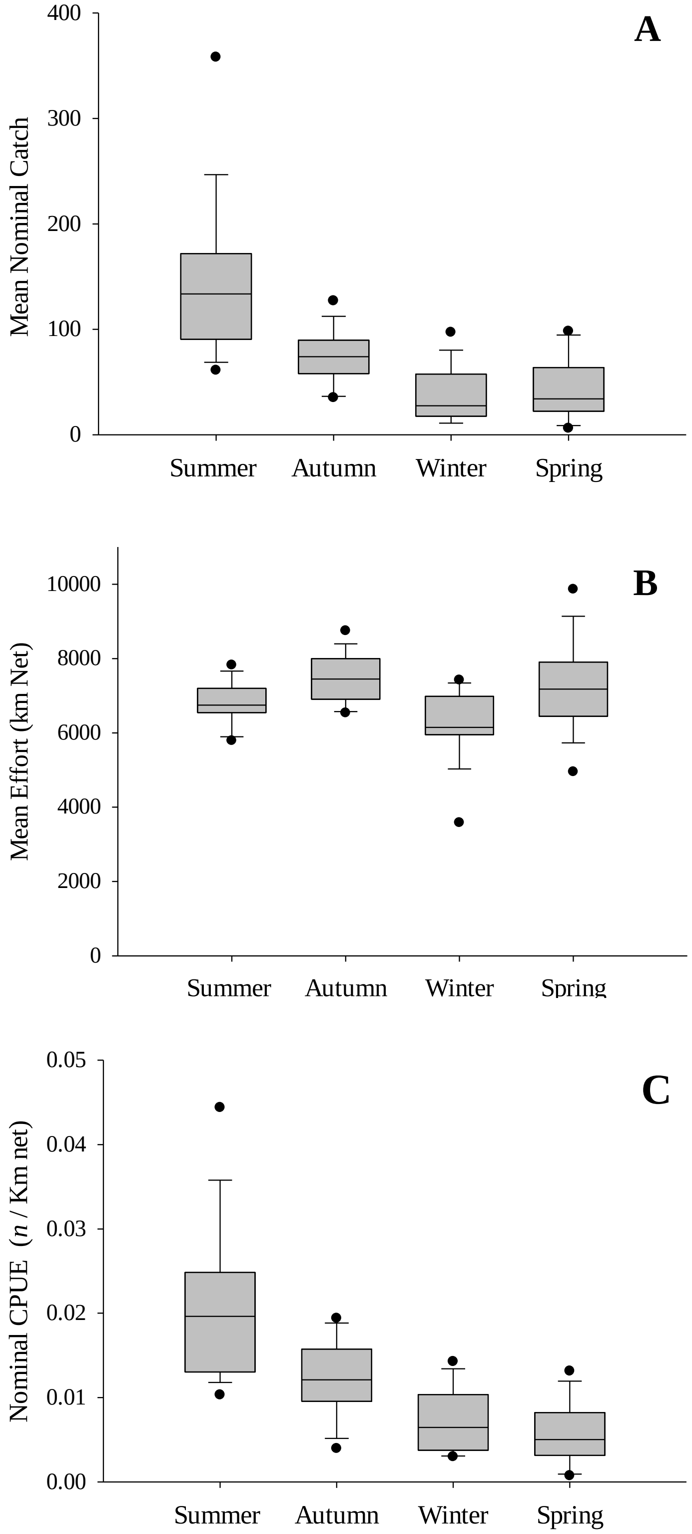


Figure 4.4. **(A)** Nominal catch, **(B)** effort and **(C)** nominal CPUE by season for gillnet sets included in the data subset from the SESSF 2000–2015. Boxes represent the median, 25th and 75th percentile, error bars represent the 10th and 90th percentile and dots represent the minimum and maximum.

SPATIAL PATTERNS OF OPERATION AND CATCH

Overall, fishing effort was higher in Victoria (46%) compared to South Australia (28%) and Tasmania (26%). Annual effort was more consistent in Victoria and Tasmania compared to South Australia (Fig 4.9). Area was also a significant factor in the best-fitted model, but only contributed 0.002% change in AIC. Large reductions in gillnet effort (>1,0000 km) in South Australia occurred between 2010 and 2012 with effort remaining low (<4,000km) from 2012 to 2015 (Fig. 4.5B). An increase in effort (≈4,500km) occurred in Victoria over the same period (2010–2012), but these reduced over the final years of the dataset (2012–2015, Fig. 4.5B). In Victoria and Tasmania, the majority of effort was concentrated in the Bass Strait region, while in South Australia the fishing effort was concentrated in the area of the Gantheaume Basin and the western coast of Eyre Peninsula (Fig. 4.1).

Annual catches of *A. vulpinus* peaked at 300 individuals in South Australia and 170 in Tasmania in 2010. The highest annual catch in Victoria of 243 individuals was recorded in 2012 (Fig. 4.5A). Annual nominal catch in South Australia was more variable (15–300 individuals) than either Victoria or Tasmania (56–243 and 39–170 individuals respectively, Fig. 4.5A). Catch rates were more variable in South Australia compared to the other states (Fig. 4.5C). Fishing effort was more evenly distributed over the area of the fishery compared to *A. vulpinus* catches. The majority (51%) of the catches came from eastern Bass Strait (Fig. 4.1). Other areas where a high proportion of catches were recorded included the Gantheaume Basin, between Cape Gantheaume and Cape Jaffa (21%), and Venus Bay (4%) (Fig. 4.1).

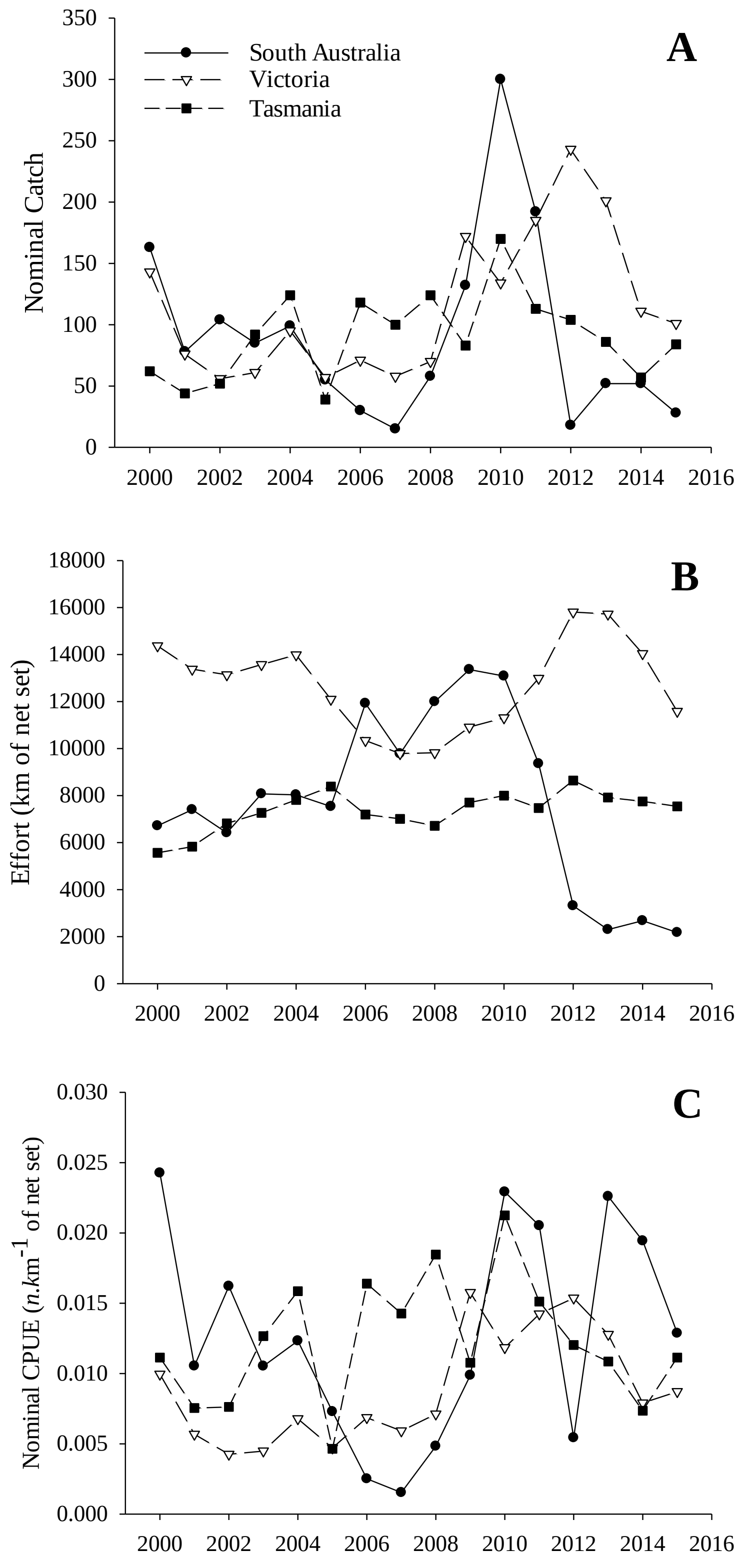


Figure 4.5. **(A)** Nominal catch, **(B)** effort and **(C)** nominal CPUE of *A. vulpinus* for gillnets in the SESSF from 2000 to 2015 for waters in the areas defined as South Australia, Victoria and Tasmania.

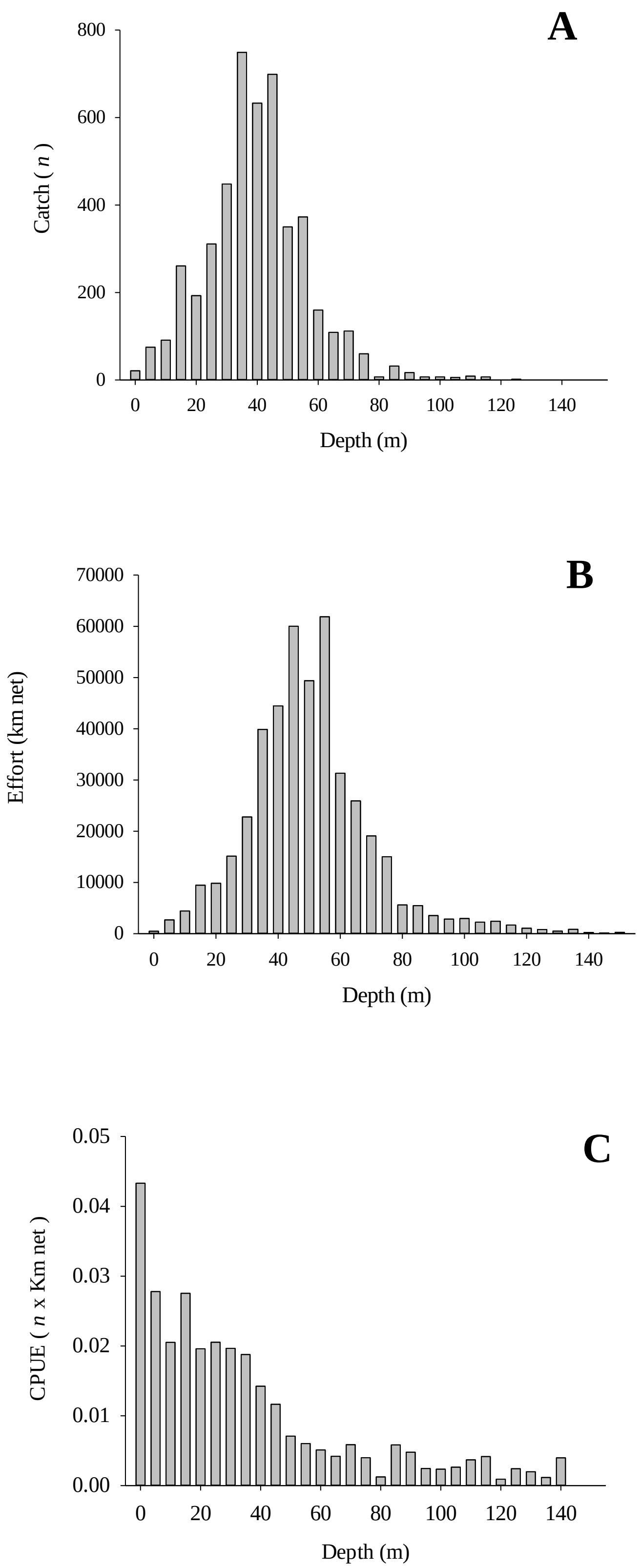


Figure 4.6 (A) Nominal catch, **(B)** effort and **(C)** nominal CPUE by depth of *A. vulpinus* from the data subset of SESSF gillnet vessels from 2000 to 2015.

The depth range of the SESSF analysed in this study was restricted to within 183 m, with the majority (85%) of *A. vulpinus* caught between 15 and 60 m (Fig. 4.6A). Depth was a significant explanatory variable in the final ZINB model, with percent change of 1.51% for AIC and 1.45% for BIC. Catches of *A. vulpinus* were recorded in shallower waters (Mean ± standard deviation: 44.4 ± 20.6 m) compared to the depth of non-positive sets (54.2 ± 36.6 m) or overall effort within the data subset (53.9 ± 36.3 m). The majority (76%) of effort concentrated between 30 m and 70 m (Fig. 4.6B). Resulting nominal CPUE of *A. vulpinus* was negatively correlated with depth with the highest catch rate (0.43 *n*/km net) in waters of <5 m and an average catch rate greater than 0.2 *n*/km net for waters shallower than 40 m (Fig. 4.6C).

DISCUSSION

Fishing mortality is one of the main threats to global pelagic shark populations, and resulted in *Alopias vulpinus* being listed as Vulnerable globally by the IUCN and included on Appendix II of the CMS (CMS, 2017; Goldman *et al.*, 2009). Studies investigating catch rates of *A. vulpinus* have previously focussed on pelagic longline (e.g. Cao *et al.*, 2011; Simpfendorfer *et al.*, 2002) or offshore drift gillnet fisheries (e.g. Hanan *et al.*, 1993; Urbisci *et al.*, 2016), with little information on bycatch of *A. vulpinus* from demersal gillnets. This study provides the first analysis of catch rates for *A. vulpinus* from Australian waters and the first analysis for a demersal gillnet fishery operating in coastal and shelf waters. Standardised catch rates for *A. vulpinus* showed no discernible trend over the 15-year period of this study. Season and depth were identified as the most important variables in the model of *A. vulpinus* catches within the SESSF with higher catch rates in summer and in shallower waters. While area had a relatively minor effect on catch rates, a high level of variation occurred in the level of effort expended within different state waters related to a range of area closures to reduce bycatch of marine mammal species within this fishery. Improved understanding of the factors influencing catch rates provides avenues to reduce the incidence of bycatch and manage this highly migratory species.

Fisheries-dependent data represent some of the only sources of information available in relation to fisheries sustainability and stock status for *A. vulpinus* in Australian waters. High levels of uncertainty relating to discard rates and underreporting of catches of non-target species has been highlighted previously for the SESSF (Braccini *et al.*, 2011; Walker & Gason, 2007). With the move towards ecosystem-based management of Australian fisheries an improved reporting for non-target species would be expected in the time period of the present study (2000–2015) compared to previous assessments of non-target species (e.g. *Callorhinus milli* 1976–2006) in this fishery (Braccini *et al.*, 2011; Pikitch *et al.*, 2004; Scandol *et al.*, 2005). The data subsetting procedure employed in the present study used similar criterion to those previously used in bycatch assessments for this fishery (e.g. excluding vessels and areas where catch was infrequently reported) to standardise the catch rates of *A. vulpinus* despite effort not being specifically directed at this species within the SESSF (Braccini *et al.*, 2011; Punt *et al.*, 2000). We acknowledge that our results are sensitive to these subjective judgements and the limitations created by subjective judgements in data subsetting should be considered when giving management advice based on these results.

Standardising the catch rates of bycatch species is a crucial step in assessing their vulnerability to fisheries (Maunder & Punt, 2004; Ortiz & Arocha, 2004). While there was a distinct peak in catches in 2010, there was no discernible trend in annual catch rates over the study period. The Californian Drift Gillnet fishery (CA-DGN), for *A. vulpinus* experienced declines of over 80% in catch rates in the 1980s prompting a change in target species to broadbill swordfish (*Xiphias gladius*) (Hanan *et al.*, 1993). Management measures that were implemented, i.e. reduction in fleet size and seasonal closures, resulted in the stabilisation of the catch and recovery of the stock to over half the estimated pre-fished biomass (PFMC, 2016; Smith & Aseltine-Neilson, 2001). Catches from the CA-DGN fishery demonstrates the rebound potential of *A. vulpinus*. While much lower levels of exploitation are present in the SESSF, bycatch of *A. vulpinus* should be monitored as extensive declines have also been observed in regions of high commercial exploitation, e.g., the Mediterranean Sea where *A. vulpinus* stock is estimated to have declined by over 95% (Ferretti *et al.*, 2008; Megalofonou, 2005).

Season and depth had the greatest effect on catch rates of *A. vulpinus* which were consistently higher during the summer months compared to the rest of the year. A similar pattern has been observed in the CA-DGN fishery where over 50% of the annual catch was taken between May and July. Catch rates of *A. vulpinus* in the present study were higher in shallow depths suggesting higher abundance or encounterability in inshore waters. The percentage of the water column covered by demersal gillnets, which is increased in shallower waters, may have contributed to the inverse relationship between depth and catch rate (Kraus *et al.*, 2017). Gear depth is an important factor in predicting bycatch rates of *A. vulpinus* and many other pelagic shark species (e.g. *A. superciliosus, Prionace glauca, Carcharhinus longimanus* and *C. falciformis*) caught in longline fisheries (Bigelow & Maunder, 2007; Cao *et al.*, 2011; Clarke *et al.*, 2013). While similar relationships between depth and catch rates of *A. vulpinus* have not previously been recorded in gillnet fisheries, satellite tagging studies have indicated that depth is an important factor in the selectivity of *A. vulpinus* to gillnets in Australian waters and in the CA-DGN fishery (Chapter 2; Cartamil *et al.*, 2010a; Cartamil *et al.*, 2011). In California, declines in *A. vulpinus* in the 1980s preceded a seasonal closure for all gillnetting within 75 miles of the coast within the area of the CADGN fishery (Hanan *et al.*, 1993; Holts *et al.*, 1998). These seasonal closures restrict fishing during the *A. vulpinus* pupping season, and have been an effective management measure to reduce the incidence of *A. vulpinus* bycatch, contributing to their recovery in this region (Hanan *et al.*, 1993; PFMC, 2016; Urbisci *et al.*, 2016).

In the present study, effort was concentrated between 30 and 80 m depth contours, which is consistent with other assessments of this fishery (Walker *et al.*, 2005). Limitations to the depths available to specific gear types were considered as part of a recent ecosystem-based management model of the SESSF, but targeted closures were shown to produce more balanced management outcomes across species for the fishery (Fulton *et al.*, 2014). In 2007, restrictions of the maximum depth range to 183 m for the gillnet sector of the SESSF were implemented to reduce incidence of *G. glaeus* catches (AFMA, 2016b). Similar limitations on the minimum depth range may provide a targeted approach to reduce the incidence of *A. vulpinus* bycatch within the SESSF. For example, restricting this fishery to waters deeper than 40 m would affect less than a quarter (23.6%) of effort but almost half (45.3 %) of *A. vulpinus* catches (AFMA, 2015b).

Although area did not have a large effect on catch rates, South Australia showed greater variability in catch and effort of *A. vulpinus* than the other states. This variability is likely to be reflective of the range of management measures that have been imposed on the fishery in that region (AFMA, 2014c). Large declines in effort in South Australia between 2010 and 2012 are reflective of gillnetting restrictions in South Australian waters following the introduction of area closures to reduce marine mammal interactions in the Gantheaume Basin (Coorong dolphin closure) and other areas of the eastern Great Australian Bight (AFMA Australian Sea Lion management strategy) (AFMA, 2010; AFMA, 2014a). The two main areas, the Gantheaume Basin and west coast of Eyre Peninsula, that were identified in this study to have produced the highest catches of *A. vulpinus* within South Australia are encompassed by these gillnet closures. The implementation of the Australian Sea Lion management strategy has resulted in area closures covering up to 70% of the fishery in South Australian waters (Knuckey *et al.*, 2014). In addition to closures, the requirement to carry observers on gillnet vessels in the majority of South Australian waters and the fact that this cost of this is borne by the vessel operator has resulted in large reductions in the number of vessels operating in this area (AFMA, 2010). This study observed steep declines in gillnet effort in the South Australia following the implementation of area closures, independent observer or camera coverage on gillnetting vessels. Some of the effort was initially displaced to Victoria between 2010 and 2012, but these levels of effort did not persist. While these management regulations were implemented to reduce bycatch of marine mammals, the subsequent reduction in fishing effort in South Australia has also had the benefit of reducing bycatch of other species, including *A. vulpinus*.

Although post-release survival rates for many non-target shark species caught by gillnets in the SESSF are high (e.g. *Heterodontus portusjacksoni* = 97%, *Cephaloscyllium laticeps* = 94% and *Squalus megalops* = 87%), post-release survival of *A. vulpinus* is much lower (18%) (Braccini *et al.*, 2012). In addition, at-vessel mortality for *A. vulpinus* is much higher (66%) in gillnets in the SESSF than for longlines in the southern California Bight (5%) (Braccini *et al.*, 2012; Hight *et al.*, 2007). Measures that prohibit the retention of all *Alopias* species have been introduced in the longline fisheries of the Western Tuna and Billfish Fishery (WTBF) in line with the a resolution by the Indian Ocean Tuna Commission (IOTC, 2012) and have been adopted by AFMA for the WTBF and the Eastern Tuna and Billfish Fishery (ETBF) (AFMA, 2018a; AFMA, 2018c). Given the low estimates of post-release survival for *A. vulpinus* in gillnets, management measures, such as a restrictions on retaining live sharks, are less likely to be effective. In the SESSF, demersal longlines are being considered as an alternative to gillnets in waters that are subject to gillnet closures (Knuckey *et al.*, 2014). While it is unclear what impact this may have on catches of *A. vulpinus*, the potential change from gillnets to longlines within South Australian waters provides an opportunity for improved survival of released *A. vulpinus*.

Conclusions

Understanding trends in catches of vulnerable non-target species is critical to their effective management and conservation. We found that catches of *A. vulpinus* in the SESSF were relatively low compared to other fisheries and were stable over the study period. This study highlights areas in eastern Bass Strait, Gantheaume Basin and western Eyre Peninsula as areas of high catches of *A. vulpinus*. The implementation of management measures for reducing the bycatch of marine mammals in South Australia has led to a decline in catches of *A. vulpinus* by the SESSF in this area. Potential exists to further reduce bycatch within the SESSF through restriction of gillnet effort in inshore and shelf waters (<40 m) and during times of peak catches in summer.

5

INFLUENCE OF TEMPERATURE, BATHYMETRY AND GEAR CONFIGURATION ON BYCATCH OF PELAGIC SHARKS IN AUSTRALIAN LONGLINE FISHERIES

ABSTRACT

Pelagic sharks are recognised as vulnerable to over-exploitation due to their interaction with open ocean fisheries and life history traits that result in a low intrinsic rate of population increase. Three thresher shark species (*Alopias* spp.), shortfin makos (*Isurus oxyrinchus*), porbeagles (*Lamna nasus*) and blue sharks (*Prionace glauca*) are all listed Appendix II of the Bonn Convention on the Conservation of Migratory Species of Wild Animals (CMS) and are commonly caught as bycatch and byproduct in Australian pelagic longline fisheries. We used fishery-dependant logbook data from 2000 to 2007 to investigate catch and effort trends for pelagic shark species caught in the Eastern and Western Tuna and Billfish Fisheries. Biophysical and operational variables were derived from *in situ* measurements and bathymetry data and included water depth, sea surface temperature, slope of the sea floor and depth of the gear. The relative importance of these variables to the spatially explicit catch composition and occurrence of pelagic sharks were investigated using a multivariate modelling approach. Models explained more than 20% of the variation in species composition, and for *P. glauca* and *I. oxyrinchus*, while those for *Alopias* spp. and *L. nasus* explained less than 10% of the variation. Sea surface temperature was identified as the most important variable explaining the species composition and the distribution of the catch of *P. glauca*, *I oxyrinchus*, and *L. nasus* while depth was the most important variable in predicting the catch distribution for *A. vulpinus*. Understanding the influence of these variables on the catch distribution of sharks provides avenues for the management of bycatch of these species in pelagic longline fisheries. Future studies should seek to validate fishery-dependant data using observed datasets and integrate these with tracking data to assess the spatial overlap between key species and fishery gear types that are most likely to lead to higher rates of bycatch.

INTRODUCTION

Pelagic ecosystems are increasingly under threat from anthropogenic impacts such as marine pollution, climate change, and the industrialisation and expansion of fishing fleets (Avio *et al.*, 2017; Gallagher *et al.*, 2014; Hoegh-Guldberg & Bruno, 2010; Horodysky *et al.*, 2016a). Despite a long history of research into the status of commercially targeted species in the open ocean our understanding of the impacts of fisheries on bycatch species is limited (Davies *et al.*, 2009; Maunder & Punt, 2004). Under the ecosystem-based approach to fisheries management (EBFM), more attention is being given to broad ecosystem consequences of each fishery (Pikitch *et al.*, 2004) particularly within the management jurisdictions of nations with progressive fisheries management regimes such as Australia, New Zealand, South Africa, Norway and the USA (Pitcher *et al.*, 2009) . One of the key elements of EBFM is the collection of catch data of non-target species (Fulton *et al.*, 2014; Pikitch *et al.*, 2004). Understanding the environmental preferences of bycatch species is central to understanding their susceptibility and encounterability to different fishing gears, and therefore assessing the suitability of different management regimes (Horodysky *et al.*, 2016a). In the case of pelagic fisheries, an understanding of the spatiotemporal distribution patterns of pelagic species is important (Coelho *et al.*, 2017). For example, identification of specific environmental and operational drivers of bycatch can aid in the spatial management of fisheries in the open ocean (Hazen *et al.*, 2017). This understanding provides a basis for reducing the incidental catch of non-target species which is a key objective of EBFM (Hahlbeck *et al.*, 2017).

Pelagic sharks are wide ranging, often highly migratory species (HMS) that inhabit the waters of the open ocean and over the continental shelf (Compagno *et al.*, 2008). Pelagic sharks have been identified as highly vulnerable to exploitation due to a combination of high encounterabilty to commercial fisheries and life history traits that result in a low intrinsic rate of population increase for many species (Dulvy *et al.*, 2008; Gallagher *et al.*, 2014). These factors have led to the listing of numerous pelagic shark species on Appendix II of the Conservation of Migratory Species of Wild Animals list of highly migratory species (CMS) over recent years (CMS, 2017). A suite of species, hereafter collectively referred to as 'pelagic sharks', that have been listed include: the blue shark (*Prionace glauca*); shortfin mako (*Isurus oxyrinchus*); porbeagle (*Lamna nasus*) and; three species of thresher sharks (*Alopias* spp.); including the common thresher shark (*A. vulpinus*), bigeye thresher shark (*A. supercciliosus*) and the pelagic thresher shark (*A. pelagicus*). These species, most commonly interact with Australian fisheries as bycatch in longline fisheries that target tuna (*Thunnus* spp) and billfish (*Istiorphoridae* spp). As a member country of the CMS, Australia is bound to endeavour to conclude agreements covering the conservation and management of migratory species included in Appendix II of the CMS (CMS, 2017).

Australia has a history of industrialised fishing by international fleets. The tuna longline fishery in the southern hemisphere was initiated by Japan in the 1950s, and licensed to fish within the Australian Exclusive Economic Zone (EEZ) when it was established as part of the 1979 United Nations Convention on the Law of the Sea (Ward & Hindmarsh, 2007). In 1997, foreign flagged longline vessels were excluded from fishing within the Australian EEZ (Stevens & Wayte, 2009). Australia is in a unique situation where large declines in longline fishing effort have occurred within the EEZ over the past two decades due to the exclusion of the international fleet and declines in fleet size and effort of domestic vessels in the Eastern Tuna and Billfish Fishery (ETBF) and Western Tuna and Billfish Fishery (WTBF) (Campbell, 2012). Assessments of the stock status have been conducted for most targeted stocks in Australian fisheries and some non-target shark species (e.g., *Callorhinchus milii*), but there remains a lack of comprehensive research on the status and trajectories of pelagic shark populations (Flood *et al.*, 2012).

Australia was one of the first nations to implement EBFM across many of its commercial fisheries (Costello *et al.*, 2012; Fulton *et al.*, 2014). Reducing the non-target catch of sharks within fisheries is considered an issue of medium-high priority under the Australian National Plan of Action for Sharks (DAWR, 2012). A range of management measures that are relevant to pelagic sharks have been incorporated within the management plans of Australia's tuna and billfish fisheries. The AFMA implements a 20 shark trip limit within both the ETBF and the WTBF and a 100 shark limit on the high seas, while, sharks must be landed with their fins still attached to the carcass (AFMA, 2009b). The use of wire traces was banned in the WTBF in 2001 and in the ETBF in 2005 and, since 2009, *I. oxyrinchus*, *L. nasus* and *Alopias* spp. that are landed alive must be released (AFMA, 2016a). Tuna fisheries in Commonwealth waters are managed by AFMA but operate across the jurisdictions of two regional fisheries management authorities (RFMOs). The WTBF operates within the jurisdiction of the Indian Ocean Tuna Commission (IOTC) while the ETBF is part of the Western and Central Pacific Fisheries Commission (WCPFC). IOTC resolutions, designed to facilitate the conservation of some pelagic shark species, such as a ban on the retention of live *Alopias* spp. (Resolution 12/09) have been taken up by the WTBF (AFMA, 2018c).

While the use of fishery-dependent data presents a range of challenges for fisheries managers and scientists, due to the logistical difficulty and cost involved in accessing pelagic ecosystems, these data often represent the only available information on many pelagic species in many regions (Maunder & Punt, 2004). In these cases, fisheries-dependent data provide researchers with opportunities to investigate key knowledge gaps in relation to pelagic shark distribution and relative abundance (Gilman *et al.*, 2008). The effects of environmental factors on species abundance is particularly difficult to determine for these highly mobile apex predators (Heupel & Simpfendorfer, 2014). The effects of these factors have previously been investigated for a range of shark species (Bigelow *et al.*, 1999; Campana *et al.*, 2011; Cao *et* *al.*, 2011; Heupel & Simpfendorfer, 2014). The objective of the present study was to use Australia's longline fisheries bycatch records to investigate the environmental and operational conditions that may predict an increased occurrence of pelagic sharks. We aimed to: 1) examine the spatial patterns in occurrence of pelagic sharks in the ETBF and WTBF; 2) investigate the patterns in environmental and operational variables in these fisheries; 3) identify which of these variables best explained the patterns in species composition and distribution for pelagic sharks and; 4) model the influence of these variables on the composition and distribution of pelagic sharks taken as bycatch within Australian longline fisheries. Due to the issues surrounding the use of fisheries-dependent data to create indices of abundance, we adopted a permutational modelling approach where we used the incidence of pelagic shark bycatch as a record of occurrence rather than using the catch rate. We restricted our analysis to pelagic shark species that are recognised to be threatened globally and contribute a large proportion of the shark bycatch within Australian waters (*P. glauca, I. oxyrinchus, L. nasus,* and *Alopias* spp.).

METHODS

DATA SOURCE

All commercial vessels operating in Australian waters record catch and effort data in daily logbooks that are provided to the Australian Fisheries Management Authority (AFMA) as a continuous record of fishing operations. We obtained an extract of all longline effort and bycatch of *Alopias* spp., *I. oxyrinchus, L. nasus* and *P. glauca* from 2000 to 2007 from the AFMA database. Effort information included operational variables (number of hooks set, gear configuration and sea surface temperature), fishing time and location (latitude and longitude), and the weight and number of the catch and bycatch. This time period was selected because *in situ* measurements of sea surface temperature (SST) and gear configuration (e.g. number of hooks between floats), used in the analysis, were not available for other periods.

LONGLINE FISHERIES

Pelagic longline equipment used to target tuna and billfish in Australian waters consists of a monofilament mainline hung in a sagging curve between two floats (Campbell & Young, 2012). A number of branch lines, terminated with baited hooks, are attached to the main line between floats. The number of branch lines between floats (hooks per float, HPF) is commonly used as a proxy for the depth range fished by a particular longline set (Beverly *et al.*, 2009; Ward & Myers, 2005a). Previous studies on the depth range of longline gear in the ETBF, found that all longlines deployed with less than 10 HPF fished very similar depths while longlines with more than 15 HPF fished considerably deeper depths (Campbell & Young, 2012). Based on these findings, data for HPF in the present study were combined into three categories: <10 HPF, 10–15 HPF and >15 HPF.

The WTBF includes all Australian waters to the west of the tip of Cape York in the north and the border between South Australia and Victoria in the south, including the waters around the Cocos Keeling Islands, Christmas Island and the high seas of the Indian Ocean (Fig. 1.1; AFMA, 2018c). The ETBF operates in Australian waters east from the tip of Cape York to the border between Victoria and South Australia including the waters around Tasmania, Lord Howe Island and the high seas of the Pacific Ocean (Fig. 1.1; AFMA, 2018a). Fishing within the ETBF is spread across a much larger latitudinal range than the WTBF and incorporates the northern swordfish fishery which characteristically sets its gear at a much greater depth (Fig. 5.1 and 5.2B).

DATA SUBSET

Spatial and temporal analyses were performed by analysing changes in occurrence rates within 1° grid squares where five or more vessels reported catches within that area over the time period. Records were rejected where the data needed for analysis were missing (no depth, SST, gear type, or location). To reduce the influence of vessels that did not consistently report bycatch of pelagic sharks, all effort data for vessels that recorded shark bycatch for fewer than 5 years of the time period were excluded. After removing records with anomalous values, and records from vessels that inconsistently recorded shark bycatch throughout the fishing periods, the dataset consisted of 89 396 longline sets and 31 527 sets recording the catch of one or more species of pelagic sharks.

Environmental Variables

The following variables were used to assess their influence on pelagic shark bycatch composition and occurrence: sea surface temperature (SST), ocean depth, slope of ocean floor and gear depth (HPF). Depth and slope were matched to start of set locations using the *'extract values to points'* tool in ArcGIS, ArcMap 10.3.1. The number of hooks between floats provided a measure of the approximate depth of the gear in the water column (<10 HPF = 0 – 80 m, 10 – 15 HPF = 20 – 160 m, and >15 HPF = 40 – 300 m) as estimated by Campbell and Young (2012). Mean SST and HPF were calculated for each square degree based on *in situ* measurements recorded by vessels.

Multivariate analysis

Permutational Multivariate Analyses Of Variance (PERMANOVA) were used to investigate bycatch composition of pelagic sharks within Australian longline fisheries at a spatial resolution of one degree. Permutational approaches have the advantage of not being constrained by many of the typical assumptions of parametric statistics (Legendre & Anderson, 1999). Bray-Curtis distance matrices were calculated using square-root transformed occurrence data to reduce the asymmetry of the species composition data. A Euclidean distance matrix was calculated for normalised gear (HPF) and environmental (SST, Depth, and Slope) variables. PERMANOVA for bycatch rates were based on unrestricted permutations of raw data with 999 permutations using a Type III (Partial) sum of squares. To address Aim Four, a distance-based linear model (DistLM) with stepwise regression as selection procedure, using Akaike Information Criterion (AIC) as the selection criterion, was used to derive the most parsimonious models predicting pelagic catch rates communities, and for the distance-based redundancy analysis (dbRDA) models (Anderson *et al.*, 2008). Individual DistLM were used to identify predictor variables (on the normalised scale) that contributed significantly to the patterns observed in the occurrence rate for each species as well as to determine how much variation was explained by environmental and gear variables. Distance based redundancy analysis (dbRDA) plots were used to visualise the results of the step-wise DistLM analysis with significant environmental variables plotted as vectors. (Fig. 5.4 and 5.5). Simple linear regression plots are provided to summarise the direction of influence on occurrence for the explanatory variables that explained the highest percentage of variation for each species. Analyses were performed in PERMANOVA+ as implemented in PRIMER version 6 (Anderson, 2005)

Table 5.1. Effort and number of vessels for the ETBF and WTBF during the period of this study (AFMA, 2008; AFMA, 2009a)

	WTBF		**ETBF**	
Year	**Hooks set (millions)**	**Active vessels**	**Hooks set (millions)**	**Active vessels**
2000/01	5.02	46	10.09	136
2001/02	6.08	50	11.8	143
2002/03	4.93	45	12.69	140
2003/04	2.61	25	11.11	131
2004/05	1.02	17	9.37	113
2005/06	0.81	7	9.33	92
2006/07	0.71	7	8.9	71

RESULTS

FISHERIES COMPARISON

Total effort in the ETBF and the WBTF declined between 2000 and 2007 in line with decreases in the number of active vessels. The largest reductions in active vessels and effort occurred in the WTBF (Table 5.1). During the period of the present study (2000–2007), the total number of hooks deployed by the WTBF reduced from ~4.91 million hooks in 2002 to approximately1.02, 0.81 and 0.71 million hooks in 2005, 2006, and 2007 respectively (Zhou *et al.*, 2009). Over the same period, the ETBF experienced a 50% reduction in the number of vessels operating in the fishery (Table 5.1). Within the ETBF the effort was concentrated along the shelf slope, around Lord Howe Island and extended into high seas areas outside of the Australian EEZ with the easternmost effort reported at 170°E (Fig. 1). Effort in the WTBF extended west to 102°E but was concentrated along the shelf slope, and within the Mentelle Basin off the southwestern coast of WA. The ETBF fished across a larger latitudinal range (10°S–40°S) than the WTBF (16°S–38°S).

Overall, nominal catches were dominated by *P. glauca* which comprised 85% of catches from the whole dataset with *I. oxyrinchus* contributing 13% and *Alopias* spp. and *L. nasus* contributing less than 1% to total catches. Catches in the WTBF, were dominated by one species (*P. glauca* ~ 95%) while in the ETBF all four species contributed to the catch (*P. glauca* ~ 65%, *I. oxyrinchus* ~ 32%, 2% *Alopias* spp. ~ 2% and *L. nasus* ~ 1%).

Figure 5.1 has been removed due to confidentiality.

Figure 5.1. Total longline effort (number of sets) within the WTBF and ETBF from 2000 to 2007. Data combined over total time period and into 1 degree with cells representing data from less than 5 boats excluded to maintain confidentiality of the data.

Initial inspection of the data highlighted differences in environmental and operational conditions in each fishery (Fig. 5.2). There was a clear latitudinal gradient in both fisheries with SST decreasing with increasing latitude. Overall, sea surface temperatures were slightly warmer in the ETBF (mean ± standard deviation: 23.66 ± 2.62°C) than the WTBF (20.84 ± 2.50°C) (Fig. 5.2A). Both fisheries predominantly used shallow set gear (<10 HPF). Vessels in the ETBF deployed the majority (90%) of their gear with <10 HPF, while 59% of gear was set with <10 HPF in the WTBF. Medium set gear (10–15 HPF) represented 40% of the gear set in the WTBF and only 5% of the gear set in the ETBF. Deep set gear (<15HPF) was almost exclusively used in northern area of the ETBF (6% of sets) with less than 1% of sets in the WTBF using deep set gear (Fig. 5.2B). Maximum depth of water fished was 6 036 m in the WTBF and 5312 m in the ETBF. Overall, the ETBF fished in slightly shallower waters (2 803 ± 1 271 m) than the WTBF (3 200 ± 1 630 m).

Figure 5.2 has been removed due to confidentiality.

Figure 5.2. Environmental variables for longline sets within the WTBF and ETBF from 2000 to 2007 by degree cell including; mean SST recorded *in situ* (A), most frequent categorical gear depth (B), mean ocean depth (C) and mean degree slope of ocean floor (D).

Figure 5.3 has been removed due to confidentiality.

Figure 5.3. Relative incidence of four pelagic shark species in longline sets within the WTBF and ETBF from 2000 to 2007 by degree cell including; *P. glauca* (A), *I. oxyrinchus* (B), *Alopias* spp. (C), and *L. nasus* (D). Data combined over 1 degree with cells representing data from less than 5 boats excluded.

SPECIES COMPOSITION

Based on 999 permutations in the 'RELATE' procedure, we found a significant relationship between catch and environmental and operational data ($p = 0.0001$; Spearman's rank correlation coefficient = 0.314). All four variables explained some of the variation in the patterns of pelagic species composition (Table 2). Sea surface temperature was the most important variable as shown by the spread of the data along the horizontal axis of Fig. 5.4 and explained 22.2% of the variation in the data. The catch composition in the ETBF was more influenced by HPF, Depth and Slope as shown by the greater spread of ETBF data along the vertical axis, however, this explained a small proportion (3.3%) of total variation in species composition (Fig. 5.4).

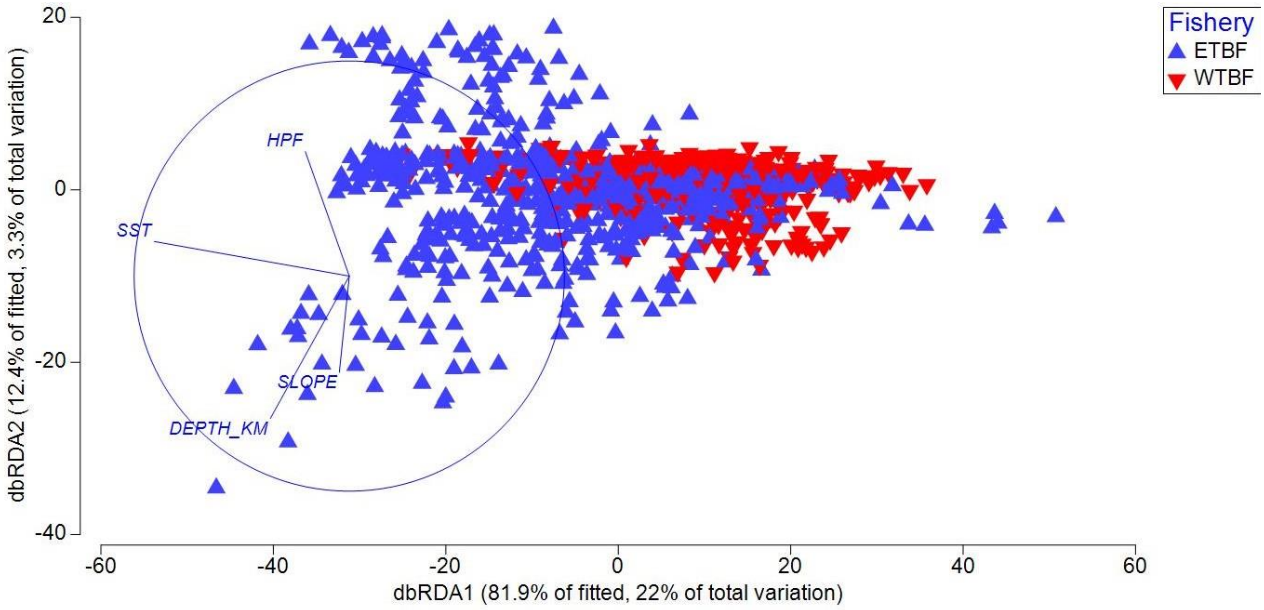


Figure 5.4. Distance-based linear model of species compositions by fishery for each location (square degree) from 2000 to 2007. Blue triangles represent areas within the ETBF and red triangles represent areas within the WTBF. Length and direction of the vectors within the circle indicate the strength and direction of the influence of the environmental variables selected by the DISTLM (Table 5.2).

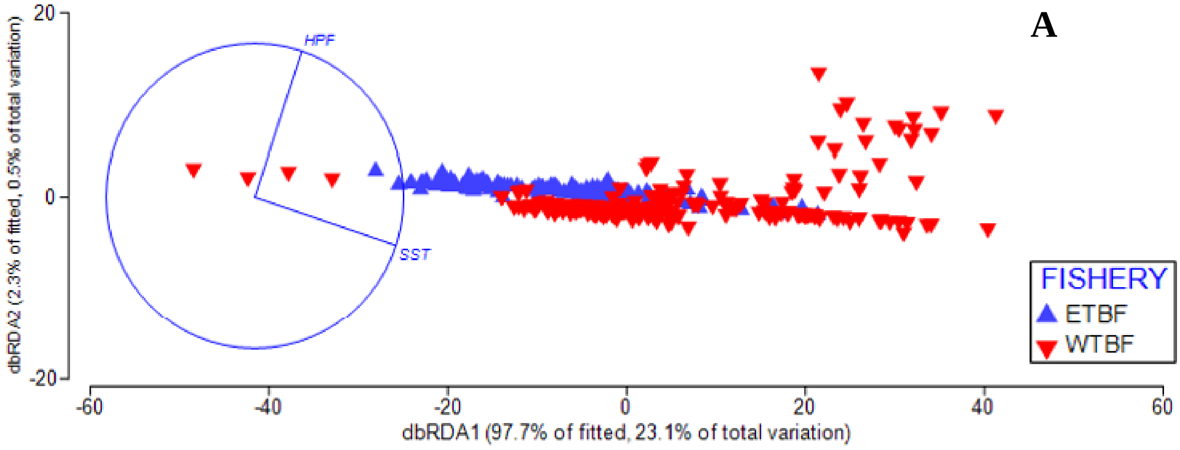
Table 5.2. Results of distance based linear model (DistLM) for species composition and pelagic shark species. Variables are listed in order of their contribution to explaining variation in the distribution of catches of pelagic sharks with only significant variables included. Percentage variation represents the explained variation attributable to each variable added to the model.

Model	Variable	Pseudo-F	P	% Variation
Species composition				
	SST	278.4	0.001	19.2
	Depth	71.6	0.001	4.7
	HPF	35.3	0.001	2.2
	Slope	13.2	0.001	0.8
Prionace glauca				
	SST	112.6	0.001	22.4
	HPF	6.1	0.009	1.2
Isurus oxyrinchus				
	SST	67.6	0.001	15.2
	HPF	52.5	0.001	12.2
	Depth	4.3	0.018	1.1
Alopias spp.				
	Depth	9.5	0.002	4.4
	HPF	6.0	0.004	2.7
	Slope	2.5	0.076	1.1
Lamna nasus				
	SST	10.2	0.001	6.6

Multivariate relationships by species

Distance-based linear models identified the environmental and operational variables that were most effective in explaining the distribution of pelagic shark catches. Sea surface temperature was the most important variable in explaining the variation in occurrence of bycatch for three species; *P. glauca*, *I. oxyrinchus* and *L. nasus* (Table 5.2). Sea surface temperature and HPF accounted for 23.6% of the observed variation in the occurrence of *P. glauca*. Rates of occurrence for *P. glauca* were negatively correlated with SST (Fig. 5.9). There was a high likelihood (62%) of *P. glauca* bycatch in colder waters (SST <19°C) when compared to warmer waters (SST >19°C = 23%). Occurrence rates were higher (42%) in medium set gear (10 – 15 HPF) when compared to shallow set gear (<10 HPF = 22%) or deep set gear (>15 HPF = 18%).

A combination of SST (15.2%), HPF (12.2%) and depth (1.1%) explained 28.5% of the variance for the model of *I. oxyrinchus* occurrence. Mean rates of occurrence of *I. oxyrinchus* were higher (22%) for longline sets in waters between 18 and 23°C when compared to colder (<18°C = 15%) and warmer waters (>23°C = 11%). Occurrence rates of *I. oxyrinchus* were also higher for shallow (>10 HPF) and medium (10 – 15 HPF) set gear (18% and 16% respectively) when compared to deep set gear (>15 HPF = 10%). Occurrence of *I. oxyrinchus* was slightly higher (21%) in longlines set in waters shallower than 1 000 m when compared to deeper waters (16%).



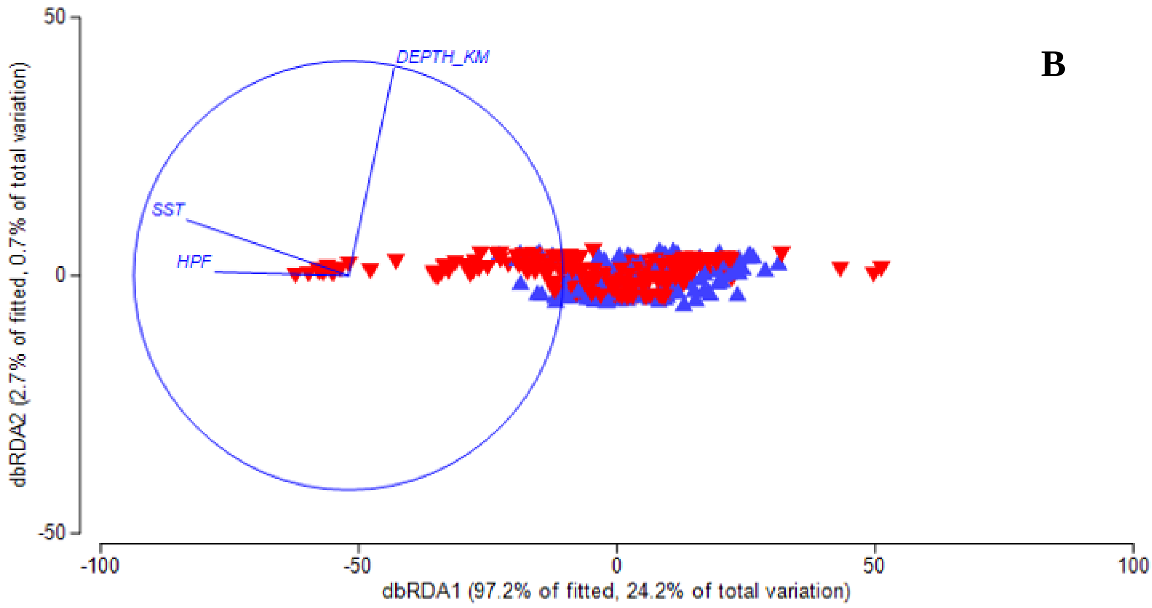


Figure 5.5. Multivariate relationship between catches within each square degree from 2000 to 2007 by fishery for *P. glauca* **(A)** and *I. oxyrinchus* **(B)**. Blue triangles represent areas within the ETBF and red triangles represent areas within the WTBF. Length and direction of the vectors within the circle indicate the strength and direction of the influence of the environmental variables selected by the DISTLM (Table 5.2).

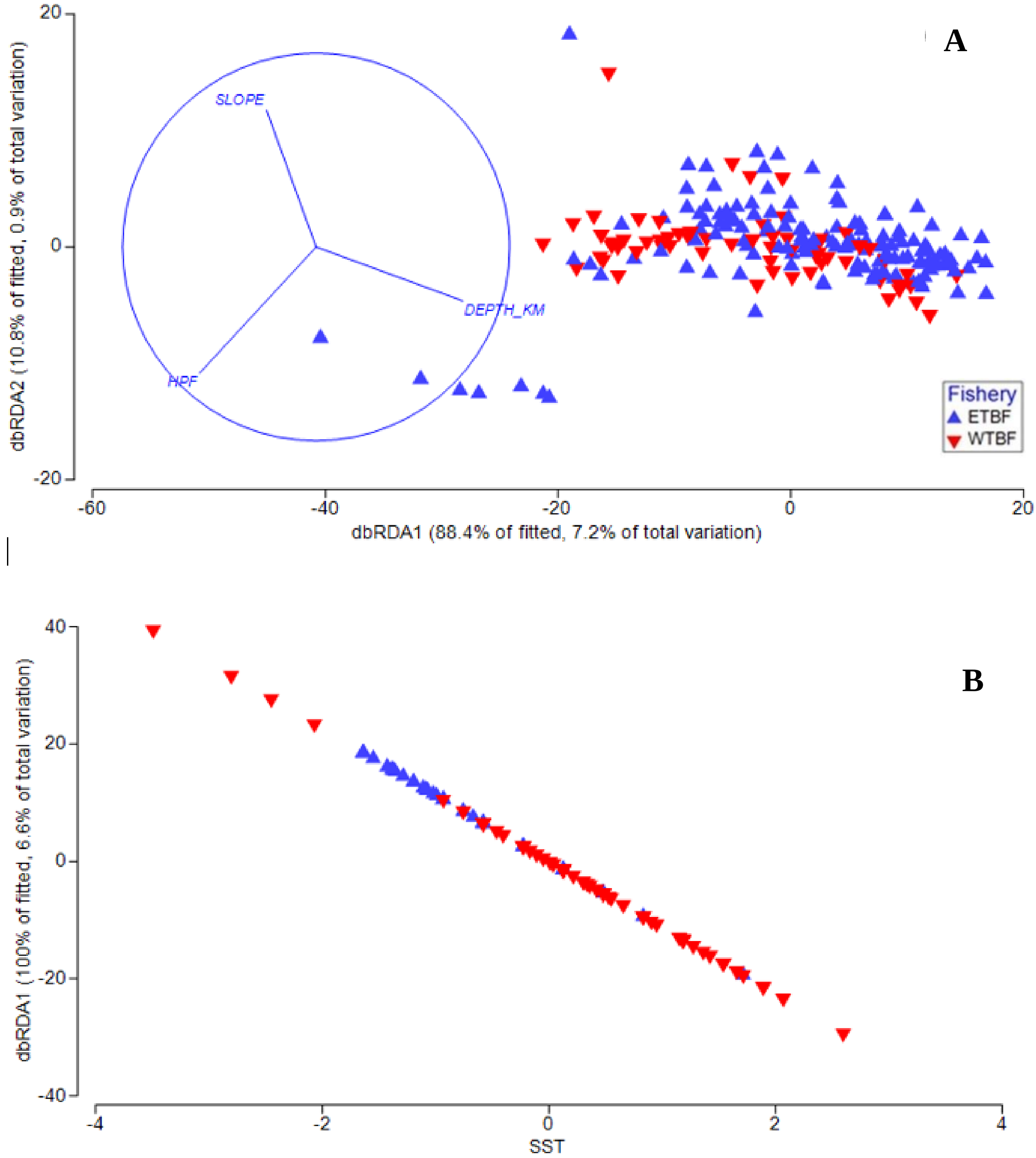


Figure 5.6. Multivariate relationship between catches within each square degree from 2000 to 2007 by fishery for *Alopias* spp. **(A)**, and *L. nasus* **(B)**. Blue triangles represent areas within the ETBF and red triangles represent areas within the WTBF. Length and direction of the vectors within the circle indicate the strength and direction of the influence of the environmental variables selected by the DISTLM (Table 5.2). Dependent variable (SST) included on x-axis for *L. nasus*.

Occurrence rates for *P. glauca* (24%) and *I. oxyrinchus* (17%), were significantly higher than for *Alopias* spp. (1%) and *L. nasus* (0.5%). Distance based linear models identified depth (4.4%) as the most important variable for *Alopias* spp. however, combined with HPF (2.7%) and slope (1.1%) the total variance explained by this model was only 8.2%. A slight negative relationship was also apparent between depth and the occurrence of *Alopias* spp. (Fig. 5.8). Rates of occurrence for *Alopias* spp. were higher in areas on the continental shelf and continental and slope (<2 000 m = 1.4%) when compared to longline sets in waters deeper than 2 000 m (0.8%). While HPF and slope contributed to the final models there was minimal difference between *Alopias* spp. occurrence rates for shallow, medium and deep set gear (1.0%, 0.9% and 1.0% respectively) or based on the slope (<10 degrees = 0.9%, >10 degrees = 1.3%). The variance explained by the *L. nasus* model was even lower where SST explained 6.6% of the variance (Table 5.2). Mean rates of occurrence for *L. nasus* were far higher for longline sets in waters with SSTs colder than 16°C (10%) when compared to waters warmer than 16°C (0.4%). Linear regression showed a negative relationship between SST and occurrence of *P. glauca*, *I. oxyrinchus* and *L. nasus* (Fig. 5.7).

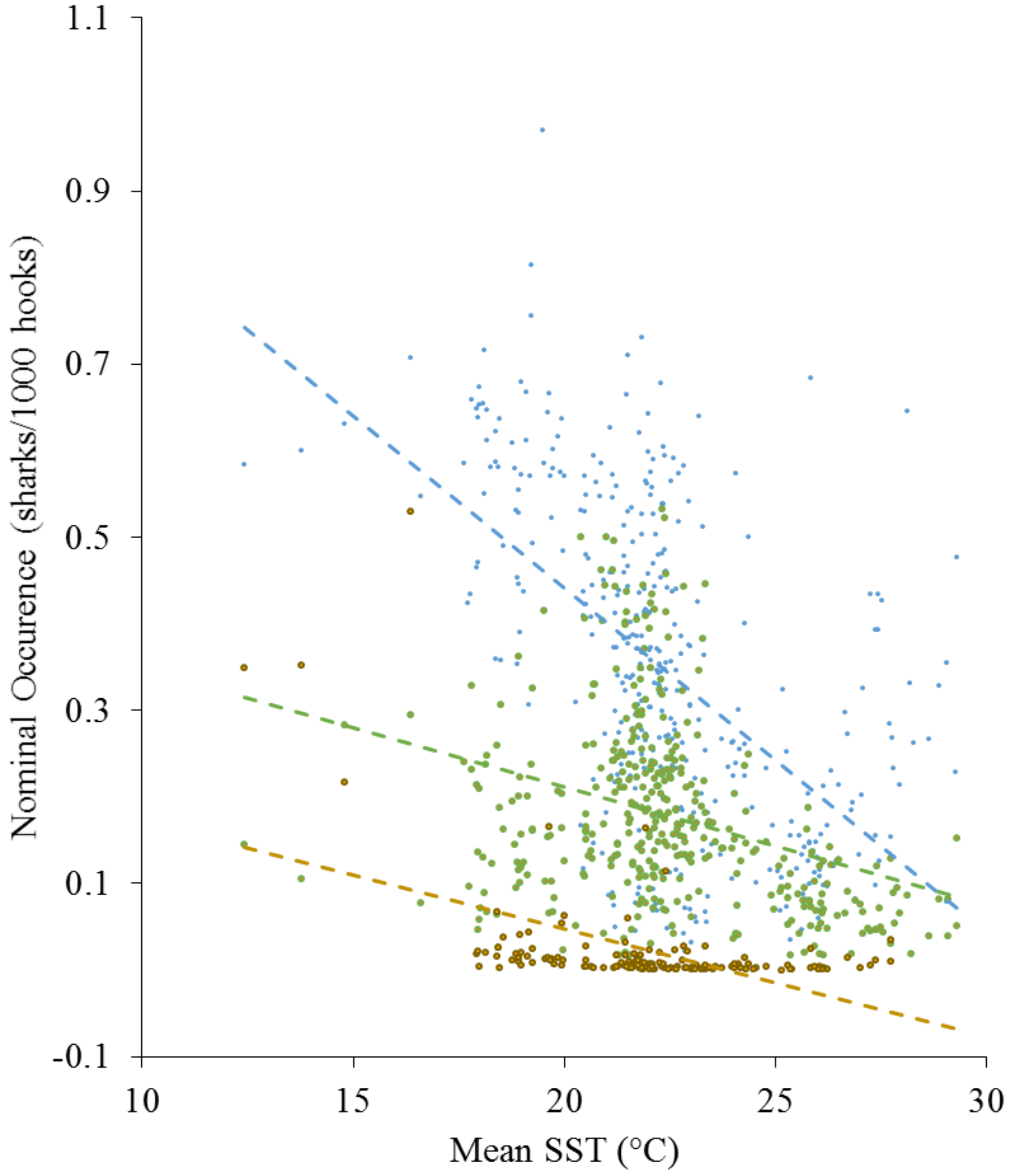


Figure 5.7. Linear regression of nominal occurrence and sea surface temperature (SST) for pelagic sharks, *P. glauca* (blue), *I. oxyrinchus* (green), and *L. nasus* (orange) for 1° areas where catches were recorded by longlines in Australian waters. *Alopias* spp. not included as SST was not a significant variable for the model of *Alopias* spp. catch.

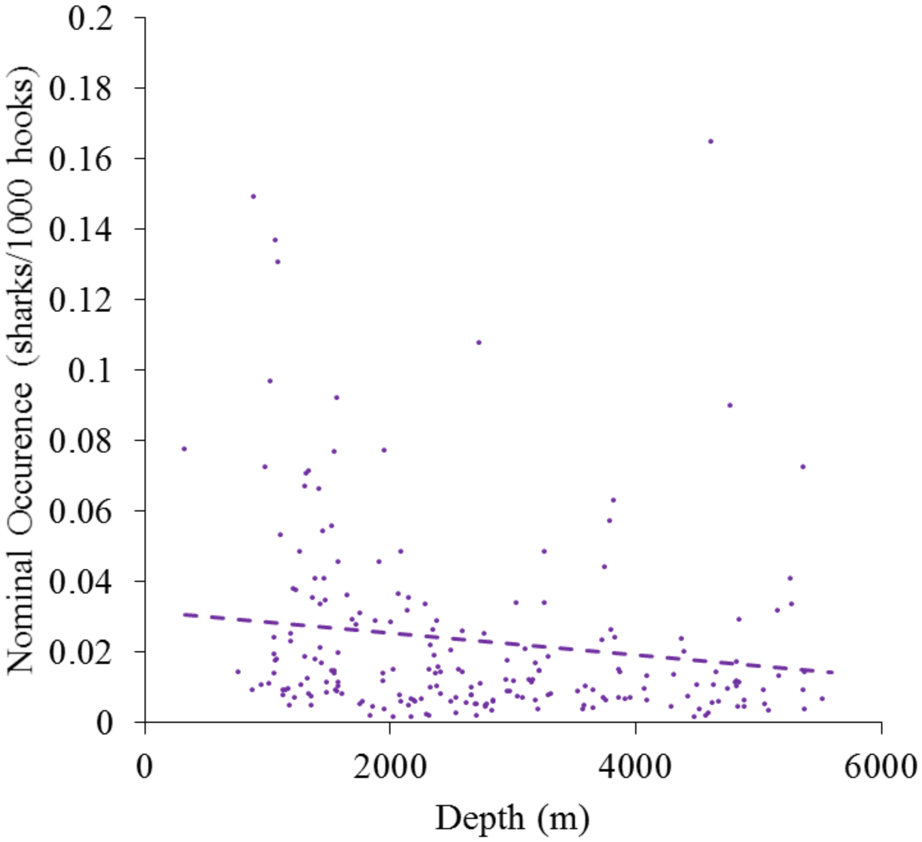


Figure 5.8. Linear regression of nominal occurrence and depth of *Alopias* spp. for 1° areas where catches were recorded by longlines in Australian waters.

Discussion

This study aimed to investigate the effects of environmental and operational variables on pelagic shark bycatch in pelagic longline fisheries operating in Australian waters. The permutational modelling approach and analysis of occurrence rates rather than catch rates allowed us to deal with the zero-inflated catch data, which is common in many fishery-dependent bycatch datasets. Variation in the patterns of bycatch of pelagic sharks within Australian longline fisheries were explained by both environmental and operational factors. We found that SST was the most important variable explaining species composition as well as the occurrence of *P. glauca*, *I. oxyrinchus* and *L. nasus*. Gear configuration was also an important variable for explaining the variation in occurrence of *I. oxyrinchus* and explained some of the variance in *P. glauca* and *Alopias* spp. occurrence. Depth was the most important factor in the occurrence of *Alopias* spp. and explained a small amount of the variance for *I. oxyrinchus* while slope was only a factor in the *Alopias* spp. model and explained a negligible amount of variance in occurrence rates for these species. Factors as water temperature, depth and gear configuration have all previously been linked to increases in bycatch rates of pelagic sharks species (Bigelow & Maunder, 2007; Cao *et al.*, 2011; Damalas & Megalofonou, 2010). Overall, the contribution of *P. glauca* to the species composition for the entire dataset was comparable to what was reported for the Japanese longline fishery that operated in Australian waters until the late 1990s (Stevens & Wayte, 2009). There was some variance in the species composition between the WTBF and the ETBF with a higher proportion on *I. oxyrinchus* caught in the ETBF.

Sea surface temperature

Sea surface temperature was the most important predictor of species composition and occurrence of *P. glauca, I. oxyrinchus,* and *L. nasus*, with catches increasing with colder surface temperatures. Sea surface temperature represented the largest percentage of variation for *P. glauca* with the peak occurrence in waters colder than 19°C. Sea surface temperature has been shown to influence catch rates of *P. glauca* in other longline fisheries around the globe, for example, catch rates peak at a SST of 16–17°C in the Atlantic Ocean, and at a SST of 16°C in the Pacific Oceans (Bigelow *et al.*, 1999; Carvalho *et al.*, 2011; Damalas & Megalofonou, 2010). Simpfendorfer *et al.* (2002) reported peaks in catch rates of *P. glauca* for female sharks at 15°C while for males, peak catch rates were associated with slightly warmer temperatures (19°C) in the North Atlantic. Satellite telemetry studies of pelagic sharks have also highlighted the importance of sea surface temperature to the movements and habitat preference of many species (Hammerschlag *et al.*, 2011; Pade *et al.*, 2009; Stevens *et al.*, 2010).

In contrast to *P. glauca,* peak occurrence rates for *I. oxyrinchus* were slightly warmer with preference for SST's between 18°C and 23°C and lower rates of occurrence outside of this range. A similar preference has been observed for these species in pelagic longlines in the western Pacific with *I. oxyrinchus* showing a seasonal preference for warmer waters when compared with *P. glauca* (Kai *et al.*, 2017; Ohshimo *et al.*, 2016). The SST range reported in the present study is also warmer than the range reported for *I. oxyrinchus* that were satellite tagged in the Great Australian Bight and in the southeastern Pacific Ocean (Abascal *et al.*, 2011; Rogers *et al.*, 2015).

Lamnid sharks (e.g. *I. oxyrinchus, Alopias* spp. and *L. nasus*) are known to be physiologically adapted to colder waters (Bernal *et al.*, 2001; Wolf *et al.*, 1988). In the present study, *L. nasus* in particular showed a preference for the coldest waters of the fishery with rates of occurrence greatly increased in waters with a SST below 16°C. The incidence of catches of *L. nasus* was particularly high in areas off the southern coast of Tasmania which was the area with the coldest mean sea surface temperatures across both fisheries. Similar distributions have previously been reported for longline catches of *L. nasus* by the Japanese fleet in the waters to the south and east of Tasmania (Campbell, 2012).

GEAR DEPTH

Due to the nature of the pelagic ecosystem, and the habitat preferences of pelagic sharks, gear depth is well known to affect encounterability to longline gears (Ward & Myers, 2005a). We found that gear depth was a factor in the occurrence of *P. glauca*, *I. oxyrinchus*, and *Alopias* spp. with the greatest variation explained for *I. oxyrinchus*. Excluding the northern swordfish fishery, gear was predominantly set shallower in the ETBF compared to the WTBF which may have explained some of the increased incidence of *I. oxyrinchus* in this fishery. In comparison to the Japanese longline fishery that operated in Australian waters in the 1980s and 1990s, which primarily used deeper set longlines (60m – 250m), the longlines set in the ETBF had a far higher proportion of shallow set gear (20m – 160m) (Campbell & Young, 2012; Stevens, 1992). The increased catchability of *I. oxyrinchus* in shallower set longline gear has previously been reported for pelagic longlines in the Pacific Ocean (Ward & Myers, 2005a). Previous studies have also found both behavioural plasticity and diel movements for pelagic species which affects their susceptibility to longline fisheries dependent on the depth of the gear and the time it is deployed (Chapter 2; Campana *et al.*, 2009; Cartamil *et al.*, 2016; Stevens *et al.*, 2010; Vaudo *et al.*, 2016).

SLOPE AND DEPTH

Combined, depth and slope were only significant for two of the species in the present study and explained a minor amount of the variation in occurrence. This result is unexpected as we know that pelagic shark species can be associated with different water depths (e.g *I. oxyrinchus* show habitat preference for the shelf slope) (Rogers *et al.*, 2015). The lack of contribution of slope is most likely due to a combination of the data subsetting procedure, which averaged the slope each area, and the fishery distribution, with a high number of areas in the open ocean, where the sea floor is homogeneous. Increased incidence of *Alopias* spp. in waters >2000m and with greater degree of slope indicates a preference for areas on the shelf slope for these species. The distribution of the ETBF and the WBTF encompasses the range of all three species of thresher sharks (*A. pelagicus, A. superciliosus* and *A. vulpinus*). The three species within the Alopias genus occupy different depth ranges and habitats although it is likely that the majority of *Alopias* spp. reported were *A. vulpinus* as it is the most common of the three species and is known to occur across the entire range of the fishery (Last & Stevens, 2009; Stevens *et al.*, 2010). Negative relationships between depth and catch rates of *A. vulpinus* have been reported for other fisheries within Australian waters (Chapter 4), in the eastern Pacific Ocean (Holts *et al.*, 1998) and in the northwestern Atlantic Ocean (Simpfendorfer *et al.*, 2002). These studies have suggested that the higher abundancies of *Alopias* spp. are likely to be related to the aggregation of prey species along the shelf slope and in shallower waters. It is likely that, in the present study, the effect of both slope and depth on the occurrence of *Alopias* spp. shows a preference to shelf and slope habitats in Australian waters.

LIMITATIONS, IMPLICATIONS AND FUTURE RESEARCH

The heterogeneous nature of the distribution of fishing effort, with a concentration of effort along the shelf slope in the ETBF and in the Mentelle Basin in the WTBF provided challenges in the analysis of pelagic shark occurrence rates. It is likely that our data subsetting procedures, where data was combined over a 1 degree area, may have reduced the influence of oceanographic features on the measurement of slope and our ability to directly relate this to the occurrence of pelagic sharks. Based on the assumption that positive catches in logbooks are considered fairly accurate (Baum *et al.*, 2003), the occurrence based approach of this study allowed the use of fishery-dependant data to investigate the ecology of several data-poor bycatch species. There are a number of constraints to the use of fisheries-dependant bycatch data for quantitative fisheries analysis including: reliability of species identification; high proportion of zero catches; and the need to maintain the confidentiality of the data, (Campbell, 2015; Maunder & Punt, 2004; Maunder *et al.*, 2006). Despite the limitations of the data used in this study, we provide useful insights into the environmental and operational variables that influence the catch of pelagic sharks. This is a vital first step toward developing catch standardisations or risk analyses for pelagic shark species (Bigelow *et al.*, 1999).

Pelagic sharks are highly susceptible to at-vessel and post-release mortality when caught by longline gear (Campana *et al.*, 2009; Dapp *et al.*, 2016a; Ellis *et al.*, 2017). High at-vessel mortality rates (68%) have been recorded for *A. superciliosus* in the Indian Ocean (Coelho *et al.*, 2011). Mortality for *I. oxyrinchus* on pelagic longlines has been recorded as 33% in the Atlantic Ocean and 56% in the Indian Ocean (Coelho *et al.*, 2012; Coelho *et al.*, 2011). In the northwestern Atlantic, at-vessel mortality rates ranged from 15% for *P. glauca*, and 26% for *I. oxyrinchus*, up to 44% for *L. nasus* (Campana *et al.*, 2015). Significant levels (20–55%) of post-release mortality has also been estimated for pelagic sharks in longline fisheries (Ellis *et al.*, 2017). While Australian fisheries have implemented management measures such as the mandatory release of pelagic sharks, high levels of at-vessel and post capture mortality, reduce the effectiveness of these measures. Pelagic shark bycatch within Australian longline fisheries is currently managed through a combination of gear restrictions, trip limits, and mandated release of live sharks. In addition to considering the threatened status of pelagic shark species, many fisheries have expressed a desire to minimise pelagic shark interactions due to the cost of repairing gear exceeding the revenue raised by catching sharks, (Gilman *et al.*, 2008). This research provides an approach to use fishery-dependant datasets to inform managers on the factors that may increase the occurrence of pelagic shark bycatch. This information can be used to improve the management of pelagic longline fisheries in an effort to reduce both the cost of pelagic sharks on longline fisheries as well as impact of longline fisheries on pelagic shark populations.

6

GENERAL DISCUSSION

OVERVIEW

Using a combination of satellite telemetry, recreational game fishing surveys, and commercial catch data modelling, this study provides critical information to assess the interactions between pelagic shark species and the commercial and recreational fisheries that operate within Australian waters. This research had two broad objectives: 1) explore the levels of catch of vulnerable pelagic shark species within Australian fisheries; 2) determine the factors that influence the susceptibility and encounterability of pelagic sharks to Australian fisheries. The key findings of this study include: 1) distinct diel vertical movements patterns of blue sharks (*Prionace glauca*) in the southeastern Indian Ocean, and; 2) preference of *P. glauca* for productive upwelling regions; 3) tournament anglers were identified as key stakeholders in the management of pelagic sharks in Australian waters; 4) tournament anglers recognise the value of pelagic sharks and are supportive of best practice methods (BPM) to improve post-release survival but the use of these methods is limited; 5) inshore and shelf waters along the southern coast of Australia provide important habitat for *A. vulpinus*, and; 6) the importance of sea surface temperature to the species composition and occurrence of pelagic shark bycatch within Australian longline fisheries. These key findings, how they relate to the thesis objectives, and their broad implications are discussed below.

MOVEMENT PATTERNS OF PELAGIC SHARKS

Pop-up locations of satellite tags indicated a preference by pelagic sharks for upwelling regions. Upwelling systems are known to be sites of aggregation for small pelagic teleosts (Pauly & Christensen, 1995) and oceanic squids (Anderson & Rodhouse, 2001), which are important prey for both *P. glauca* and *A. vulpinus* (Preti *et al.*, 2012; Rogers *et al.*, 2012). Sharks returning to the Bonney Upwelling region and movement to the upwelling region south of Java, Indonesia, highlighting the importance of these regions to pelagic predators and is likely to be linked to the availability of prey in these areas. A recent analysis of pelagic shark movements within the North Atlantic also highlighted the importance of highly productive areas and has linked these with high levels of longline fishing effort which is commonly concentrated in regions of high productivity (Queiroz *et al.*, 2016).

We identified vertical movement patterns as a key knowledge gap in the understanding of pelagic shark susceptibility and encounterability to fisheries in Australian waters. Although pelagic sharks have previously been tagged off the eastern coast of Australia (Stevens *et al.*, 2010), this study provides the first investigation of the vertical movement patterns of *P. glauca* and *A. vulpinus* in the southeastern Indian Ocean (Chapter 2). We acknowledge that the satellite telemetry data presented for *A. vulpinus* was based on a three-month deployment on one individual however the movement patterns that we report are similar to those reported for A. vulpinus in other studies (Cartamil *et al.*, 2010a; Stevens *et al.*, 2010). The satellite telemetry data provided fine scale depth-by-time recordings allowing a detailed examination of the vertical movements of *P. glauca* in the context of both plasticity and diel patterns. High levels of variability in movement patterns were observed with an average of four changes in vertical movement patterns per shark throughout the tagging period. Normal diel vertical movement (nDVM), characterised by shallower night time depth distribution compared to daytime depth distribution, was the dominant movement pattern exhibited by all sharks. Other vertical movement patterns included surface-oriented movements, reverse diel vertical movement (rDVM), and irregular shallow movements. Diel vertical movement is common across a range of large pelagic shark species and has previously been attributed to foraging, thermoregulation, predator avoidance, or orientation (Campana *et al.*, 2011; Cartamil *et al.*, 2010a; Coelho *et al.*, 2015; Francis *et al.*, 2015; Queiroz *et al.*, 2012; Shepard *et al.*, 2006).

Diel vertical movement patterns are also exhibited by many prey species, such as oceanic cephalopods, which are known to aggregate around the thermocline during the day and move towards the surface to feed at night (Roper & Young, 1975). It is likely that the vertical movement patterns exhibited by *P. glauca* in this study are related to foraging on oceanic squid species which have been shown to be their primary prey species in many areas of the globe, and are abundant in waters off southern Australia (Kubodera *et al.*, 2007; Preti *et al.*, 2012) (Smith, 1983; Stark, 2008). Foraging is also a likely explanation for the diel movement patterns of the *A. vulpinus* tagged in this study. The diet of *A. vulpinus* in waters off southern Australia is primarily composed of small pelagic teleost fishes of which, the Australian anchovy (*Engraulis australis*) and the Australian sardine (*Sardinops sagax*) are the most important prey items (Rogers *et al.*, 2012). Small pelagic teleosts are known to exhibit diel migrations and to move inshore during warm months, which coincides with the movements of the individual *A. vulpinus* tagged in the present study (Gutierez *et al.*, 2007; Stenevik *et al.*, 2007).

In addition to improving our understanding of the ecology of pelagic sharks, the vertical movement patterns found in this study may be useful in developing methods to mitigate *P. glauca* bycatch in the longline fisheries that operate within this region. Diel movement patterns of marine species lead to changes in their susceptibility and encounterability to the different fisheries depending on the depth range of the gear and the time of day that the gear is deployed. The prevalence of nDVM for *P. glauca* indicates an increased night time encounterability to the longlines set throughout much of the ETBF and WTBF (Campbell & Young, 2012). During the day, *P. glauca* inhabited depths that would render them more susceptible to capture by the deep longlines of the Japanese fleet which operates outside the Australian exclusive economic zone (Hampton *et al.*, 1998). These insights into the movement patterns of pelagic sharks may also inform commercial fishers on ways to improve their practices in order to minimise unwanted shark bycatch. For example, normal diel vertical movement was the dominant movement pattern for *P. glauca* indicating that Australian long liners, which predominantly use shallow set gear, could avoid interactions with these sharks by having their gear set during the day rather than during the night.

In the present study, nDVM and irregular shallow movements were the most common movement patterns for the single satellite tagged *A. vulpinus* (Chapter 2). Diel movement patterns have been reported for *A. vulpinus* off the eastern coast of Australia (Stevens *et al.*, 2010) and off the Californian coast (Cartamil *et al.*, 2011) where foraging and thermoregulation were suggested as possible explanations for this behaviour. Cartamil *et al.* (2011) highlighted the implications of diel movement patterns on the susceptibility of *A. vulpinus* to the Californian drift gillnet fishery and suggested that catches of this species could be reduced through management measures, such as increasing the minimum depth of gillnet gear in the fishery. The importance of depth to the encounterability of *A. vulpinus* to gillnet gear in Australian fisheries is also highlighted in the present study (Chapter 4) with similar management measures suggested in the pelagic sharks in commercial fishing section below.

The diel movement patterns of sharks in this study interfered with the light based geolocation used for Microwave Telemetry™ pop-up satellite tags presented significant challenges in providing reliable estimates of the location of sharks in this study. By moving between the photic and aphotic zone during twilight, inaccurate measurements of dusk and dawn were recorded which prevented any confident estimation of the position of the tag between deployment and pop-up. This also limited our ability to match movement patterns to specific areas or oceanographic features. Previous studies of *P. glauca* within the Atlantic Ocean have recorded specific movement patterns associated with oceanographic features, such as the Gulf Stream (Campana *et al.*, 2011) and the continental shelf (Vandeperre *et al.*, 2016). There remains some uncertainty surrounding the influence of different oceanographic features on the movements of *P. glauca* in Australian waters despite the tagging effort of the present study and other studies in the Great Australian Bight (Rogers *et al.*, 2016) and off the East Coast of Australia (Stevens *et al.*, 2010). With tags deployed on only one *A. vulpinus* and five *P. glauca* it was not possible to make any conclusive intra-species inferences about sex- and size-based segregation. Further tagging of male and mature female *P. glauca* is required to assess whether sexual or ontogenetic differences occur as suggested by our data and by many studies in the Atlantic and Pacific (Campana *et al.*, 2011; Nakano & Stevens, 2008; Vandeperre *et al.*, 2014; Vandeperre *et al.*, 2016).

PELAGIC SHARKS IN RECREATIONAL FISHERIES

This study found evidence of a sufficient level of catch by recreational anglers to consider tournament anglers as a key stakeholder in the management and conservation of pelagic shark species (Chapter 3). Tournament anglers had higher levels of individual fishing effort than the general recreational angling population which has previously been reported in other recreational fisheries (Henry & Lyle, 2003; Wilde *et al.*, 1998). In the present study, tournament anglers predominantly reported catches of shortfin makos (*Isurus oxyrinchus*), with approximately 60% of the sharks being released. While this release rate is lower than the national average (80%) for sharks and rays (Henry & Lyle, 2003), *I. oxyrinchus* are considered more edible than many other shark and ray species as evidenced by the prevalence of anglers providing “consumption” as a reason for retaining sharks (Chapter 3). Many game fishing tournaments in Australia continue to award prizes for capture where the fish must be retained and weighed, but tagging is increasingly being promoted as an alternative (Lowry & Murphy, 2003). The fate of sharks caught during competition is intrinsically linked with the competition structure with “competition” ranking in the top two reasons for both retaining and releasing sharks (Chapter 3).

Within the recreational tournament angling community there was some correlation between angler beliefs about sharks and their behaviours towards sharks. Anglers that placed a high value on catching a shark were more likely to target pelagic sharks and were more likely to use best practice methods (BPM). Almost all anglers had very strong beliefs around the value of releasing a shark in good condition, but many were not using gear, such as circle hooks, in line with current BPM (Arlinghaus *et al.*, 2007; McLoughlin & Eliason, 2008). In general terms, there is a diminishing social licence for unsustainable practices within fisheries (Worm & Branch, 2012). This societal transformation is a key driver in the change in tournament angling practices towards a larger acceptance of catch and release as well as best practice methods. When considering the behaviours of tournament anglers, we must also consider what effect perceived social norms will have on these behaviours (Madden *et al.*, 1992). For example, in the case of using circle hooks over J-hooks, circle hooks are widely accepted to reduce the rate of post release mortality and evidence from commercial fisheries shows minimal difference or increased catchability for sharks (Cooke & Schramm, 2007; Cooke & Suski, 2004; Ward *et al.*, 2009; Yokota *et al.*, 2006). As more anglers accept that the use of circle hooks is the better practice when targeting pelagic sharks for catch and release or tagging, this should influence the hook choice of their fellow anglers. Game fishing clubs currently play a role in educating anglers, encouraging catch and release, and improve angling practices through promotion of best practice. Through changing social norms, increases in the use of best practice and catch and release by tournament anglers should have a broader influence on the behaviours of the general recreational fishing population. Since the conclusion of this research, guidelines for handling and release of pelagic sharks have been developed by the South Australian Research and Development Institute, VRFish, the peak recreational fishing body in Victoria have also developed BPM for *A. vulpinus* and the Department of Primary Industries and Regions have produced a Shark and Ray Handling Procedures for recreational anglers in South Australia (PIRSA, 2018; Rogers & Bailleul, 2015; VRFish, 2017). The promotion of these resources through game fishing clubs should increase the use of best practice methods throughout the tournament and recreational angling community.

PELAGIC SHARKS IN COMMERCIAL FISHERIES

This study provided the first multi-species analysis of the bycatch composition of pelagic sharks in Australian long-line fisheries and the first analysis of gillnet catch rates of *A. vulpinus* for any fishery operating in Australian waters. Australia is in a unique situation where there have been large declines in commercial longline fishing effort in the past two decades following the exclusion of the international longline fleets and reductions in the size of the domestic fleet (Stevens & Wayte, 2009). The implementation of management measures for reducing the bycatch of marine mammals in South Australia has led to a decline in catches of *A. vulpinus* by gillnets in this area (Chapter 4; Knuckey *et al.*, 2014).

Understanding the trends in catches of vulnerable non-target species is critical in their effective management and conservation (Hall *et al.*, 2000). We found that, compared to other gillnet fisheries, catches of *A. vulpinus* in the SESSF were relatively low and stable between 2000 and 2015. We highlighted several areas within Bass Strait and the Gantheaume Basin that exhibited high catch rates for *A. vulpinus* indicating specific areas of higher abundance for this species. The exclusion of gillnet fishing from the Gantheaume Basin due to the implementation of the Coorong Dolphin Sanctuary Zone has led to a large decrease in the catch of *A. vulpinus* in the SESSF. Analysis of gillnet data identified season and depth as important factors in models of catch rates of *A. vulpinus* in the SESSF (Chapter 4). Catch rates of *A. vulpinus* were consistently higher in summer months compared to the rest of the year. The seasonal pattern is similar to the gillnet fishery off the Californian coast where over half of the yearly catch is taken between May–July (Urbisci *et al.*, 2016). Water depth was identified as an important factor to the catch rates of *Alopias* spp. within both gillnet (Chapter 4) and longline fisheries (Chapter 5) suggesting a higher abundance or encounterability in shallow waters.

While management measures have been introduced to many Australian fisheries restricting the retention of live *A. vulpinus*, these measures are likely to be less effective in gillnet fisheries where post-capture survival is significantly lower than longline fisheries. A more effective approach may be to limit the incidence of *A. vulpinus* bycatch through time- and area-based restrictions on the gillnet fishery or through changes in gear used within this fishery. The importance of season and depth in affecting catch rates indicates that reductions in *A. vulpinus* bycatch may be achieved through restriction of gillnet effort in inshore waters and during times of peak catches in summer. In addition, within the SESSF, longlines are being considered as an alternative to gillnets in waters that are subject to gillnet closures (Knuckey *et al.*, 2014). Although it is unclear what impact this may have on catch rates of *A. vulpinus*, this change provides an opportunity for improved management of *A. vulpinus* in this fishery with catch and release more viable for longlines compared to gillnets.

Gear depth has been shown to be an important factor in predicting rates of bycatch of *A. vulpinus* and many other pelagic shark species (e.g. *A. superciliosus, P. glauca,* *Carcharhinus longimanus* and *C. falciformis*) caught in longline fisheries (Bigelow & Maunder, 2007; Cao *et al.*, 2011; Clarke *et al.*, 2013). Gear depth was also identified as an important factor for the capture of *I. oxyrinchus* in longline fisheries in this study (Chapter 5). Understanding of the environmental factors that influence the occurrence of a species or increase catch rates can provide avenues to reduce the incidence of bycatch and manage migratory species under national and international obligations (Techera & Klein, 2017).

Sea surface temperature was also identified as the major factor in determining the occurrence of *P. glauca, I. oxyrinchus*, and *Lamna nasus* caught by longlines in Australian waters (Chapter 5). Temperature is widely recognised as a key factor in determining the distribution of pelagic shark species (Campana & Joyce, 2004). The depth of satellite tagged sharks in this study were also closely associated to levels of activity and water temperature (Chapter 2). Water temperatures have previously been linked to changes in the depth distributions of pelagic sharks including *P. glauca* and *I. oxyrincus* in the northwestern Atlantic (Campana *et al.*, 2011; Vaudo *et al.*, 2016).

Remote electronic monitoring (REM) has recently been implemented by AFMA in all commercial fisheries investigated in this study and presents an opportunity to improve data collection on the capture of bycatch such as pelagic shark species in fisheries where on-board observers are impractical (AFMA, 2015c). REM provides a more cost-effective method to verify records of fishing activities and obtain reliable reports of bycatch species (Mortensen *et al.*, 2017). The use of REM data should provide more confidence in the accuracy of logbook data for bycatch species and improve the recording of pelagic shark bycatch. Greater certainty around the level and type of interactions present between Australian longline fisheries and pelagic sharks will provide an avenue construct standardised catch rates of pelagic sharks to construct indices of abundance and abundance for these species.

FUTURE RESEARCH DIRECTION

There remains much to be learned about the movement patterns and impacts of fisheries on pelagic shark species in Australian waters. Studies of pelagic sharks in this region, and more broadly within the Indian Ocean, are particularly poorly represented in the literature. This thesis expands the existing knowledge of the interactions between pelagic sharks and the various recreational and commercial fisheries that operate within Australian waters. A better understanding of the extent and impact of these interactions is particularly timely and relevant given the range of responses by the Australian government to the listing of several pelagic shark species on Appendix II of the CMS (CMS, 2017; Secretariat, 2015).

The threatened status, along with the recognition of many pelagic shark species as migratory species, with large ranges across multiple jurisdictions, has resulted in their protection and management under international agreements such as the Bonn Convention on the Conservation of Migratory Species of Wild Animals (CMS) (Compagno *et al.*, 2008; Lyster, 1989). There have now been two cases where the listings of migratory species (*I. oxyrinchus* and *A. vulpinus*) has not been translated into listings of these species under the *EPBC Act*. We do not attempt to assert that the current levels of fishing are a threat to these species, however while uncertainty remains around these threats, it is imperative that legislative action follows the precautionary principle when managing these species.

Both species that were satellite tagged in this study (*P. glauca* and *A. vulpinus*) can also be tagged with fin mounted or towed smart position or temperature (SPOT) tags (Hammerschlag *et al.*, 2011). The use of a combination of SPOT and PSAT tags in future studies may provide further information on the association between specific areas or oceanographic features and the vertical movement patterns that we observed in the present study. An increased sample size of both males and females would provide clarity on any sexual or ontogenetic diversion in movement patterns or habitat use. Water temperature and level of activity explained much of the variability in the depth distribution of both species, providing a promising avenue for future investigations of pelagic shark habitat preference. Recent research has used satellite telemetry to assess the overlap between the fishing effort of longline fleets and the habitats of pelagic shark species (Queiroz *et al.*, 2016). Fishing fleets are increasingly using technology to identify and select productive habitats which leads to dynamic fishing effort patterns and at a regional scale (Kroodsma *et al.*, 2018; Queiroz *et al.*, 2016). The present study provided valuable insights into the variables that may lead to an increase in pelagic shark catches. Pairing fisheries effort data with a larger satellite tagging dataset would clarify specific habitat preferences for pelagic sharks and provide better estimates of fisheries mortality and overlap of critical habitats with fishing effort (Byrne *et al.*, 2017; Queiroz *et al.*, 2016). In many cases, simply managing bycatch by banning the retention of threatened species may not be adequate and introducing measures that actually reduce the incidence of bycatch may be required (Tolotti *et al.*, 2015)

We present two contemporary approaches to utilise fisheries dependant data for species where observer coverage is not adequate for catch standardisation. Future analyses of bycatch data from Australian fisheries will benefit from the integration of REM. Increased confidence in the accuracy of commercial logbook data will enable the standardisation of catch rates to provide indices of abundance for bycatch species. These indices, along with the data obtained in the present study will be useful in the development of risk assessments (e.g., Hobday *et al.*, 2011) of pelagic shark vulnerability to the various fisheries that operate in Australian waters. Understanding the potential effects of these fisheries on the conservation status of pelagic sharks in the region is crucial in determining the most efficient and effective management options for these species.

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APPENDICES

Appendix 1. *Removed from open access version due to copyright*

Heard, M., Rogers, P., Bruce, B. D., Humphries, N. E., & Huveneers, C. (2018). Plasticity in the diel vertical movement of two pelagic predators (*Prionace glauca* and *Alopias vulpinus*) in the southeastern Indian Ocean. *Fisheries Oceanography, 27,*199-211

Appendix 2. Heard, M., Sutton, S., Rogers, P., & Huveneers, C. (2016). Actions speak louder than words: Tournament angling as an avenue to promote best practice for pelagic shark fishing. *Marine Policy, 64*, 168-173.