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Review of potential fisheries and marine management impacts on the south-western Australian white shark population

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Executive Summary

Following five fatal incidents involving white sharks (*Carcharodon carcharias*) off the lower west coast of Western Australia between September 2011 and July 2012, as well as other highly-publicised non-fatal encounters with this species, in 2012 the State Government funded several new initiatives to better understand white sharks in Western Australia and the likely effectiveness of any community safety interventions in Western Australian waters.

One of the factors that may have affected the incident rate of shark attacks over time is potential changes in the abundance of white sharks in Western Australian waters resulting from shifts in the levels of fishing-related and other mortalities. As there is now strong evidence that there are two separate populations of white sharks in Australian waters, this report examines the possible effects on the south-western Australian population (in waters west of Bass Strait, Victoria) from the various changes to fishing activities and management arrangements over time since 1938/39, including the 1997 protection of this species under both State and Commonwealth legislation.

The specific objectives of this study were to reconstruct the levels of annual catch of white sharks by commercial and recreational fishing in southern and western Australia since 1938/39 and to combine these estimates of catch with current life-history parameters available for white sharks (including key uncertainties) to generate a comprehensive series of potential population trajectory scenarios.

Historical catches of white sharks of the south-western Australian population are either poorly documented or not documented at all. Although contemporary catch estimates are available from the protected species bycatch data collected in many commercial fisheries' logbooks since 1997, their accuracy has not been substantiated. To provide a basis for more accurate estimation of historical white shark catches an examination was undertaken of the likely levels of mortality associated with each the various commercial and recreational fisheries that currently operate, or have operated in this region, plus other potential sources since 1938/39. This analysis concluded that most of the captures of white sharks have historically come from the Western Australian Temperate Demersal Gillnet and Demersal Longline Fisheries (TDGDLF), the Gillnet Hook and Trap Sector (GHaT) of the Commonwealth Southern and Eastern Scalefish and Shark Fishery, the South Australian Marine Scalefish Fishery (MSF), and to a lesser extent, the various forms of 'open-access' commercial fishing and recreational fishing in both South Australia and Western Australia. The other potential sources of mortality were collectively considered to be negligible at the population level.

For those fisheries/sources where a first stage analysis identified that more substantial catches had occurred at some point in their history more detailed analyses were completed. This included commercial fishers operating in the TDGDLF being surveyed about their historical white shark catches during confidential, face-to-face interviews. Historical catch estimates derived from these interviews were matched with fishing effort data reported in statutory fishing returns. Because these data have high levels of uncertainty, two approaches were used to scale-up interviewed fishers' catch information to provide the best estimates of the TDGDLF white shark catch. These two approaches resulted in mean estimates between 1988/89 and 1996/97 of 59 and 81 sharks yr^{-1}. For the first period after protection (1997/98–2004/05), the estimated catch was 28 yr^{-1} and for the most recent period (2005/06–2012/13) it was 35 $yr^{-1}$for both approaches.

The TDGDLF catch rate estimates were considered to be the best-available proxy for changes in the white shark catch rates in both the GHaT and the MSF but these were applied using a number of different assumptions. The catches from various forms of 'open-access' commercial fishing and recreational fishing in Western Australia and South Australia were also estimated and combined to generate four catch reconstruction histories of the south-western population of white sharks. All four suggest that cumulative catches increased rapidly during the 1970s and early 1980s. Estimated captures peaked in the late 1980s when gillnet fishing effort in the TDGDLF, GHaT and MSF was greatest with up to 270–401 and 627–975 (50^{th} percentiles) white sharks captured per year under the lowest and highest catch scenarios. White shark captures declined through the 1990s mainly as a result of the reduction in gillnet effort in each of these key fisheries. Current captures of white sharks (all of which must be released) across the region are estimated to now be between 45–56 and 61–79 sharks (50th percentiles) under the lowest and highest catch scenarios, including 35 yr^{-1} within Western Australia.

To develop scenarios for the changes in population abundance through time, uncertainty in the productivity and abundance of the south-western Australian population was quantified using two life history strategies (low and high productivity), the four different reconstructed catch histories, three levels of post-capture mortality (PCM, 0%, 50% and 100%) and a series of assumed initial total (unexploited) population sizes (3,000–20,000). These were all used as inputs within a simulation model to estimate the potential range of current abundance levels and trajectory histories for both the entire population and larger sized individuals (> 3m Total Length (TL)), which is the size component identified as responsible for most attacks on humans for the south-western Australian population of white sharks.

While calculating a definitive estimate of the current abundance of white sharks and their population trajectory since protection in 1997 was not possible, the set of population trajectories generated by this method was still highly informative. The model suggested that depending upon the life history strategy, the potential annual increases in population abundance varied from 2–7% per year. Furthermore, depending upon model inputs, there was a wide range of potential declines in abundance since 1938/39 and significant differences in the potential population trajectories since protection in 1997.

Given the wide range of starting values used within the model, 40% of the 120 modelled scenarios for the entire population had either a negligible (< 10%) change in their total abundance since 1938/39, or the population had declined to extinction before 2012 (the latter is clearly not plausible). For the remaining 60% of scenarios, some of those based on the most biologically 'pessimistic' inputs (e.g. lower productivity and higher post capture mortality) suggest that declines in white shark abundance could still be occurring. By contrast, some of those scenarios based on the most 'optimistic' biological inputs (e.g. higher productivity and lower release mortality), suggest that the total population abundance of white sharks could have increased significantly (> 20%) since their protection in 1997 and, for larger white sharks (> 3m TL), this increase could have been even greater (> 40%). Each of the scenarios has been broadly grouped into one of the following five categories:

(1) **Negligible (< 10%) overall decline in total abundance since 1938/39.**
Scenarios that had high initial population levels plus some with moderate initial levels when combined with a high productivity life history.

(2) **Total abundance had declined by more than 10% before protection, but may have been increasing slowly from this level since protection in 1997(< 10% increase in total population or <20% increase in white sharks > 3m TL since 1997).**
Scenarios that had small or moderate initial population levels (with high productivity) when also combined with high PCM.

(3) **Total abundance had declined by more than 10% before protection, but may have been increasing significantly from this level since protection in 1997(> 10% increase in total population or > 20% increase in white sharks > 3m TL since 1997).**
Scenarios that had small or some moderate initial population levels when also combined with low to moderate PCM.

(4) **Total abundance had declined by more than 10% before protection and may have declined further from this level since protection in 1997.**
Scenarios that had small (with high productivity) or moderate (with low productivity) initial population levels when combined with high PCM.

(5) **Total abundance declined and became extinct before 2012 (noting that this category is not plausible)**
Scenarios that had low initial population levels when combined with low productivity or the highest catch level.

Whether the current population trajectory for white sharks is declining, steady, increasing slowly or increasing significantly has major implications for management and the development of appropriate public policies. Given that scenarios with different input combinations had similar population trajectory patterns, the range of potential current population sizes within each of the four plausible categories was wide and often overlapping. Consequently, even if an estimate of the current abundance of white sharks is generated through a genetic-based or other technique, this may still not resolve which of these population trajectory categories is correct. Until this aspect can be resolved, the policy implications of these different categories and their relative likelihoods should continue to be considered. Furthermore, any strategy should be sufficiently agile to enable the rapid inclusion of additional scientific information that assists in refining which of these categories, and potentially which specific scenario in that category, was more likely.

To assist in reducing the levels of uncertainty and thereby narrowing the range of plausible scenarios both for the current abundance and population trajectories for this population of white sharks a number of lines of investigation could be pursued. By comparing among these scenarios and undertaking additional sensitivity testing we have identified which of the key model inputs has the biggest impact on model outputs and therefore where future studies should best be directed. The potential enhancements include improving the reporting of commercial catches, quantifying post capture mortality, and increasing the collection of biological data potentially through the development of more innovative sampling methods. Continued collection of genetic material, as already outlined, could lead to more precise estimates of current and historic effective genetic population sizes. Other, more indirect monitoring programs may also become more valuable through time for monitoring the status of this population and for use in modelling-based or risk-based assessments.

It must be acknowledged that there are many inherent difficulties associated with conducting studies on white sharks. Successfully progressing many of these additional investigations will require ongoing commitment from government and the fishing industry and increased recognition by the broader community of these challenging logistics. This potentially includes changing attitudes towards the relative benefits obtained from increasing our understanding of this species through the capture, examination and/or release of potential specimens.

1 Introduction

1.1 Background

Shark attacks are rare events that can have traumatic consequences for the individuals directly affected. Despite being a very infrequent cause of injury and death in Australian waters in comparison to drowning (RLSA 2014), shark attacks receive relatively high levels of media attention (Francis 2011; Neff 2012; Neff & Yang 2013). These incidents may, therefore, affect the wellbeing of affected communities including declining participation for aquatic activities and possibly even flow-on economic effects for tourism and other related marine industries.

Following five fatal incidents involving white sharks off the lower west coast of Western Australia between September 2011 and July 2012, as well as other highly-publicised non-fatal encounters with this species, in 2012, the State Government funded several new initiatives to better understand white sharks in Western Australia and the likely effectiveness of any community safety interventions in Western Australian waters. Three of these studies have already been completed, including a correlation study of the potential risk factors associated with white shark attacks in Western Australia (DoF, 2012); a desktop study on the effectiveness of shark meshing and shark exclusion barriers as a shark hazard mitigation strategy in Western Australia (McPhee, 2012) and, most recently, a study that investigated the movement patterns of white sharks and evaluated passive acoustic telemetry approaches for monitoring and mitigating shark hazards off the coast of Western Australia (McAuley et al. 2016).

One of the factors that may have affected the incident rate of shark attacks and encounters over time is the potential change in the abundance of white sharks in Western Australian waters that may have resulted from shifts in the level of fishing-related and other mortalities. This report therefore examines the possible effects to the south-western Australian population of white sharks from the various changes to fisheries management arrangements over time, including the 1997 protection of this species under both State and Commonwealth legislation.

The objectives of this study were to (1) reconstruct the levels of annual catch of white sharks in southern and western Australia over the period for which catch estimates are available and (2) combine these estimates of catch with current life-history parameters available for white sharks (including key uncertainties) to generate a comprehensive series of potential population trajectory scenarios for this population. These scenarios will be used to determine which future studies could reduce the levels of uncertainty in our understanding and population estimates.

1.2 Impacts of fisheries management changes on white shark captures

The most likely sources of mortality for white sharks in southern and western Australia have been generated by fishing activities (Malcolm et al. 2001). There are a large number of commercial and recreational fisheries that have operated within this region with the potential to capture white sharks. Each of these will have had differing targeting and fishing practices, with histories of development that have involved many changes to their management arrangements primarily aimed at achieving sustainable catches of target species. The resulting changes in total effort levels, types of fishing gear used, their duration and areas of use, and the rate of release of non-targeted catches may also have affected the levels of capture and therefore the population trajectory of white sharks. This study will undertake an examination of all existing white shark catch data from each of the commercial fisheries operating in the southern and western regions of Australia in conjunction with information available on the recreational catch from this region to generate potential population trajectory scenarios.

1.3 Legislated protection of white sharks

In addition to standard fisheries management changes, the white shark was declared a protected species in Australia under Tasmanian legislation in 1995/96 and shortly thereafter elsewhere (between 1997 and 1999) either under State fisheries Acts, including Western Australia, some States' conservation laws and the Commonwealth Endangered Species Protection (ESP) Act (Malcolm et al. 2001). This resulted in white sharks no longer being able to be targeted in Australia, and it also made it illegal to retain or deliberately kill any white shark that was captured by any fishing or other activity.

In 1999, the ESP Act was replaced by the Environment Protection and Biodiversity Conservation (EPBC) Act, under which white sharks were listed as 'vulnerable' due to 'evidence of continued population decline', its conservative life history characteristics (longevity and low reproductive capacity), limited local distribution and abundance and, at the time of listing, ongoing pressure from the Australian commercial fishing industry (Environment Australia 2002). It is important to note, however, that at the time of white sharks' listing under Commonwealth legislation, the species was notionally considered to constitute a single Australian population. There is now strong evidence that there are two separate populations of white sharks in Australian waters; a south-eastern population and a south-western population, with the Bass Strait the approximate boundary (see Section 1.5). This report will focus on the south-western Australian population.

White sharks are also listed as a protected species in other countries, including in South Africa, Namibia, Israel, Malta and the American states of California and Florida (Fergusson et al. 2009). It is also listed under international agreements: Appendix II of the Convention on International Trade in Endangered Species of Fauna and Flora (CITES) and on Appendices I and II of the Convention on Migratory Species (CITES 2004). These listings recognise the cumulative international impacts that threaten the conservation of species and the need for international cooperation in their management.

1.4 Reviews of the Australian white shark population(s)

The first nationally-consolidated review of the species' status was commissioned through the first national White Shark Recovery Plan process (Malcolm et al. 2001). This report included the first attempt to quantify unreported historical catches of this species and the outputs from a mathematical model that calculated the theoretical size of the (total) Australian white shark population necessary to at least sustain those estimated catches. The authors emphasised that they could not determine the magnitude of white shark catches over time (and whether those catches were sustainable). Consequently, their model outputs could not be relied upon to infer actual population size and were not equivalent to a quantitative stock assessment.

More recent reports by DEWHA (2009), SEWPAC (2013a) and the revised national Recovery Plan (SEWPAC 2013b) have provided updates on the current understanding of the species' biology, exploitation and threats. These studies have all, however, highlighted the considerable level of uncertainty remaining in the biological attributes of this species and lack of reliable catch data, both of which are required to accurately assess changes in the abundance of fish populations using standard fisheries based techniques. Such deficiencies have been cited as significant obstacles to assessing historic trends and contemporary status of this species.

1.5 Population structure

A significant advance in our understanding of Australian white sharks' population status has been generated from analyses of its genetic population structure using mitochondrial analysis (Blower et al. 2012) and electronic tagging (Bruce et al. 2006; Bruce & Bradford 2012). These studies have demonstrated strong evidence of genetic and behavioural structuring of white sharks that effectively defines two functionally-separate Australian populations, east and west of Bass Strait. One important implication of this differentiation of populations in eastern and south-western Australian waters, is that data derived from the New South Wales and Queensland shark control programs (Reid & Krogh 1992; Reid et al. 2011), that indicated a historic decline in abundance, are not directly relevant to assessing trends in abundance of sharks west of Bass Strait. Furthermore, as the commercial fishing histories in the two regions are very different, there may be significant differences in both the historical exploitation and current status of these two populations.

Given this information, this study will examine the capture levels and potential impacts on what is now commonly described as the south-western Australian population of white sharks.

1.6 Scope and specific objectives of this study

This report documents the findings from new surveys of all fishing sectors in the southern and western regions of Australia combined with updated analyses of available fishery catch and effort data to develop comprehensive estimates of the historical catch levels for the newly-defined south-western Australian white shark population. These estimates have been used together with the most current information available on the biology of white sharks within a stochastic demographic model of the population to evaluate various scenarios based on a range of possible life history parameters, initial population sizes and catch histories.

The information from this study is designed to inform the public and decision makers about the potential impacts of changes in management arrangements on the south-western Australian white shark population. Moreover, it will provide a better basis for determining what, if any, current monitoring programs or additional research programs could cost-effectively refine future calculations of population abundance and/or trajectory estimates for white sharks off Western Australia.

2 Overview of fisheries operating within the south-western Australian white shark population

2.1 Introduction

Estimating the incidental catch of ‘unwanted’ species, and especially for rare species (which includes many protected species), is a common problem for many fisheries (Lewison et al. 2004; Molina & Cooke 2012). Unlike targeted species, the level of catch for unwanted species has historically often gone unreported or underreported in logbooks (Baum et al. 2003). In recent years, the adoption of ESD/EBFM policies (e.g. Fletcher 2002, Fletcher et al. 2005, 2010, 2012), National Plan of Action (NPOA) for the conservation and management of sharks, Recovery Plans (SEWPAC 2013b) and EPBC Act accreditation processes have highlighted the importance of obtaining accurate protected species catch information. However, even where these data are reported, they are usually unverified and only provide information on recent catches. The absence of historical catch information and questionable accuracy of more recent catch data are impediments to assessing the current status of (i.e. abundance and trends) and impacts on many protected species.

There are multiple potential sources of human-induced mortality for white sharks across southern and south west Australia. These include a large number of commercial and recreational fishing activities each of which may have potentially captured from less than one white shark per year up to more than 100 per year (refer to Chapter 5). Consequently, to provide a basis for more accurate estimation of historical white shark catches, an examination was undertaken of the likely levels of mortality associated with each of the various commercial and recreational fisheries that currently operate, or have operated in this region, plus other potential sources of mortality. This first stage analysis covered fisheries where white shark catches had been reported but also fisheries where the fishing gear used or other activities could have potentially resulted in the capture or death of white sharks.

For those fisheries where the first stage analysis identified the potential for more substantial catches at some point in history, a more detailed set of analyses was completed (refer to Chapter 3 and 4). Finally, based on the estimates generated for each of these sources, a combined catch reconstruction for the south-western Australian population is presented in Chapter 5.

2.2 First Stage Analysis

2.2.1 Western Australian Temperate Demersal Gillnet and Demersal Longline Fisheries

The Western Australian Temperate Demersal Gillnet and Demersal Longline Fisheries (TDGDLF) are known to be the main source of white shark catches in Western Australia (Malcolm et al. 2001; McAuley & Simpfendorfer 2003; DoF, unpublished data) and as such a detailed catch reconstruction in these fisheries is presented in Chapter 3 and 5.

2.2.2 Northern shark fisheries in Western Australia

Various foreign and domestic shark fisheries have existed in northern Western Australia since the 1970s (Stevens 1999). A Taiwanese pelagic gillnet fishery targeted sharks off northern Australia between 1974 and 1986. This fishery operated in offshore waters between the Northwest Shelf and the north of the Gulf of Carpentaria and landed nearly 10,000 t of processed shark at its peak in 1977. These Taiwanese fishing vessels mostly operated off the Northern Territory coast and it is therefore unlikely that significant numbers of white sharks were caught.

The domestic Northern Shark Fisheries comprise the State-managed Western Australian North Coast Shark Fishery (WANCSF) in the Pilbara and western Kimberley, and the Joint Authority Northern Shark Fishery (JANSF) in the eastern Kimberley. Historically, these fisheries developed using demersally-set 800–1,000 hook dropline and longlines. Pelagic longlines were also used, although they were generally configured to target mackerel (Scombridae), using monofilament rather than metal snoods (Department of Fisheries 2005). A small amount of pelagic gillnetting also occurred in the JANSF but there has been a cessation of fishing activity in these fisheries since 2009 (Department of Fisheries 2011).

The Northern Shark Fisheries have variously targeted sandbar and blacktip (*C. limbatus*, *C. tilstoni*) sharks and have also caught relatively sizable quantities of tiger (*Gaelocerdo cuvier*), lemon (*Negaprion acutidens*) and hammerhead (family Sphyrnidae) sharks. Previously, the majority of these fisheries' income came from the sale of shark fins for export, which created a financial incentive for fishers to target larger sharks (Department of Fisheries 2005; McAuley et al. 2005). Domestic vessels operating in the western half of the WANCSF, however did operate within the species' known range. A photographic record confirmed the capture of a single white shark by a demersal longline off North West Cape in 2002. However, DoF research staff observed no white shark captures by WANCSF longliners between 2000 and 2005 (Bensley et al. 2010, Appendix E). As the majority of fishing effort in the Northern Shark Fisheries occurred outside of the known distribution of the south-western white shark population, this potential source of mortality is not considered material for inclusion in the subsequent analysis.

2.2.3 Western Australian 'wetline' methods

Wetline fishing mostly refers to commercial hook and line fishing activities but can, however, also be used more broadly to describe other types of commercial fishing activities, such as netting, jigging and hand fishing methods. The term is mostly associated with fisheries or activities that are not (or were not) regulated by specific legislation such as management plans or Section 43 orders (Department of Fisheries 2006).

Until the practice was prohibited in November 2002 (Reg. 56A), some West Coast Rock Lobster (WCRL) fishers are known to have attached large hooks and metal wire snoods/chains to their pot-floats to target large sharks, primarily for their fins (Borg & McAuley 2004). This activity was also practiced by some TDGDLF operators, who attached hooks to net floats until the use of metal trace material was generally prohibited throughout Western Australian commercial fisheries in November 2008 (although this was uncommon after the pot-hook prohibition in 2002). It is not possible to accurately quantify how many fishers used droplines, when they were used or what their catches were, as this information was not reliably reported in catch returns. However, wetline hook methods contributed to an unquantified fishing mortality of older dusky sharks outside the target fisheries, causing a slow decline in breeding stock biomass and recruitment of neonate sharks to the fishery (Borg & McAuley 2004).

While DoF staff also reported occasionally observing pot-hooks being used in the WCRL Fishery, it is unclear how many vessels used them, how often they used them or how much of the 'dropline' shark catch recorded in fishing returns statistics was taken by this type of targeted fishing gear. The only recorded information on pot-float shark catches is from a voluntary research logbook filled out by a single B Zone WCRL fisher in 1999/2000. This fisher recorded using up to eight hooks per set for most of a single season (December to June). In total, 149 sharks were caught including one white shark (approximately 4 m TL) that was dead upon retrieval. Tiger sharks and dusky sharks comprised the majority of the catch (55% and 37% by number, respectively). Another WCRL fisher who was known to have used droplines was also interviewed. This fisher recalled catching fairly large numbers of sandbar sharks and bronze whaler sharks (*C. obscurus* and *C. brachyurus*) on float hooks in B Zone but reported never catching a white shark. He also corroborated first-hand reports from research staff that droplines were only ever used by a minority of fishers in the WCRLF. White sharks caught using this 'wetline' method were included in the historical catch reconstruction and the assumptions required to estimate these catches are outlined in Chapter 5.

2.2.4 South Coast Nearshore and Estuarine Finfish Fisheries

Within the near-shore waters of the South Coast Bioregion, beach-based fishers have used a variety of methods to catch finfish such as Australian herring (*Arripis georgianus*), Australian salmon, small quantities of southern sea garfish (*Hyporhamphus melanochir*) and sea mullet (*Mugil cephalus*). These species have been targeted using trap nets (herring only), beach seines, haul nets and gillnets (Smith et al. 2013). Although no white shark catches have been reported in commercial South Coast nearshore and estuarine fishing returns, they are known to be caught occasionally by the small-mesh (i.e. <114 mm) gillnets that are used. Although white sharks might be unlikely to be entangled in these nets' light gauge (diameter) monofilament mesh, headlines and groundlines, the capture of a 4.1m FL adult shark in a herring net off Cheynes Beach in April 2013, demonstrates that such captures are possible. However, due to these gear characteristics, the short net lengths used and these fishing activities' proximity to shore, white shark catches in these fisheries are believed to be rare and sporadic.

Beach-based netting for Australian salmon has occurred around the South West and South coasts of Western Australia since at least the 1940s. White sharks are known to feed on Australian salmon and anecdotal reports suggest that they are occasionally spotted swimming among salmon schools. Given this likely association between white sharks and schools of this prey species, and the long history of commercial salmon fishing in Western Australia, it is probable that white sharks have occasionally been caught by salmon fishers. Historical accounts from one fishing family (1929–2004) confirm the occasional capture of sharks, including white sharks, by salmon fishers (Heberle 2006). However, according to this account, it is unclear how many white sharks were caught and whether they were caught using nets or hooks. Interviews with several long-term operators in these fisheries, suggest that white shark captures in salmon nets are extremely rare. These potential catches have not been included in the catch reconstruction.

2.2.5 Western Australian Purse Seine Fisheries

The South Coast and West Coast Purse Seine Fisheries mainly catch pilchards (*Sardinops sagax*) and the tropical sardine (*Sardinella lemuru*, also known as scaly mackerel or sardinella, Molony et al. 2014). Combined fishing effort has declined substantially in both of these fisheries since its peak of over 12,000 fishing days in the early 1990s to less than 3,000 days since 2008. Both South Coast and West Coast Purse Seine fleets have also shrunk by more than 60% to a combined total of 19 vessels in 2013.

Purse seine fishery catch records contain very small catches (<1t per annum) of demersal shark species, comprised of mainly 'bronze' whaler sharks (Carcharhinus spp.; DoF, unpublished data) but no records of white shark captures. The size composition of these catches cannot be determined from returns data. These fisheries are referred to in this report on the basis of a single capture of a (live) white shark that was reported to DoF staff as a possible tagging opportunity by a West Coast purse seiner in 2012 and several captures by South Australian vessels (refer to Section 2.2.13.). Catches in these fisheries are therefore known to occur but suspected to be very rare and all are likely to be released alive and have therefore not been included in the subsequent analysis.

2.2.6 Recreational fishing in Western Australia

Successive recreational fishing surveys have recorded that sharks have historically been a very small component of boat-based recreational catches in Western Australia (Sumner & Williamson 1999; Ryan et al. 2013). Sharks comprised less than 1% of the total state-wide boat-based recreational catch (retained and released) in 2011/12 (Ryan et al. 2013). This catch consisted mostly of whaler (*Carcharhinus spp.*), gummy, Port Jackson (*Heterodontus portusjacksoni*) and wobbegong sharks (family Orectolobidae). A total of 79% of all boat based recreationally-caught sharks were estimated to have been released in 2011/12 (Ryan et al. 2013).

Recreational shark catches include those from game fishers who commonly fish beyond the continental shelf break in oceanic waters (Cheshire et al. 2013). Game fishing has occurred in Western Australia for over 60 years, with the establishment of the Western Australian Game Fish Association in 1949 (WAGFA 2014). Currently, there are approximately 1,400 fishers registered with WAGFA, the majority of who fish on the West Coast north of Geographe Bay (John Webber, *pers comm*). In comparison to Victoria, New South Wales and South Australia, sharks are less of a target for game fishers in Western Australia, although a small number of fishers reportedly target whaler sharks, makos and hammerheads. Whalers and tiger sharks have been tagged and released by recreational game fishers, particularly in Exmouth and Broome where game fishing for marlin and other billfish is popular (Pepperell 2011).

There are no requirements under the Fish Resources Management Act (1994) for recreational fishers to report catches to DoF. Information on recreational white shark catches are therefore obtained or inferred from recreational fishing surveys, game fishing records and anecdotal reports from fishers. Recreational fishing surveys are typically designed to provide robust catch estimates for commonly caught recreational species and not for rarely caught species, such as white sharks. The fact that no white sharks have been reported in recent and past surveys of boat-based fishers suggests that this species is rarely caught by recreational fishers in Western Australia (Sumner & Williamson 1999; Ryan et al. 2013). Furthermore, only a very small number of surveyed fishers targeted sharks with the majority using fishing gear not suitable for retaining large sharks. Consequently most white sharks that are hooked by recreational fishing gear are highly likely to break loose.

White shark captures are absent from Western Australian Game Fishing Association (WAGFA) records and the species' protection now excludes them as a valid gamefish species. Anecdotal accounts indicate that even prior to their protection, white shark captures by game fishers in Western Australia were extremely rare (J. Webber, *pers comm*). However, as not all game fishing activities are conducted under the auspices of a club or the State association, occasional historical captures cannot be ruled out. These sources of mortality are not considered material for subsequent analysis.

2.2.7 Recreational white shark catches at Albany whaling station

White sharks were anecdotally known to have been caught and killed in King George Sound during the latter years of the Albany whaling station's operations in Frenchman's Bay in the 1970s. A DoF officer (now retired) who was stationed in Albany during this period was interviewed to verify and quantify these anecdotal reports. He reported that a very small number of individuals associated with the whaling station, chaser boat crew, locals and game fishers occasionally fished for white sharks off the whaling station (C. Ostle, *pers comm*). He also reported that he was unaware of any white shark catches occurring before his time in Albany but doubted that there were many. Based on detailed personal records that he kept of almost all white shark catches around the whaling station throughout most of the 1970s, he reported that 10–12 white sharks were caught each year in King George Sound over a 7 year period before the closure of the whaling station in 1978. These catches were included in the historical catch reconstruction (refer to Chapter 5).

2.2.8 Other non-commercial sources of white shark mortality

One Albany-based commercial fisher who was interviewed about his TDGDLF catches, claimed to have shot a white shark that was scavenging a whale carcass at Cheynes Beach around the time the whaling station was still operating (i.e. before protection) and also reported having seen a recreational fisher shoot another under the same circumstances. Along with multiple anecdotal reports of people shooting large sharks in other popular fishing locations around Western Australia, it is possible that there have been multiple instances prior to protection of white sharks being shot at when they have been perceived as being a nuisance to various fishing activities. However, as these anecdotal reports are impossible to substantiate and the levels of mortality were not considered material for use in subsequent analysis.

2.2.9 Commonwealth Southern and Eastern Scalefish and Shark Fishery

The Commonwealth-managed Southern and Eastern Scalefish and Shark Fishery (SESSF) is a geographically-extensive, multi-sectoral, multi-species fishery that operates from south-western Western Australia to South East Queensland (Walker & Gason 2009). Targeted fishing for gummy sharks occurs within the gillnet, hook and trap (GHaT) sector. This fishery is believed to have had the largest historical catch of white sharks from the south-western Australian white shark population (Malcolm et al. 2001). All available catch data are reported in Chapter 4 and a catch reconstruction for this fishery is presented in Chapter 5.

2.2.10 South Australian Marine Scalefish Fishery

The South Australian Marine Scalefish Fishery (MSF) operates in coastal waters of South Australia including gulfs, bays and estuaries from the Western Australian border to the Victorian border (Noell et al. 2006). The term 'scalefish' is a misnomer, in that the fishery catches over 60 species of teleosts, sharks, molluscs, crustaceans and annelids using 27 different fishing methods (Noell et al. 2006). King George Whiting (*Sillaginodes punctatus*), southern garfish (*Hyporhamphus melanochir*), snapper and southern calamari (*Sepioteuthis australis*) comprise 60% of the commercial harvest by weight (Fowler et al. 2012). Within the MSF, whaler sharks (primarily bronze whaler sharks) have been targeted using longlines and large mesh size gillnets. This fishery is believed to have captured relatively substantial numbers of white sharks (Malcolm et al. 2001) and as such, all available catch data are reported in Chapter 4 and a catch reconstruction for this fishery is presented in Chapter 5.

2.2.11 South Australian Charter Boat Fishery

In 2010 there were 108 South Australian Charter Boat Fishery (SACBF) licence holders, of whom 77 actively participated in the fishery. Rod and line fishing is by far the most common method used in the SACBF and the primary target species are snapper and King George whiting but, regionally, include Bight redfish (*Centroberyx affinis*), snook (*Sphyraena novaehollandiae*), Australian salmon, yellow tail kingfish (*Seriola lalandi*) and samson fish (*Seriola hippos*) (PIRSA 2010). Long-term catch and effort data for the SACBF are unavailable as there were no formal data collection requirements prior to 1 July 2005. Since then, however, licencing regulations require operators to fill in fishing log sheets for each trip (PIRSA 2010).

Nine white shark interactions were reported in the SACBF between 2008/09 and 2010/11 (Knight & Vainickis 2011), five of which were reported as caught and released. The remaining four shark interactions were reported in the 'other category' and their nature is unclear. As there is a lack of any long-term information on potential white shark catches, this potential source of mortality was not considered further in the subsequent analysis.

2.2.12 Western Tuna and Billfish Fishery

The Western Tuna and Billfish fishery (WTBF, formerly the Southern and Western Tuna and Billfish Fishery) operates west from the tip of Cape York in Queensland, around Western Australia, to the border between Victoria and South Australia. Fishing occurs in both the Australian Fishing Zone (AFZ) and adjacent high seas. The fishery primarily targets bigeye (*Thunnus obesus*) and yellowfin tuna (*Thunnus albacares*), striped marlin (*Kajikia audax)* and swordfish (*Xiphias gladius*). Fishing methods include pelagic longlines with monofilament snoods, with lesser use of handline, rod and reel, trolling and polling and purse seine. Fishery products are primarily landed at Fremantle and Geraldton (Woodhams et al. 2012). Between 1979 and 2007, Japanese vessels fished within the Australian Fishing Zone under a bilateral agreement. However, as Japanese vessels exited the fishery, the domestic fleet expanded and annual domestic fishing effort peaked at over 6 million hooks and 46 vessels during the late 1990s and early 2000s, when almost 3,500 t of mostly swordfish was landed (Kailish et al. 2004; Stewart et al. 2012). Effort has since declined and is currently extremely low, with fewer than 5 boats landing less than 300 t of product in 2012.

No white sharks catches have been reported in the WTBF. Reported elasmobranch bycatch currently consists mostly of shortfin mako (*Isurus oxyrinchus*); in 2011, 481 were hooked, 31 of which were dead and 450 were released in an unknown condition (Woodhams et al. 2012). Previously, observer programs have identified blue (*Prionace glauca*) and crocodile (*Pseudocarcharias kamoharai*) sharks as the WTBF's main chondrichthyan bycatch species (Harris & Ward 1999; Ward & Curran 2004). However, concerns about unrecorded WTBF catches of continental shelf-associated shark stocks, especially dusky sharks, between the late 1990s and mid-2000s when fishing effort was concentrated relatively close to shore, contributed to an interim ban on the use of wire traces in the WTBF (Kailish et al. 2004). Given the distribution and magnitude of fishing effort during this period and evidence from independent observers of pelagic longline gear catching coastal shark species (Borg & McAuley 2004), it is possible that catches of white sharks in the WTBF may have occurred during this phase of the fishery. However, this potential source of mortality could not be quantified and was not considered any further in subsequent analysis.

2.2.13 Southern Bluefin Tuna Fishery

The Australian Southern Bluefin Tuna Fishery (SBTF) began aquaculture activities (fish farming) off Port Lincoln in 1991, following a decline in the wild stock. Now more than 98% of Australian-produced southern bluefin tuna (*Thunnus maccoyii*) is farmed (Woodhams et al. 2012). This process involves purse-seiners catching juvenile fish in the Great Australian Bight and transferring them to sea-cage facilities off Port Lincoln, where they are grown to high market-value sizes.

White sharks are reported to have been caught during SBTF purse seine fishing, towing operations and in sea cages. In 2010/11, two white sharks were reportedly caught in and released alive from a SBTF purse seine (Woodhams et al. 2012). However, as purse seine and farming operations have been modified to enable the removal of large sharks and techniques have been developed to enable sharks' release from tow cages (AFMA 2008), it seems logical to assume that white shark captures historically occurred more frequently than has been reported. This assumption is supported by anecdotal reports from fishers that catches (fate unknown) in tuna tow cages and in inshore tuna farm cages may have been between 2 and 20 sharks a year (Malcolm et al. 2001). As this potential source of mortality could not be substantiated any further, it was not considered in subsequent analysis.

2.2.14 Recreational fishing in South Australia

An estimated 236,463 South Australians fished recreationally in the 12 months prior to October 2007 (Jones, 2009). Rod and line fishing is by far the most popular method, although fishing with pots and traps also occurs. Sharks comprised less than 1% of the total recreational catch in South Australia during 2007/08 and mostly consisted of gummy sharks. Prior to white sharks' listing as a protected species, targeted game fishing occurred in South Australia (Bruce, 1992). According to Game Fishing Club of South Australia (GFCSA) records, white sharks were mainly caught within South Australian State waters, adjacent to Australian sea lion and New Zealand fur seal colonies such as Dangerous Reef, Pages, Sir Joseph Banks Group, Streaky Bay and Ceduna (Malcolm et al. 2001).

Unlike in Western Australia, game fishers in South Australia targeted and recorded catching white sharks. Long-term GFCSA records confirm the capture of 171 white sharks between 1938–1990, the majority of which would have been landed (Bruce 1992). These records were used in the historical catch reconstruction (refer to Chapter 5).

3 White shark catch reconstruction in Western Australian Temperate Demersal Gillnet and Demersal Longline Fisheries

3.1 Introduction

Commercial fishing for sharks in Western Australia began with a single boat setting demersal longlines to catch gummy sharks in the Leschenault Inlet and off Bunbury in 1941 (Heald 1987). By 1942, there were six boats targeting sharks in coastal waters close to Bunbury. During the late 1940s, 1950s and 1960s, shark fishing expanded to the ports of Albany, Fremantle and Geraldton and targeted shark fishing effort steadily increased (Figure 1). Over this time, multi-filament and then mono-filament demersal gillnets gradually replaced longlines as the preferred commercial shark fishing method. Despite a brief decline in shark fishing due to concerns about mercury contamination during the early 1970s (Hancock et al. 1977; Simpfendorfer & Donohue 1998), commercial shark fishing expanded around the State and into deeper coastal waters during the 1980s. However, declining catch rates of species targeted by these largely unregulated fishing activities, led to the introduction of the State's first management plan for shark fishing off the South and southwest coasts in 1988. The Joint Authority Southern Demersal Gillnet and Demersal Longline Fishery (JASDGDLF) plan restricted the use of large-mesh demersal gillnets and longlines south of 33° S to a limited number of fishers and specified the maximum effort that could be applied in two zones (McAuley & Simpfendorfer 2003).

To limit shark fishing off the west coast, the use of powered net-reels (which most dedicated shark fishing vessels relied upon) was also restricted in 1988 and the use of large-mesh gillnets and longlines between Steep Point (26.5° S) and Northwest Cape (114° E) was prohibited in 1993. An interim management plan for the use of demersal gillnets and longlines off the west coast was then implemented in 1997. The West Coast Demersal Gillnet and Demersal Longline Fishery (WCDGDLF) plan provided similar and complementary management arrangements for shark fishing as the JASDGDLF (McAuley & Simpfendorfer 2003). Due to their similarities in fishing methods, target stocks and management, these two fisheries are collectively known as the Western Australian Temperate Demersal Gillnet and Demersal Longline Fisheries (TDGDLF; Figure 2).

Fishers in the TDGDLF have traditionally targeted adult gummy and whiskery sharks and juvenile dusky and sandbar sharks using bottom set monofilament gillnets of typically 15.2 or 17.8 cm (stretched) mesh sizes. Net lengths are restricted to 8,235 m, although in practice most fishers use less than half that length. Demersal gillnets have traditionally accounted for 85–99% of standardised fishing effort in the TDGDLF but a small number of operators have used bottom set longlines to target similar stock components as the gillnet fleet. Both fisheries are managed by input controls in the form of transferrable time/gear effort units. The value of these units was reduced between 1992 and 2002 to address emerging sustainability risks to the fisheries' target stocks. In 2006/07, a more explicit hourly effort management system was introduced, which removed excessive latent effort capacity and restricted effort within each management zone to 2001/02 levels (Braccini et al. 2014). Additional gear restrictions, seasonal and area closures and size limits have also been introduced in response to specific sustainability risks since 2006. There are 57 licences in the JASDGDLF (24 in Zone 1 and 33 in Zone 2) and 20 WCDGDLF permits, however, only 5 Zone 1, 13 Zone 2 and 4 WCDGDLF vessels reported active fishing returns during 2012/13, similar to the levels of participation in the fisheries over the previous five years.

The TDGDLF is known to be the main source of white shark catches in Western Australia (Malcolm et al. 2001; McAuley & Simpfendorfer 2003; DoF, unpublished data). However, formal mechanisms for reporting protected species captures in these fisheries were only introduced in June 2005, hence there is no reliable long-term record of white sharks' catches. In the absence of long-term fishing records, personal interviews with fishers can be used to estimate catches of rarely caught or non-target species (Neis et al. 1999). For example, interviews with long-term fishers have been used to reconstruct catches of teleosts (Saenz–Arroyo et al. 2005), elasmobranchs (Maynou et al. 2011) and cetaceans (Peterson & Carothers 2013). It is recognized that catch reconstructions typically provide relative and not absolute values (Neis et al. 1999; O'Donnell et al. 2010; Golden et al. 2013) because of systematic errors caused by differences in the completeness or accuracy of the recall of past events (known as recall bias). Nonetheless, there is some evidence that more salient events are less subject to recall decay (Beegle et al. 2012) and for memorable and rare events, such as the capture of white sharks, the effects of recall bias may be less pronounced (Pollock et al. 1994).

The substantial number of current fishers who have operated in the TDGDLF for decades are likely to be the best available source of information on the magnitude of historical white shark bycatch off Western Australia and how this might have changed over time. Long-term fishers' recollections of their own white shark catches (including sharks kept and released) were therefore collected through confidential interviews and the resulting data were used to reconstruct the best-possible historical estimates of total TDGDLF bycatch in these fisheries. Ancillary information about the sizes and seasonality of white shark captures and fishers' perceptions about changes in their abundance was also recorded during interviews. Fishers' attitudes towards mandatory reporting of white shark captures were also recorded and examined to better understand the potential implications and biases of using fishery-dependent records of protected species' catches as a potential index of population abundance.

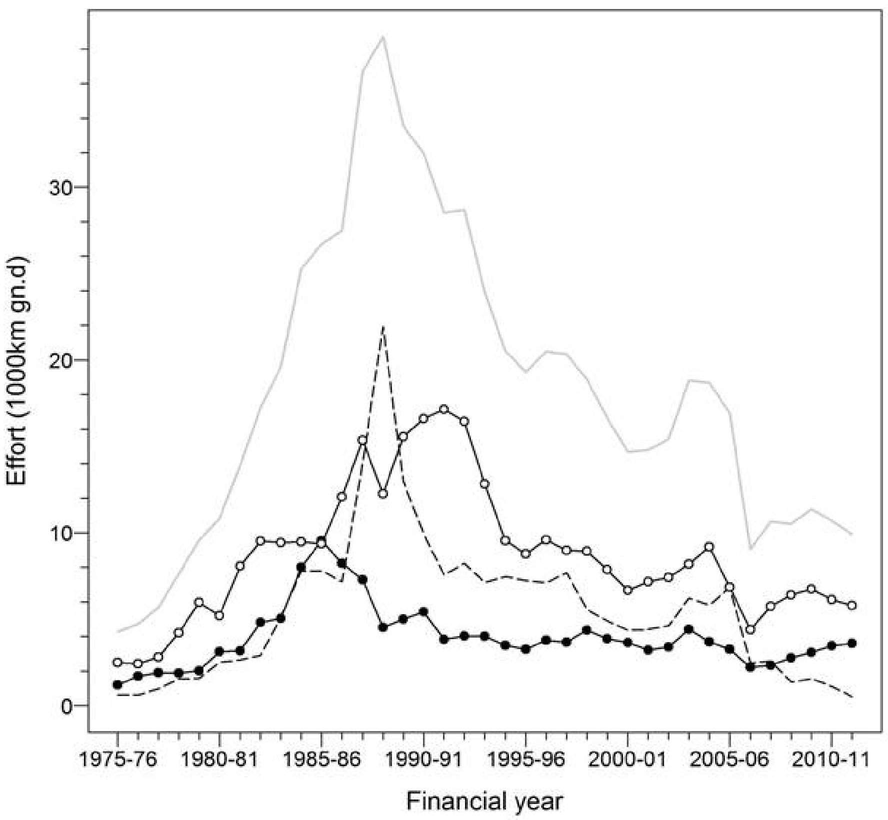


Figure 1. Standardised gillnet and demersal longline fishing effort within the Western Australian Temperate Demersal Gillnet and Demersal Longline Fisheries. Black circles = JASDGDLF Zone 1; white circles = JASDGDLF Zone 2; dashed black line = WCDGDLF; plain grey line = the total for the three management zones.

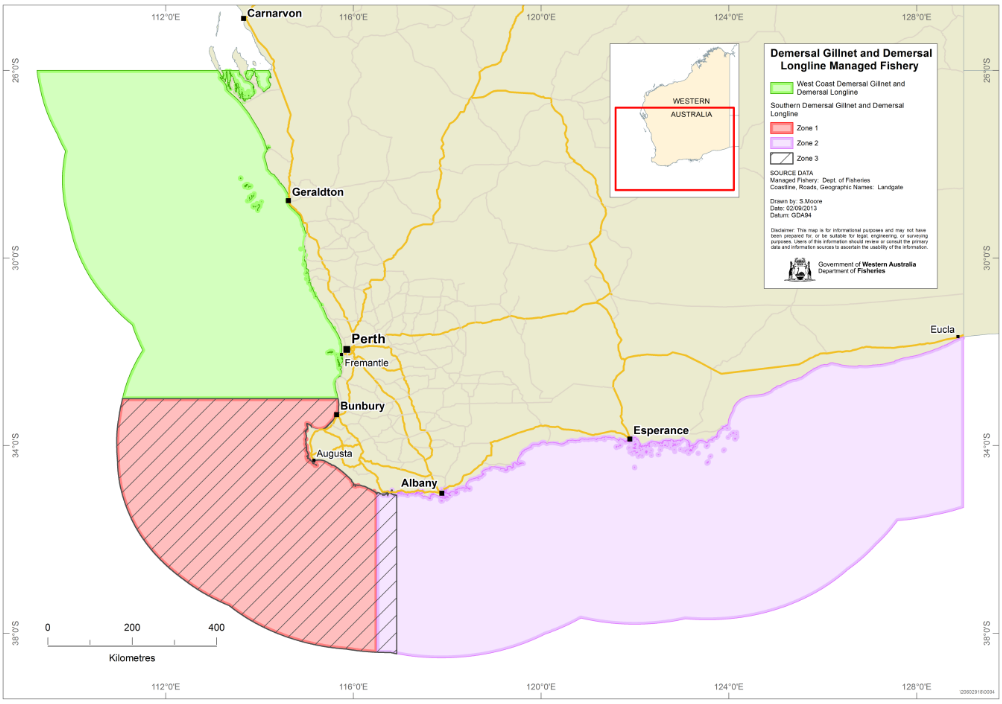


Figure 2. Management boundaries of the Joint Authority Southern Demersal Gillnet and Demersal Longline Fishery (JASDGDLF; red=Zone 1, purple=Zone 2, diagonal hatching= Zone 3) and West Coast Demersal Gillnet and Demersal Longline Fishery (WCDGDLF, in green).

3.2 Methods

3.2.1 Survey overview

Past and present TDGDLF operators were interviewed during a structured survey in 2013 (Figure 3). To ensure clarity, transparency and objectivity in the survey, the questionnaire and associated survey material were reviewed by several scientists experienced in designing surveys and then tested on a recently retired long-term TDGDLF fisher. During the survey recruitment stage (March to June 2013), every current licence holder (as of March 2013) was contacted by telephone and informed about the survey, its objectives and the confidentiality of information about white shark captures. A total of 36 current licence holders were phoned during the recruitment stage and aside from one, who was not available, all participated fully in the recruitment stage. Of the 35 licensees who were contacted, 30 were owner-operators, who were invited to take part in interviews. The other five licensees were business owners without first-hand experience of fishing operations and were therefore not interviewed in person during the second stage.

During the second (interview) stage (March to July 2013), fishers were interviewed in person, except for two, who were surveyed over the phone. The confidentiality of interviews was deemed necessary to overcome the potentially sensitive nature of reporting protected species catches. On the understanding that individuals' responses to interview questions would be treated as confidential, all fishers participated fully in the interview stage. During the interview, each fisher was asked a series of questions relating to:

- the dates they fished in the TDGDLF
- boats owned (boat names, vessel license (LFB) numbers)
- whether or not they were the only skipper and
- their fishing methods used (gillnets, longlines, droplines).

As 'droplines' are not a managed TDGDLF fishing method, their catches are discussed separately, alongside other 'wetline' methods in Chapter 5. Fishers' responses revealed that the capture of white sharks using longlines in the TDGDLF was extremely rare – only one shark was reported and this animal was foul-hooked through the caudal fin. As such, longline fishing effort was excluded from the analysis and only gillnet effort was considered.

To assist in recall of white shark catch information, the survey was split into four time periods, corresponding to key and memorable events in the fisheries (Table 1). In some instances, these timelines were annotated by fishers to include their own memorable events (both personal and professional), which assisted in the recall of catch information. Fishers were asked to think across their entire TDGDLF fishing career and recall whether they had ever caught a white shark. They were informed that white shark catches could refer to any type of fishing gear and included sharks that were retained, discarded or released. If a fisher recalled catching a white shark (or white sharks), he was asked how many and by what method within each of the survey time periods.

Table 1. Time periods used in the survey for reporting the catch of white sharks.

Time period	Relevance of time period	
	Start	**End**
1975/76–1987/88	1975/76–mandatory catch and effort data reporting introduced.	1987/88–final year before the JASDGDLF declared limited entry*.
1988/89–1996/97	1988/89– JASDGDLF management plan introduced.	1996/97–final year before white sharks protected in WA.
1997/98–2004/05	1997/98–first year in which white sharks listed as a protected species in WA**. WCDGDLF (interim) management plan introduced.	2004/05–final year of monthly catch and effort reporting.
2005/06–2012/13	2005/06–New effort management system and daily catch and effort logbooks introduced with explicit protected species reporting field.	2012/13–interviews with fishers took place.

* Joint Authority Southern Demersal Gillnet and Demersal Longline fishery (JASDGDLF) declared in May 1988

** White sharks protected under the WA Fisheries Resources Management Act (1994) in November 1997 and under the Commonwealth Protected Species Act in December 1997

Most interviewed fishers were full-time skippers, however, several were part-time and/or not always on-board their boat when it was fishing. In these cases, interviewees were asked to estimate the percentage of the time they spent fishing and, assuming constant catchability between skippers, this information was used to extrapolate their catches to account for catches by other skippers of their vessel(s), which they did not personally observe.

Fishers were given maps of the fisheries, overlaid with a grid of one degree blocks (as per the reporting blocks in their pre-2006 fishing returns) and asked to tick the blocks where they had caught white sharks. Fishers were also asked to highlight the block(s) where most white sharks were caught but were not asked to quantify how many sharks they had caught in each of the blocks because the pilot study suggested this information could not be reliably determined. Catch estimates were instead restricted to each fisher's estimated catch by fishing method within each of the time periods (see above). Similarly, it was not considered reliable to ask fishers how many sharks they caught in each season and they were instead asked in which season(s) they had caught the most. Fishers were also asked to recall the average length of captured white sharks (notionally Total Length in meters).

In the final part of the survey, fishers were asked to rank their level of acceptance with the statement "Great white shark catch data reported in daily logs provide reliable information on the total number of white sharks caught in Western Australian Temperate Demersal Gillnet and Demersal Longline fisheries". Responses were coded as 'strongly agree', 'agree' 'neither agree nor disagree', 'mildly disagree' or 'strongly disagree'. If a fisher expressed a level of disagreement, they were prompted for the reason and all responses were recorded *per verbatim* and later coded into mutually exclusive categories.

Fishers were also asked to rank their response to the following question "Would you say that the abundance of white sharks in Western Australia today, in 2013, is greater than, about the same, or less than when you started commercially fishing for sharks?" Fishers were prompted for the reason for their answer and all responses were recorded *per verbatim* and later recorded into mutually exclusive categories.

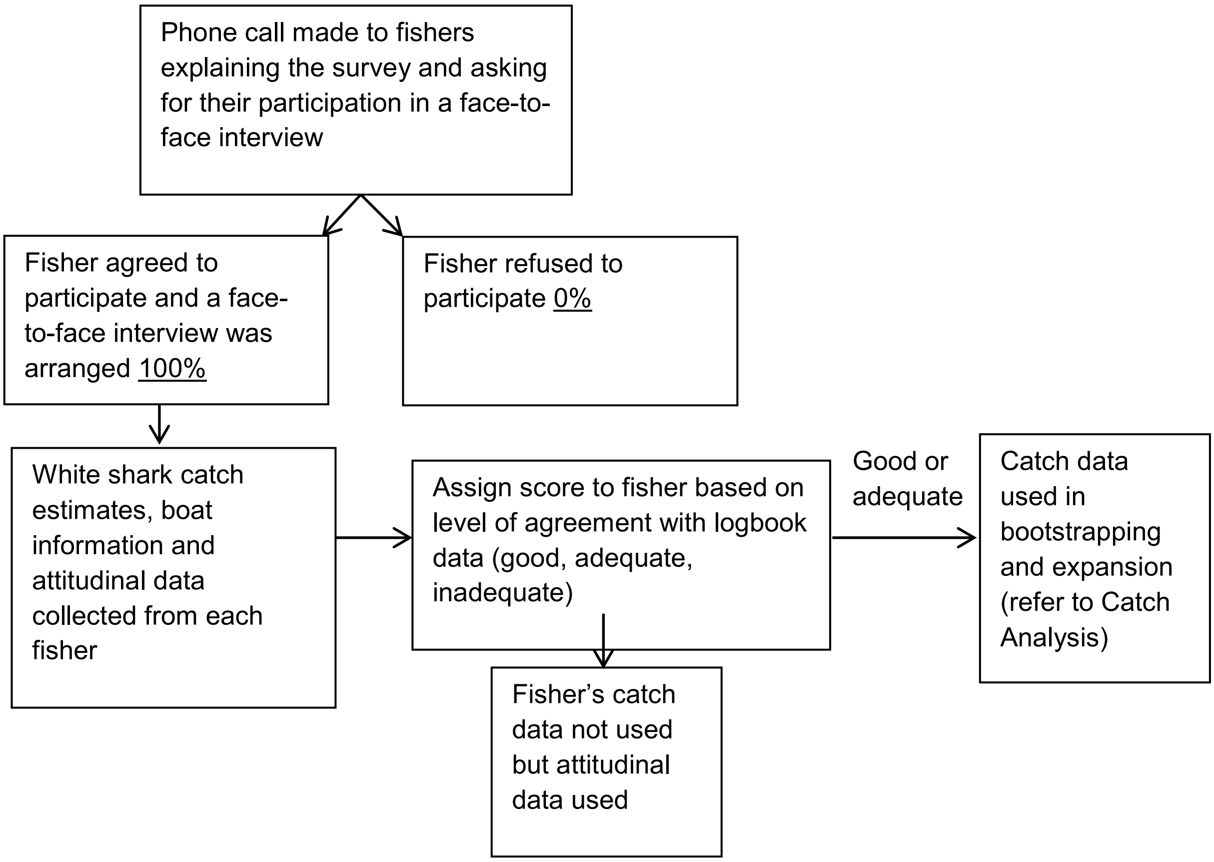


Figure 3. Overview of the survey process.

3.2.2 Linking survey and logbook information

The survey provided (1) white shark catch estimates (number of sharks per time period), while (2) fishers' monthly returns and daily logbooks provided information on fishing effort. Before these two sources of information were linked, each interviewed fisher was assigned a score of 'good', 'adequate' or 'inadequate'. These scores were based on whether each fisher could recall whether or not a white shark was caught within each of the time periods they fished in and the level of agreement between boat information (Vessel ID, boat name, skipper name, years owned) collected during the interviews and that maintained in Department of Fisheries' records. Three fishers were unable to recall whether they caught white sharks in each of the time periods they fished in (refer to Appendix A) and their catch information was not used in subsequent catch reconstruction calculations. Information from the remaining 27 fishers was used in the subsequent analysis.

Although monthly effort data have been reported in fishing returns data from 1975/76 onwards, the field 'skipper name' was only included in fishing returns in 1988/89. As a result it was not possible to independently confirm that individual fishers' survey information referred to the correct vessel effort during the period between 1975/76 and 1987/88. Catch estimates in this chapter are therefore restricted to three subsequent periods: 1988/89 to 1996/97 (Period 1), 1997/98 to 2004/05 (Period 2) and 2005/06 to 2012/13 (Period 3). An alternative approach was used to estimate TDGDLF white shark catches prior to 1988, as described in Chapter 5.

Interviewed fishers' gillnet fishing effort was calculated as a proportion of total effort in each period and management area, i.e. Zones 1 and 2 of the JASDGDLF and the WCDGDLF (referred to as West Coast). N.B. a small number of Zone 1 fishers had licence conditions (Zone 3) that allowed them access to the western 30 miles of Zone 2 (Figure 5). Because the Zone 1-Zone 2 boundary bisects the one degree blocks between 116° E and 117° E, Zone 3 catch and effort data could not be distinguished from Zone 1 data and were therefore combined.

Interviewed fishers' effort accounted for 50.1% of total TDGDLF gillnet fishing effort between 1988/89 and 2012/13. Survey coverage was highest for Period 3 when 79.8% of gillnet effort was exerted by interviewed fishers (Figure 4). Survey coverage was highest in Zone 1 and lowest in Zone 2. In Zone 2, interviewed fishers comprised only 8.6% of gillnet fishing effort during Period 1. Interviewed Zone 1 fishers' had the most experience (mean of 28.6 years, S.D.=5.1y) in comparison to a mean of 15.2 years (S.D.=11.5y) in the West Coast and a mean of 12.3 years (S.D.=6.3y) in Zone 2. This reflects a faster turn-over of fishers in Zone 2 in comparison to Zone 1 where the same fishers have tended to remain in the fishery for longer.

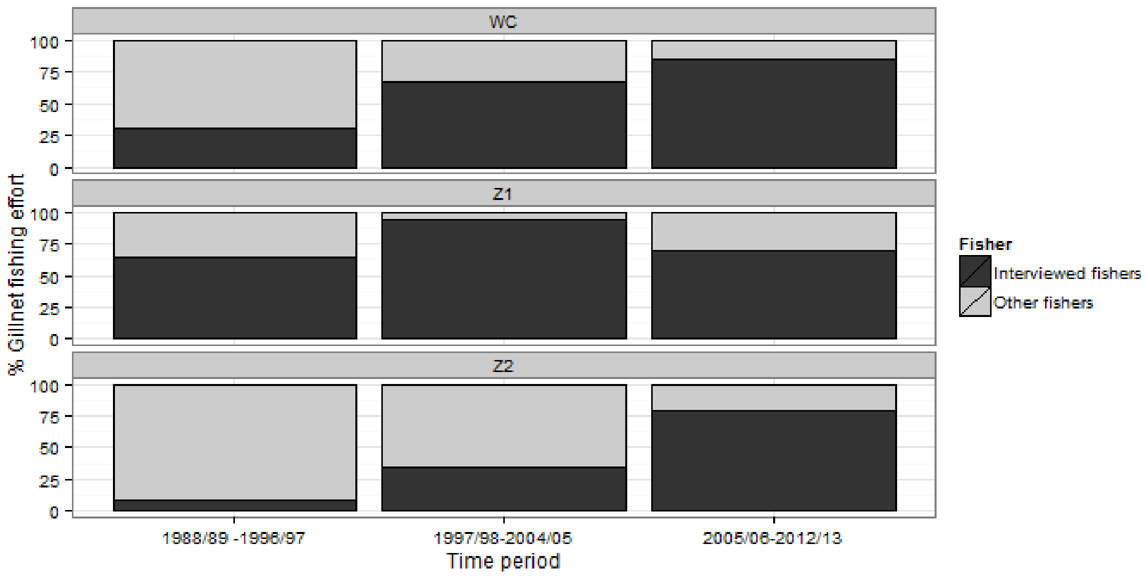


Figure 4. Gillnet fishing effort for interviewed fishers and other fishers by fishing region and time period. WC = West Coast, Z1 = Zone 1 and Z2 = Zone 2. 1988/89 to 1996/97 = Period 1, 1997/98 to 2004/05 = Period 2 and 2005/06 to 2012/13 = Period 3.

3.2.3 Catch reconstruction analysis

The underlying assumption of this catch reconstruction exercise is that interviewed fishers' white shark catch rates were representative of the total catch rate in each time period and fishing region. However, interviewed fishers were not a random sample of (past and present) all TDGDLF operators, as contact information was only available for currently licenced operators and for several recently retired fishers. Although the data obtained through the survey may not have been demonstrably representative, the gear used and areas (one degree blocks) fished by interviewed operators were generally the same as non-interviewed fishers (Appendix B). As interviewed and non-interviewed fishers also generally targeted the same stocks, it seems unlikely that individual fishing behaviours would differ sufficiently that white shark catch rates would be markedly different between vessels fishing with the same gear and in the same blocks.

The total white shark catch in each fishing region and time period was estimated using the formula:

$$\mathrm{C}_{\mathrm{p}}^{\mathrm{r}} = \mathrm{E}_{\mathrm{p}}^{\mathrm{r}} \,.\, \mathrm{R}_{\mathrm{p}}^{\mathrm{r}}$$

Where C is the total catch, E is total gillnet effort (1000 km gn.d) and R is interviewed fishers' white shark catch rate [sum of the number of sharks/sum of gillnet effort (1000 km gn.d)], within each fishing region (r) and time period (p).

A bootstrap procedure was used to account for uncertainty in interviewed fishers' catch estimates. No uncertainty in fishing effort was considered because this information came from monthly returns and daily logbooks. All bootstrapping and extrapolation routines were performed in R (R development core team 2012). In the bootstrap procedure, interviewed fishers' catch and effort data were randomly resampled (with replacement) for each region and period. While some fishers reported discrete catch estimate values, most reported their catches as a range and this variability was included in the bootstrapping routine. For example, if a fisher indicated he caught between 15 and 20 sharks and he was randomly sampled in a bootstrap iteration, a catch value of between 15 and 20 was randomly chosen. In total, 1,000 bootstrap iterations were run and the mean and 95% confidence intervals in the results were calculated.

To estimate the total catch for each region and period, bootstrapped catch estimates were extrapolated to account for un-interviewed fishers' catches in two different ways. In the first approach, bootstrapped estimates of individual fishers' catches were summed for each region and period and divided by the sum of interviewed fishers' fishing effort to provide the interviewed fishers' catch rate (R). The total catch for each region and period was then calculated as the product of interviewed fishers' catch rate and corresponding total fishing effort (i.e. interviewed and non-interviewed fishers' effort).

The second approach was used to examine the potential implications of the very low survey coverage in Zone 2 during the first 2 survey periods (8.6% and 34.7% of regional effort, respectively; Figure 4). Because Zone 2 survey coverage was high during Period 3 (78.8% of gillnet effort), there was greater confidence in the accuracy of these catch rate estimates. Based on Zone 1 survey coverage being high during all three periods, it was assumed that the relative changes in Zone 1 catch rates between periods were accurate and, it was further assumed, that the magnitude of these changes also occurred in Zone 2. Thus, Zone 2 catch rates for Periods 1 and 2 were re-estimated using the proportional changes in Zone 1 catch rates relative to the Zone 2 catch rates in Period 3, i.e.:

$$R_{P2}^{Z2} = (R_{P2}^{Z1}/R_{P3}^{Z1}).R_{P3}^{Z2}$$

and

$$R_{P1}^{Z2} = (R_{P1}^{Z1}/R_{P3}^{Z1}).R_{P3}^{Z2}$$

This approach was used in each bootstrap and the mean catch and 95% CI were estimated in the same way as the first method.

A small number of bootstraps resulted in catch totals for fishing regions and time periods that were less than the minimum values obtained from the raw survey data. These results were deemed unrealistic and were therefore excluded from further analysis. Bootstraps resulting in catch totals greater than the raw data were not excluded because this was entirely expected as the raw survey catch data related only to interviewed fishers while the bootstrapped catch totals were extrapolated to account for un-interviewed fishers' catches.

3.3 Results

3.3.1 Catch rates from interviewed fishers

The majority of interviewed fishers reported having caught a white shark (West Coast = 71.4%, Zone 1 = 100.0%, Zone 2 = 86.7%). The number of sharks caught per fisher was generally between 0 and 6 per year and in most cases was 1 or less a year (Figure 5). Multiple shark captures within one fishing event were very rare although in August 2008, one fisher reported catching four juveniles in one day in Bremer Bay, east of Albany, three of which were in the same 135 m long net panel. White sharks were mostly reported as being entangled in the float line or lead line of the net rather than being meshed.

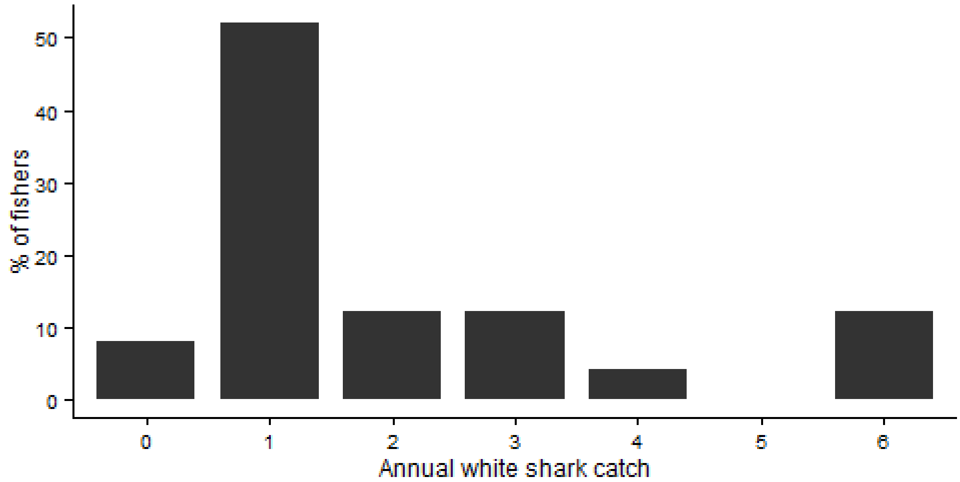


Figure 5. Interviewed fishers' annual white shark catch. The annual catch represents the estimated total number of sharks caught per fisher divided by their numbers of years' operating in the TDGDLF. Values are rounded up to the nearest whole number.

Both methods suggest that since 1988, maximum catch rates within a given zone and time period were less than 12 captures per thousand kilometre gillnet day (km gn d; Figure 6). These peak values were estimated for the periods and regions of lowest survey coverage (Zone 2 between 1988/89 and 1996/97 and in WC during the most recent period) and represent the upper limits of the most uncertain catch rate data. Most other estimates suggest that catch rates were less than half (4-6 km gn d) of the maximum estimated rates over the survey period.

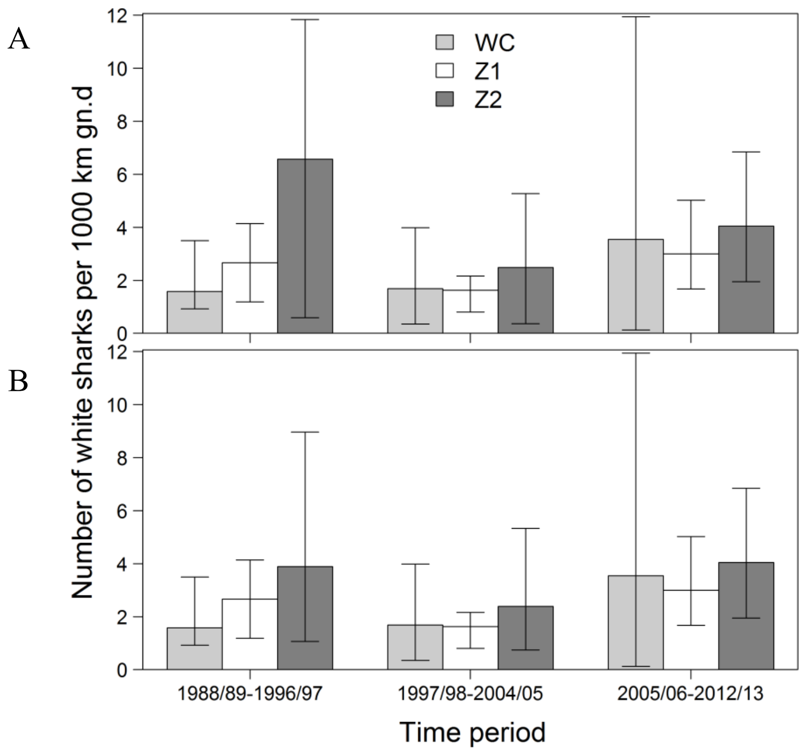


Figure 6. Catch rates of white sharks estimated from interviewed fishers' data based on (A) approach one and (B) approach two. Refer to the Catch Analysis section for a description of these two methods and the bootstrap procedure. WC = West Coast, Z1=Zone 1, Z2=Zone 2. Error bars illustrate 95% confidence intervals (CI).

3.3.2 Estimated total catch

By virtue of the larger fleet size and higher levels of fishing effort, the mean estimated catch of white sharks in Zone 2 of the JASDGDLF was 1.5 times greater than both the other zones during the most recent period (Figure 7). Annualised mean catch estimates were just over 5 in the West Coast, 8 in Zone 1 and 21 in Zone 2 during Period 3 and similar in the West Coast and Zone 1 during Period 2 (Table 2). Both estimation methods yielded similar mean catch estimates for Zone 2 catches during Period 2, which indicated that over 40% fewer white sharks were captured during the late 1990s-mid 2000s than during the most recent period, noting that the 95% confidence intervals of these mean catch estimates were large. While catch estimates for the earliest period were more uncertain than more recent estimates, survey data suggested that many more white sharks were caught between 1988/89 and 1996/97 in comparison to the subsequent two periods (Figure 7, Table 2). Relative to Period 3, approximately twice as many white sharks were caught in the West Coast and Zone 1 during Period 1 and catches could have been approximately two to three times greater in Zone 2 compared to Period 3 (according to methods 1 and 2, respectively). However, the levels of variability in the earliest estimates of Zone 2 catch dictates that these results should be interpreted with caution.

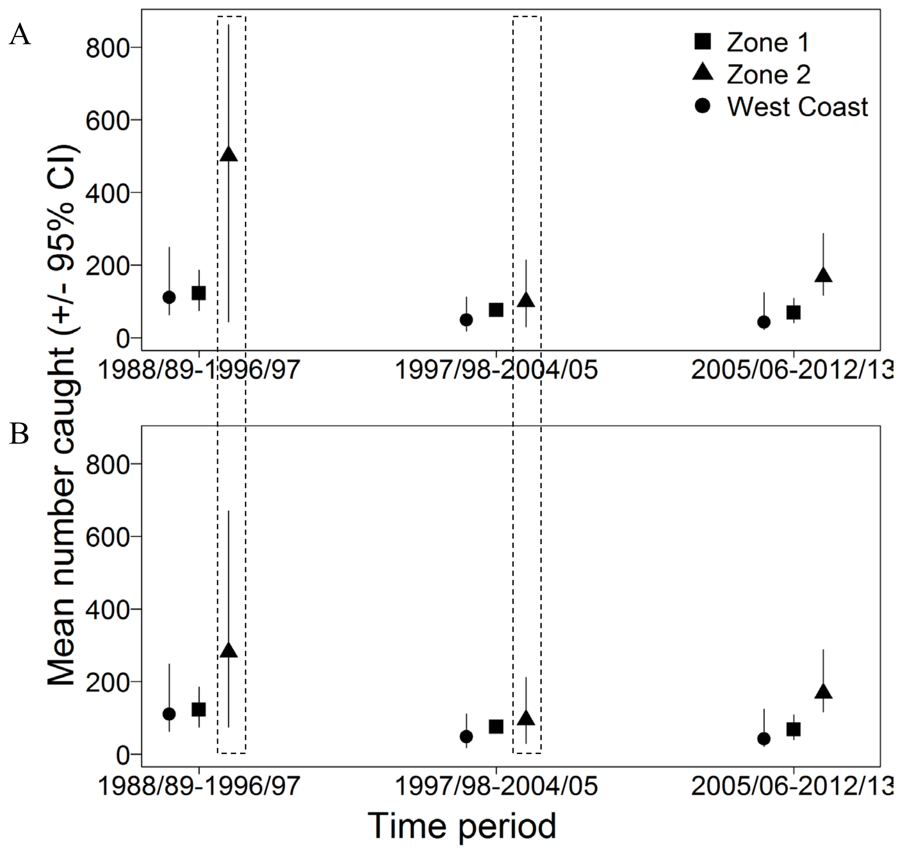


Figure 7. Estimated TDGDLF white shark catches (number of sharks) by period and region based on (A) estimation method 1 and (B) method 2. Symbols indicate the mean of bootstrapped estimates and error bars are the 95% confidence intervals of those estimates. Values within the dotted lines indicate those that changed according to which method was used. Refer to the Catch Analysis section for a description of these two methods.

Table 2. Mean estimates (and 95% Confidence Intervals) of TDGDLF white shark catches (number of sharks) by time period and region.

	Time period		
Fishing region	1988/89–1996/97	1997/98–2004/05	2005/06–2012/13
West Coast	109 (64–243)	48 (18–105)	42 (22–115)
Zone 1	124 (75–189)	77 (65–95)	67 (41–113)
Zone 2 (method 1)	495 (44–892)	99 (30–212)	171 (117–281)
Zone 2 (method 2)	299 (72–716)	102 (31–239)	171 (117–281)
Total (method 1)	728 (183–1324)	224 (113–412)	280 (180–509)
Total (method 2)	532 (211–1148)	227 (114–439)	280 (180–509)

3.3.3 Catch locations and seasonality

Interviewed fishers reported catching white sharks throughout the fishery (between the South Australian border and Kalbarri). Locations identified as being where the majority of sharks were caught tended to correspond with areas in which fishing effort was highest (Figure 8). There were however several locations off the south coast, in particular within the Great Australian Bight (GAB) and between Esperance and Eucla, where catches of white sharks were reported to be higher but where effort was relatively low. Several fishers who fished throughout much of Zone 2 also commented that they tended to catch more white sharks in the far-eastern waters of the JASDGDLF.

Fishers reported that most sharks were caught in all seasons, with 19.5% reporting this was in spring (September to November), 22.0% in summer (December to February), 29.3% in autumn (March to May) and 29.3% in winter (June to August). The slight increase in responses that most sharks were caught in autumn may have been influenced by the traditional increase in fishing effort at that time of year. The slightly higher number of fishers reporting that most sharks were caught in winter was despite the typical seasonal lull in fishing effort due to poor weather conditions and may indicate a higher abundance of white sharks throughout TDGDLF waters at that time of year (Figure 9). However, there may be more subtle regional differences in seasonal catch rates that were not examined due to the limited and unequal levels of survey coverage at finer scales.

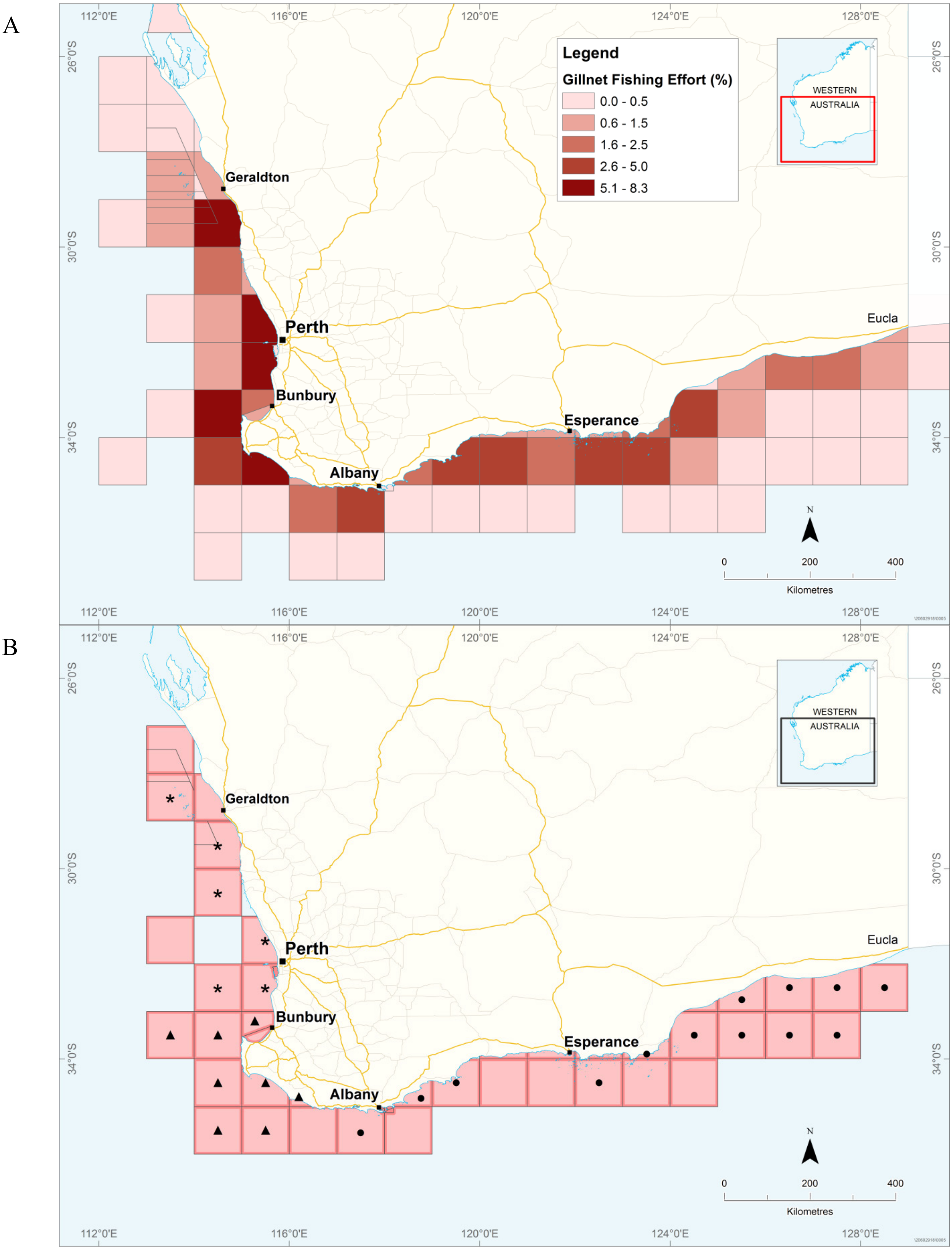


Figure 8. (A) Gillnet fishing effort (% of TDGDLF effort between 1988/89 and 2012/13) and (B) locations where white shark catches were reported between 1975 and 2013 by one degree blocks. In (B) red blocks are those where white sharks were caught. Black stars, triangles and circles indicate blocks where interviewed fishers reported catching most sharks in the WC, Z1 and Z2 regions, respectively.

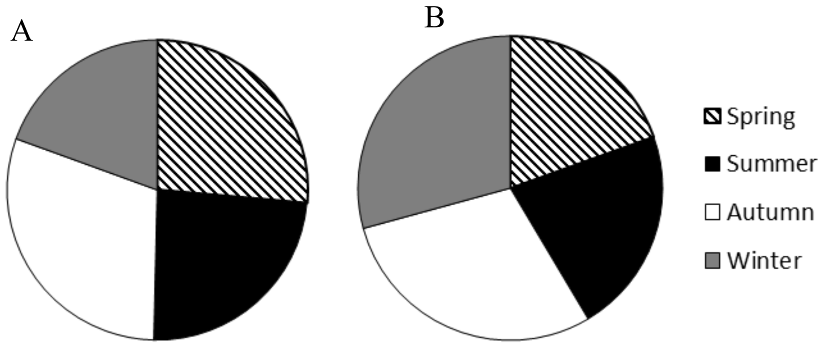


Figure 9. (A) Interviewed fishers' gillnet fishing effort by season and (B) season when fishers recalled catching the most white sharks.

3.3.4 Shark lengths

Fishers were asked to estimate the average size (approximate TL) of white sharks they had caught. Each fisher generally provided one size estimate (averaged across all sharks). While these size estimates are unlikely to be accurate as sharks were rarely, if ever, accurately measured and due to difficulties in recalling the individual sizes of multiple sharks, they provide an indicative approximation of the size composition of catches. However, fishers reported catching almost the entire known size range of between 110 and 550 cm. West Coast fishers tended to report catching larger sharks (between 410 and 550 cm TL) while fishers in Zone 1 and 2 caught a larger size range (between 110 and 500 cm TL). Several fishers in Zone 2 commented that white sharks caught in waters of the GAB tended to be smaller than in other areas.

3.3.5 Attitudes towards catch reporting

Fishers' attitudes towards the accuracy of self-reported white shark catch data appeared to be fairly evenly spread, with 20.0% strongly agreeing with the statement that "…data reported in daily logs provide reliable information on the total number of white sharks caught…", 26.7% mildly agreeing, 13.3% neither agreeing nor disagreeing, 13.3% mildly disagreeing and 26.7% strongly disagreeing. The stated reasons for disagreement mostly related to perceptions that white shark catches were deliberately under-reported (85.7%), due to industry-wide concerns that reporting leads to future fishing restrictions or closures. Other stated reasons for disagreement related to fishers lacking time or inclination to provide white shark-specific data in their logbooks.

3.3.6 Perceptions of abundance

The majority of interviewed fishers (66.7%) felt that the abundance of white sharks in Western Australia was greater in 2013 than when they started fishing, while 20.0% thought abundance was the same, 3.3% thought it was less and 10.0% were unsure. A variety of reasons were given by fishers to explain their perceptions of increased white shark abundance (Figure 10) but only 13.8% of these responses were attributed to fishers' direct observations of their own catches. Over a third of responses (37.9%) cited other fishers now catching or sighting white sharks more frequently and 17.2% stated an increase in media reports as the basis for their perceptions.

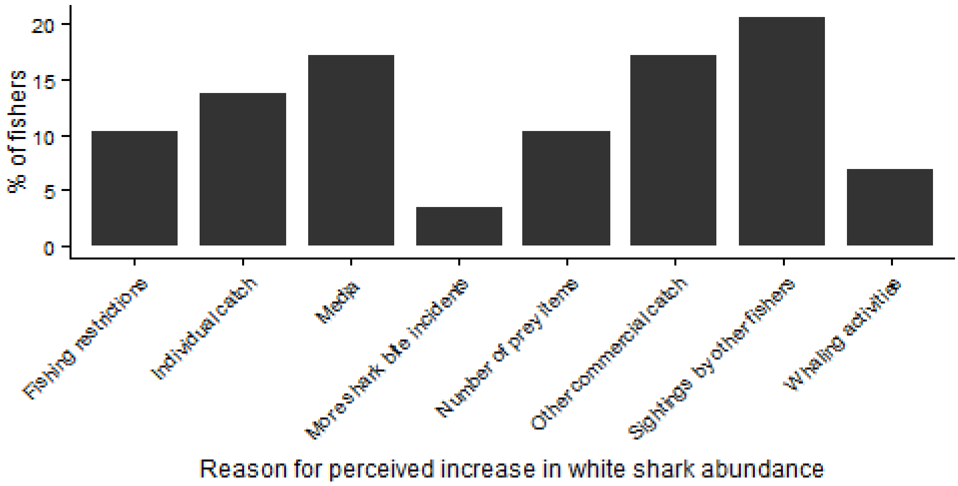


Figure 10. Categorised reasons given by fishers to explain their perceptions of an increase in white shark abundance off Western Australia.

3.4 Discussion

3.4.1 Estimating TDGDLF white shark catches from survey data

The assessment of exploited fish populations typically relies upon accurate catch information to determine the magnitude of removals and to infer relative changes in population abundance (Hilborn & Walters 1992; Quinn & Dersiso 1999; Haddon 2001; Walters & Martell 2004). Despite national and international initiatives to improve the standard of shark catch reporting, only a small number of commercially-valuable shark populations have time-series of fishery data that are long enough and sufficiently detailed to accurately reflect trends in stock abundance (Anderson 1990; Punt & Smith 1999; Simpfendorfer 1999a, 1999b, 2005; Stevens et al. 2000; Bonfil et al. 2005; McAuley et al. 2007). Obtaining reliable information about catches of protected shark species is made even more difficult by the general rarity of these catches and disincentives to report, for example the threat of prosecution or imposition of fishing restrictions to reduce those catches (Pitcher et al. 2002; Baum et al. 2003).

Before the implementation of TDGDLF daily logbooks in 2006, official fishing returns data from all of the State's commercial fisheries included a total of four white shark catch records. In addition, between 1994 and 2003, DoF staff had observed ten white shark captures by commercial fishing vessels and one during fishery-independent research in the general area of the TDGDLF. While the frequency of white shark capture reports has increased since the implementation of formal protected species reporting requirements, reported catches remain highly variable (between 3 and 22 per annum; Braccini et al. 2014) and have been collected for too short a time to be useful for traditional stock assessment purposes. Furthermore, as more than one third of interviewed fishers expressed doubts about the accuracy of self-reported white shark catch data, with some suggesting that catches are under-reported, it is unlikely that these data are accurate. Thus, the data collected during this survey represent the best available source of long-term, first-hand information about white shark catches in Western Australian waters.

The results from this survey suggest that the current catch in the TDGDLF is approximately 35 (95% CI: 23–64) sharks per year. Inferring trends in the historical catches of white sharks over time remains problematic, particularly for Zone 2 where interviewed fishers and Malcolm et al (2001) reported the majority of captures have historically occurred, and where survey coverage was lowest. Notwithstanding this high uncertainty, the catch estimates derived from this survey were used to define ranges of possible annual white shark catches in the TDGDLF and in other commercial fisheries (refer to Chapter 5).

The reliability of these survey data is also dependent on interviewed fishers' ability to accurately remember their historical catches, whether their catches are representative of the fisheries' total catch and their willingness to provide truthful information during interview. Potential biases in the survey data arising from inaccurate recall or unrepresentative sampling would logically be lower for the most recent time period (2005/6 to 2012/13). Not only was survey coverage high for this period but the rarity of white shark captures, together with intense media and public interest in shark bites and encounters during this time, are likely to have made recent captures particularly salient. Whether or not sensitivities about reporting protected species captures or intense public debate about the causes of the recent spate of shark bites influenced fishers' responses to interview questions cannot be determined. However, the fact that no fishers refused to cooperate in the survey and the general consistency between confidential answers given by active and recently-retired fishers (who presumably have less incentive to misreport), suggest that the survey data are likely to be broadly representative of the fisheries' catches.

Recall bias is more likely to have occurred for the earlier survey periods in this study, although this may have been ameliorated to some extent by virtue of white shark captures being memorable, rare events that prior to protection could also be very lucrative due to the potential monetary value of the species' teeth and jaws. Nevertheless, as survey coverage was also generally lower for the earlier periods, the potential for individual fishers' recall bias to disproportionately influence total catch estimates was high for the earlier survey periods. These issues have particular significance in Zone 2 in the 1988/89 to 1996/97 period, where survey coverage was lowest and fishing effort was greatest. According to the survey data, the mean of Zone 2's catch rate estimates (method 1) during that period was 2.5 times than that estimated for Zone 1 and more than 4 times that estimated for the West Coast (Figure 9). The resulting mean estimate of the Zone 2 catch accounted for nearly 70% of the TDGDLF's estimated mean total catch during Period 1 (Table 2). While this level of catch appears disproportionate relative to Zone 2's contribution to the total catch estimates for the latter survey periods, it cannot be determined whether this is an accurate reflection of the historical white shark catch distribution or whether biases from low survey coverage and/or recall could have distorted these estimates. Because of Zone 2's importance to the total TDGDLF white shark catch and use for inferring catches in other fisheries (see Chapter 5), a second approach (method 2) was used to examine the potential implications of overestimating this part of the

TDGDLF catch and to provide an alternative and more proportionate Zone 2 catch from this early period. This second approach reduced the magnitude of the mean catch estimate by 40% (Table 2) and provided an estimate with smaller confidence intervals; however, as both methods were based on different un-tested assumptions, it cannot be determined which provides a more reliable account of historical catches.

The annual mean estimate of 28 TDGDLF white shark captures during the 1997/98 to 2004/05 period is remarkably similar to the 22–35 reported from the more limited phone survey of TDGDLF fishers reported by Malcolm et al. (2001). Although this earlier report did not specify exactly when catch estimates referred to, fishers were interviewed in 1999/2000 and it can be assumed that the earlier catch estimates roughly equate to the time of national protection (in December 1997). As in the current study, Malcolm et al. (2001) also reported that Western Australian white shark catches were highest in Zone 2 of the fishery, although unlike this study, the previous survey reported higher catches off the West Coast than in Zone 1. Between 1994/95 and 1998/99, McAuley and Simpfendorfer (2003) reported that DoF research staff observed six (6) white shark captures during 7.4% of total TDGDLF fishing effort. While scaling this observed catch rate up to total TDGDLF fishing effort suggests an annual fishery-wide catch of 16 white sharks, the authors pointed out that because research coverage was regionally uneven (ranging between 1.8% and 19.8% of commercial fishing effort), caution should be exercised when extrapolating those observer data across such a large fishing area. Nonetheless, those independently-observed commercial catch data provide support that catch estimates from the Period 2 survey data are a realistic order of magnitude.

Reconstructed TDGDLF catch trends reflect the histories of gillnet fishing effort in each of the three management zones. The most substantial declines in estimated white shark catches occurred in all management regions between the first two periods. These declines correspond with the incremental 60% reduction in the value of JASDGDLF time-gear units between the mid-1990s and early 2000s and the introduction of unitised effort controls in the WCDGDLF in 1997 (Braccini et al. 2014). The two notable exceptions to the relationship between fishing effort and catch estimation are the increase in the mean Zone 2 catch estimates (despite relatively stable effort) and modest decline in the mean West Coast catch (despite a 60% effort reduction) between the two most recent periods.

The reported increase in white shark catch rates could indicate an increased occurrence of white sharks in TDGDLF catches since 2005/06; there are several other possible explanations for these results. For example, significant changes occurred in the West Coast region after 2006, including the closure of metropolitan waters to most forms of commercial fishing including demersal gillnetting and longlining, a Voluntary Fishery Adjustment Scheme that bought out 35% of WCDGDLF units and a large proportion of remaining effort units changing hands to new operators. New effort management arrangements were also introduced in the JASDGDLF in 2006/07, which led to a rapid 30% decline in fishing effort in 2006/07. Although total JASDGDLF effort has gradually increased to previous levels, this fundamental change in the fishery's effort management regime has contributed to changes in fishing behaviour (e.g. some vessels have increased the number of times they set and retrieve gillnets each day) which may have indirectly influenced white shark catch rates.

4 Review of existing white shark catch information in other Commonwealth and State-managed fisheries

4.1 Commonwealth Southern and Eastern Scalefish and Shark Fishery

The Commonwealth-managed Southern and Eastern Scalefish and Shark Fishery (SESSF) is one of the most valuable Commonwealth fisheries, accounting for 26% of the gross value of production of Commonwealth fisheries in 2010/2011 (Woodhams et al. 2012). The demersal gillnet component of the Gillnet, Hook and Trap (GHaT) sector of the SESSF has historically targeted gummy and school sharks, although the latter is now subject to a rebuilding strategy and is therefore no longer targeted.

Commercial shark fishing commenced in waters off Victoria in the 1920s and rapidly expanded into South Australian and Tasmanian waters during the Second World War, due to the increased demand for shark liver oil (Walker & Gason 2009). At that time, longlines comprising several hundred baited hooks attached to main lines of up to 10 km in length were mainly used to target school sharks. During the 1960s however, gillnets began to replace longlines as the preferred fishing method for sharks and by the mid-1970s most of the catch was taken using this method (Walker & Gason 2009). The SESSF was formally established in 2003, following amalgamation of four fisheries which are managed under a common set of management objectives (Woodhams et al. 2012). Current management arrangements are centred on the four sectors of the fishery which include gillnet, hook, trap and trawl fishing methods (refer to Table 3). Targeted fishing for sharks only occurs within the GHaT sector (Figure 11) and approximately 90% of the GHaT's shark catch is taken using monofilament gillnets (90%). Sharks are also incidentally-caught by automatic longlines in the GHaT (Walker & Gason 2009) and in the trawl sectors.

Table 3. Sectors within the Southern and Eastern Commonwealth Scalefish and Shark Fishery.

Sector	Geographical range of the fishery	Fishing methods
Gillnet Hook and Trap	From the WA–SA border through to South East QLD. Within SA and Victoria, the fishery operates from the coastal water limit (3 nm) to the limit of the Australian fishing zone (200 nm).	Scalefish hook, shark hook, gillnets, fish traps and automatic longlines.
Commonwealth Trawl sector	Australian Fishing zone extending from Cape Jervis in SA, along the Victorian and Tasmanian coast, north to Barranjoey Point, NSW.	Mostly otter trawl and Danish seine methods, with some mid-water trawling.
Great Australian Bight Trawl	From Cape Leeuwin, WA to Cape Jervis near Kangaroo Island, SA. Excluding shelf waters in the extreme west.	Otter trawl with some mid water trawling.
East Coast Deepwater Trawl	Restricted waters on the east coast.	Demersal and mid water trawling.

Figure 11. Boundaries of the Commonwealth-managed Gillnet Hook and Trap Sector of the SESSF (diagonally-hatched purple area, reproduced with permission from AFMA). The green line identifies the sector's inshore coastal waters (3 nm) boundary.

Commonwealth-managed shark fishing effort off Victoria, Tasmania and South Australia has followed a relatively similar trajectory to that in the TDGDLF (see Chapter 3). Following a decline in the abundance of school sharks in Bass Strait in the 1970s and a ban on the sale of large sharks between 1972 and 1985 due to concerns over mercury contamination (Walker & Gason 2009), gillnet fishing effort rose steadily through the late 1970s and most of the 1980s. This effort peaked in 1987 at 99,000 km gillnet lifts (Figure 12), which is assumed to be equivalent to 2.7 times the 1988/89 peak in TDGDLF effort of 36.7 km gn d. The GHaT's gillnet effort subsequently declined in response to management-imposed reductions in the number of operators (Walker & Gason 2009). Concerns about the bycatch of Australian sea lions and dolphins led to further restrictions on the use of gillnets off South Australia and in September 2014, an area of 27,239 km^2 off the South Australian coast was closed to gillnet fishing due to a reported increase in dolphin bycatch (AFMA 2013). These measures led to a shift of fishing effort towards hook methods (Table 4), resulting in a further reduction of gillnet effort in the GHaT, which is currently less than half of its 1987 peak (Figure 12). In 2011/12, 45 GHaT gillnet fishing vessels' effort was 34,264 km gillnet lifts, more than 3 times the TDGDLF effort of 9,902 km gn d in the same year (Braccini et al 2014).

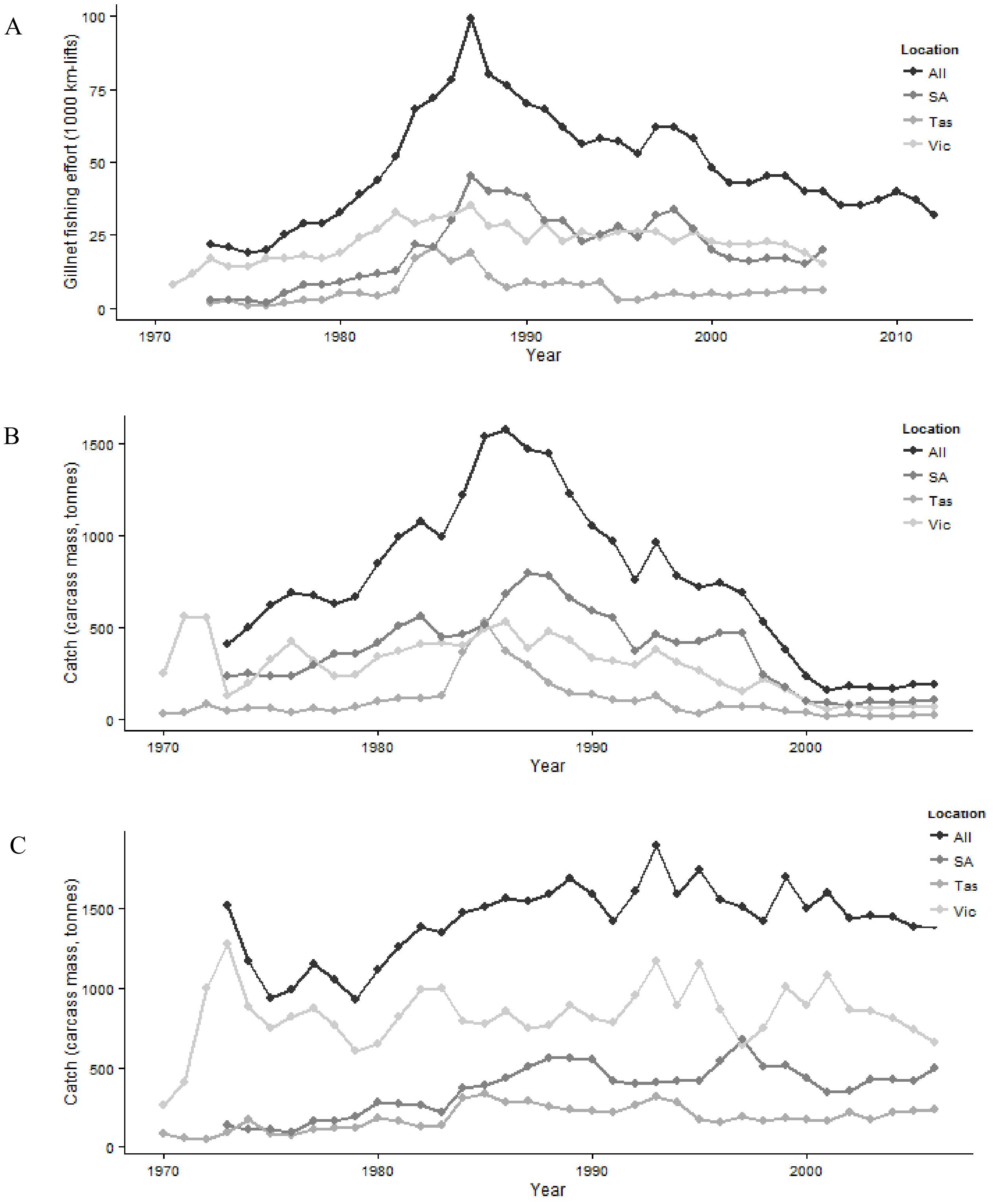


Figure 12. (A) Gillnet fishing effort (thousand km lifts) between 1970 and 2012, (B) gummy shark and (C) school shark landings (carcass weight, t) by State of landing, within the Gillnet Hook and Trap Sector, between 1970 and 2006. Data provided by AFMA.

Table 4. Key fishery statistics for gillnet and hook components of the Southern and Eastern Scalefish and Shark Fishery. Table adapted from Woodhams et al. 2012.

SESSF Fishery Statistics		2010/2011	2011/2012
Effort:	**Gillnet**	40,226 km net lifts	34,264 km net lifts
	Hook	610,612 hooks	1,174,796 hooks
Active vessels:	**Gillnet**	50	45
	Hook	21	38
Observer coverage:	**Gillnet**	1,242 km (3.1%)	2,184 km (6.4%)
	Hook	510,276 hooks (83.6%)	530,370 hooks (45.1%)

4.1.1 White shark catches in the SESSF

Logbook data

Between 2000 and 2012, 55 white shark catches west of Bass Strait (147° E) were reported in GHaT logbooks. Of these, 45 occurred west of the South Australian/Victorian border (141° E). Nearly all reported captures (91.1%) involved the use of gillnets while four sharks were caught using demersal longlines. Only four sharks (7.3%) were reported as dead upon capture. The estimated size of white sharks ranged between 1.6 m and 4.9 m with a mean size of 2.65 m (S.D. = 1.12, n = 43). All reported annual catches numbered less than 10 sharks yr^{-1} and in 2004, no captures were reported (Figure 13). Sharks were reportedly caught in all months, with 27.3% occurring in May. Although SESSF operators are required to report all protected species catches in logbooks, because logbook data cannot be routinely verified, the accuracy and completeness of white shark catch records cannot be substantiated (AFMA 2014).

Protected species interactions throughout the SESSF are also recorded by AFMA observers. Although observer coverage in the GHaT has historically been low and is not necessarily spatially or temporally representative of the gillnet fleet's effort, the proportion of observed gillnet fishing effort has steadily increased since AFMA's Independent Scientific Monitoring Program began in 2007. In 2012, approximately 7% of total gillnet fishing effort was observed, compared to 0.8% in 2007 (Figure 14). Despite observing a relatively small proportion of total commercial fishing effort between 2007 and 2012 (3%), AFMA observers recorded 6 white shark catches in the GHaT (west of 147° E) between 2007 and 2012 (average of 1 shark yr^{-1}), compared to logbook records of 27 catches (average of 5 sharks yr^{-1}) when observers were not present (i.e. no duplication). While it would be unreliable to extrapolate these limited observer data to estimate total white shark catches across such a large fishery, these observed catch rate data strongly suggest that logbook-reported catch rates are likely to underestimate actual catch rates of white sharks in the GHaT.

4.1.2 Previous survey data

Based on a phone survey of 41 fishers in the former Southern Shark Fishery (now the GHaT), Malcolm et al. (2001) estimated that 74 (± 62 S.D.) white sharks were caught per year in this fishery during the late 1990s. Despite subsequent reductions in the fishery's gillnet effort, this estimate is far higher than the mean of 4 white sharks per year reported in fishery logbooks, catch disposal records and observer programs west of Bass Strait between 2000 and 2012.

A

B

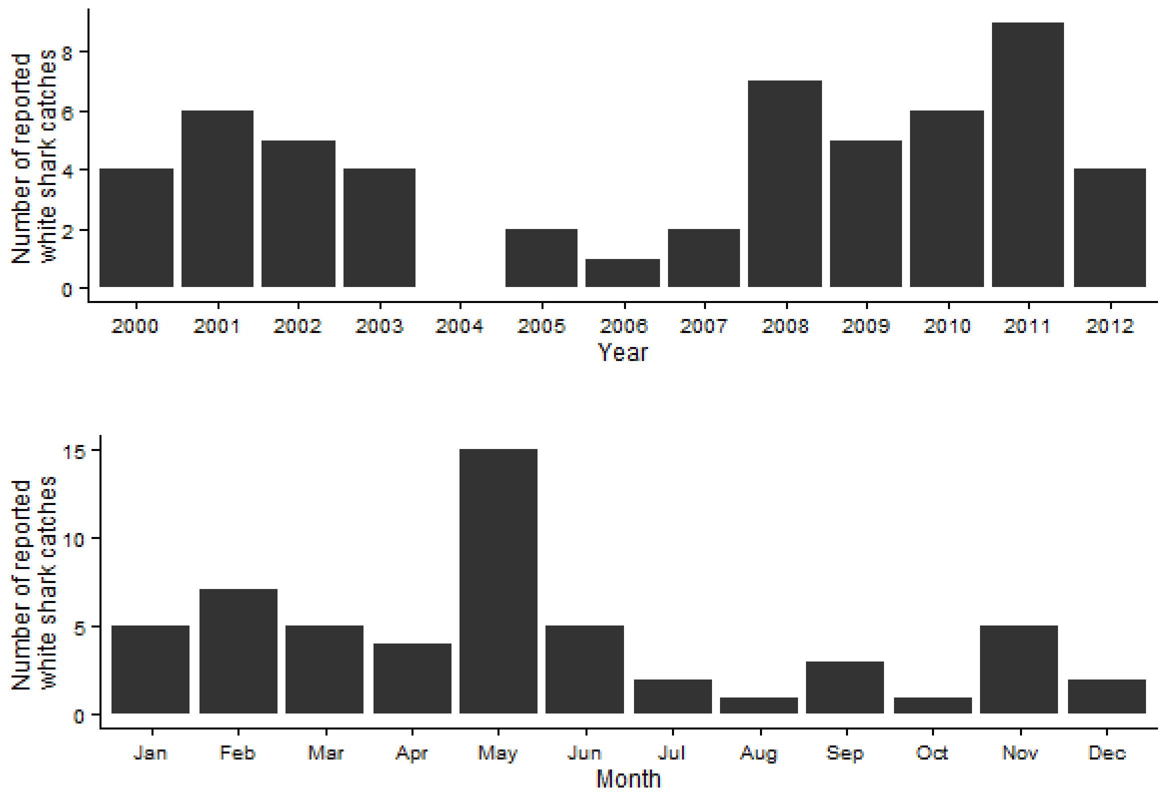
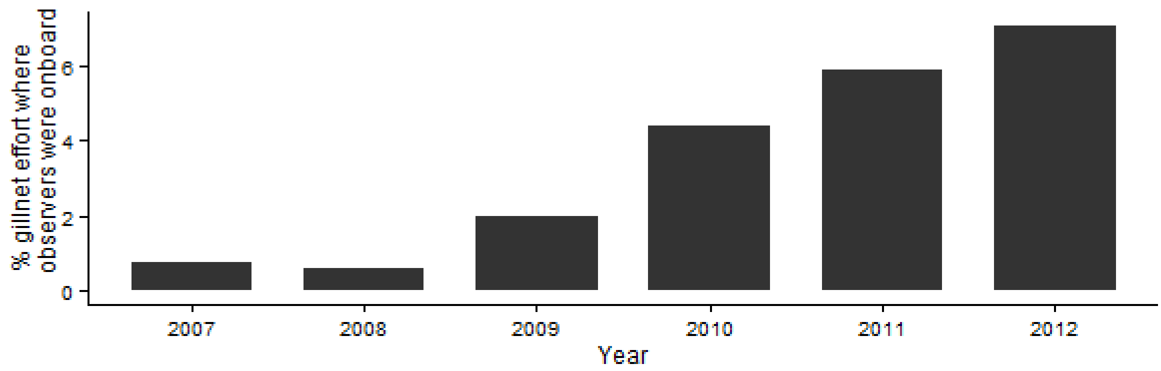


Figure 13. The number of reported white sharks caught by (A) Year and (B) Month within the Gillnet Hook and Trap sector between 2000 and 2012. Only records west of Bass Strait are displayed.

A



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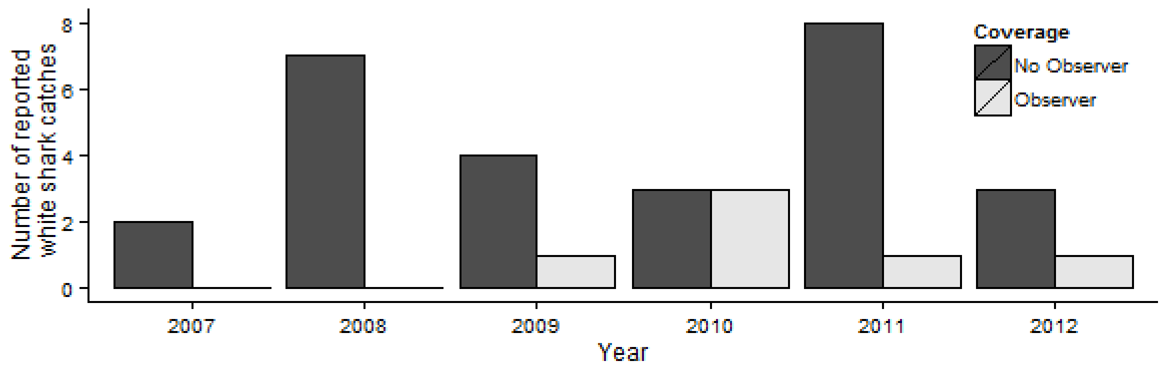


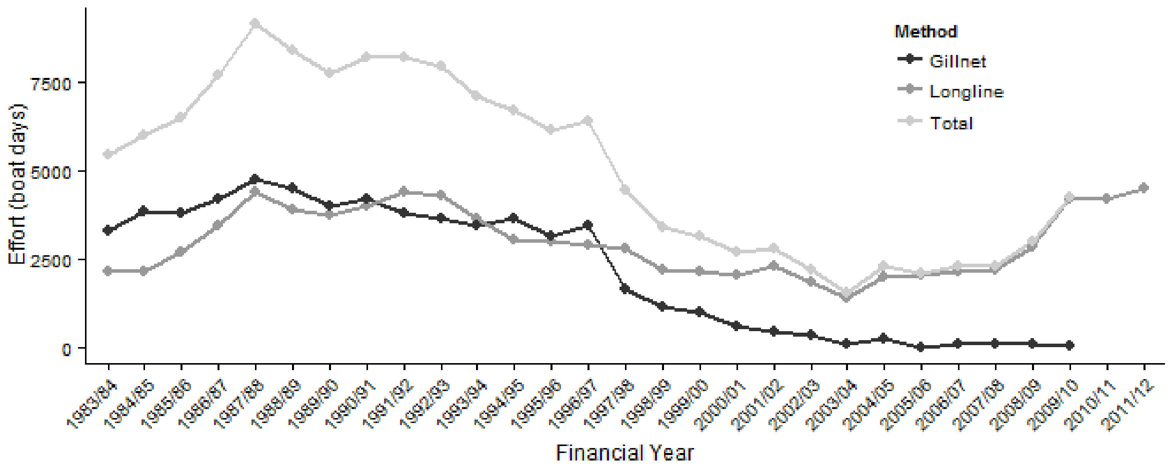
Figure 14. (A) Percentage of observed GHaT gillnet fishing effort and (B) number of reported white shark catches when observers were present and absent.

Due to the absence of long-term, accurate data on white shark catches in the GHaT, an alternative approach was used to provide some context to the historical catch in this fishery which formed part of the historical catch reconstruction (refer to Chapter 5).

4.2 South Australian Marine Scalefish Fishery

Most of the South Australian Marine Scalefish Fishery's commercial shark catch comprised of whaler sharks (primarily bronze whaler sharks), which are targeted using longlines and large mesh size gillnets (15 cm mesh size, Noell et al. 2006). Gillnet fishing effort peaked in 1987/88 at 4,408 fishing days (assumed to be equivalent to 14% of TDGDLF effort in that year, see 5.3) before declining gradually through the 1990s. Since 2005/06, gillnet effort has been less than 200 fishing days a year (Figure 15). In contrast, longline effort has increased in recent years, peaking in 2011/12 at 4,501 fishing days. Between 1983/84 and 1987/88 whaler shark catches increased from 24 t to 70 t, since when they have averaged approximately 80 t per year despite the overall decline in fishing effort. Following an anomalous peak catch of 149 t in 2009/10, the catch in 2011/2012 was 86 t.

A



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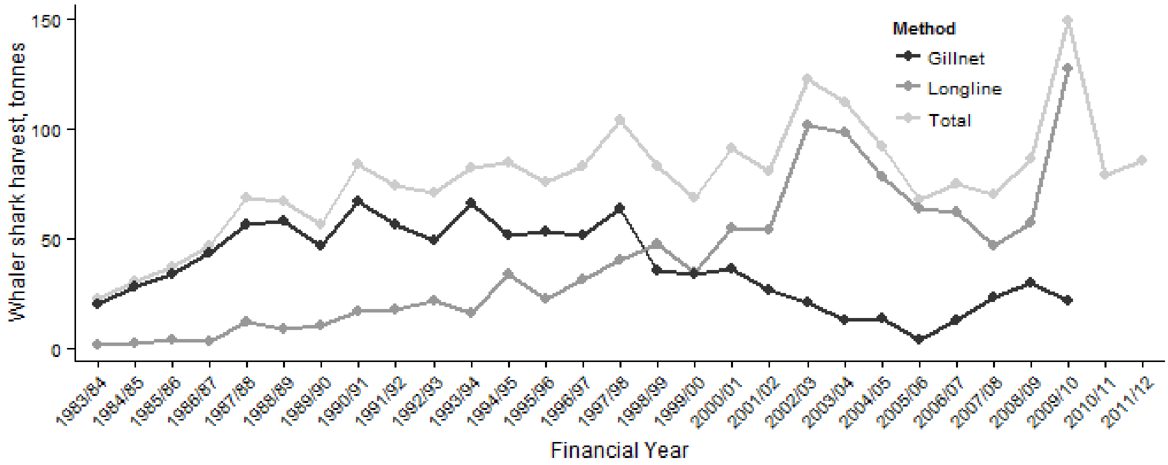

Figure 15. (A) Gillnet and longline fishing effort and (B) whaler shark landings in the South Australian Marine Scalefish Fishery. Gillnet data are unavailable for 2010/11 and 2011/12 due to confidentiality issues. Data provided by the South Australian Research and Development Institute.

Handlines are used to fish for snapper in the South Australian gulfs, west coast waters and Investigator Strait (Noell et al. 2006). Overall, handline fishing effort has decreased throughout the last 30 years although the decline in effort has not been consistent between years. Handline fishing effort peaked in 1983/84 at almost 8,000 fisher days while effort was lowest in 2011/12 at almost 1,500 fisher days (Noell et al. 2006). The South Australian Sardine Fishery (SASF, purse seine gear endorsement within the MSF) began in 1991 and is conducted mainly in southern Spencer Gulf (Ward et al. 2012). The fishery is managed through gear entry limitations, gear restrictions and individual transferable quotas. Purse seine nets must not exceed 1,000 m in length or 200 m depth with mesh sizes of 14 to 22 mm. In 2012 there were 13 licence holders. Between 2001 and 2005 annual effort in the SASF increased from 205 boat nights to 1,233 boat nights but stabilised at 713 to 902 boat nights between 2006 and 2011 (Ward et al. 2012).

4.2.1 White shark catches in the Marine Scalefish Fishery

In 2007, the Department of Primary Industries and Resources of South Australia (PIRSA) introduced new arrangements for South Australian commercial fisheries to report interactions with Threatened, Endangered and Protected Species (TEPS). Reported interactions from 2008 onwards are published in South Australian Research and Development Institute (SARDI) reports (Knight & Vainickis 2011). Information on TEPS catches prior to 2008 is not available and the accuracy of the data subsequently reported in the wildlife interaction logbook is unknown (Knight & Vainickis 2011). Between 2008/09 and 2010/11, 12 white shark 'interactions' were reported in the MSF: seven occured in the SASF, two by longliners (both in 2010/11) and three by handliners. However, because some of these interactions were reported in the 'other category', not as 'caught' or 'entangled' (refer to Knight & Vainickis 2011), it is unclear whether these records refer to actual catches. All but one of the sharks that interacted with a longline was reportedly alive.

Malcolm et al (2001) estimated the annual catch of white sharks by MSF gillnets, longlines and handlines to be between 15 and 40 (mean of 30). Most of the estimated catch came from fishers using gillnets and longlines and catch rates using handlines were deemed to be negligable as sharks hooked using handlines tended to break free of the line or bend the hooks rather than being caught (Malcolm et al. 2001). This study did not provide an estimate for sharks caught using purse seines. Due to the absence of long-term, accurate data on white shark catches in the MSF, an alternative approach was used to provide some context to the historical catch in this fishery, which formed part of the historical catch reconstruction. This approach incorporated catches from both gillnet and longline operators (refer to Chapter 5).

5 Reconstruction of historical white shark catches

The lack of reliable records of white shark catches from fisheries operating across the south-western Australian white shark population's range precludes accurate assessment of its current status or historical trends in abundance. The first-hand information collected from long-term Western Australian demersal gillnet fishers in this study (refer to Chapter 3) has therefore been used to provide some context to the possible magnitude of undocumented catches in other fisheries. The results given in this chapter therefore reflect indicative ranges of possible annual white shark catches.

5.1 Temperate Demersal Gillnet and Demersal Longline Fisheries

Estimates of TDGDLF white shark catches for the three survey periods between 1988/89 and 2012/13 are described in Chapter 3. Because fishing returns prior to 1988 did not include fishers' names, it was impossible to reliably attribute interviewed fishers' catches to their corresponding fishing effort before then. Also, because relatively few interviewed fishers were active before the early 1980s, the earliest catches reported during interviews may be less representative of catches across the whole fishery. Therefore, the methods used to estimate catches during the three survey periods, were not considered appropriate for assessing earlier catches. Instead, catches prior to 1988/89 were estimated as the product of annual gillnet fishing effort (from what became known as the TDGDLF only) and survey-derived catch rate estimates for period 1 (1988/89 to 1996/97), according to the following methods.

Because commercial gillnet fishing effort data have been formally-reported since July 1975, annual catches between 1975/76 and 1987/88 were estimated as the product of annual gillnet effort in each of the three survey regions (Zone 1, Zone 2 and West Coast) and the corresponding regional catch rates estimates for Period 1. To account for uncertainty in these catches, 10,000 estimates of regional catch rates were randomly sampled (with replacement) from separate lognormal distributions with means and standard deviations derived from the original bootstrapped estimates (according to methods 1 and 2, see Chapter 3). As fishing effort was not reported before 1975, previous gillnet effort was inferred from historical shark catch information. Until the late 1950s, shark catches were known to have been taken mostly by demersal longlines (Heald, 1987), which contemporary survey data suggest rarely caught white sharks (Chapter 3). Therefore, 1955/56 was considered to be the first year in which white sharks were caught by gillnets in what became known as the TDGDLF in 1988. As shark catch estimates in the southern half of Western Australia showed a fairly steady increase between 1955 and 1975 (Heald 1987), annual gillnet effort was assumed to have increased linearly from zero between 1955/56 and 1975/76. These assumed annual fishing effort values were multiplied by catch rate estimates that were randomly sampled (with replacement) from a lognormal distribution with mean and standard deviations equal to the original bootstrapped TDGDLF estimates for period 1 (see Chapter 3).

The methods used to hind-cast white shark catches in the TDGDLF prior to 1988/89 rely on the simplistic assumption that catch rates prior to 1988/89 were inter-annually invariant, which based on survey data is clearly unrealistic. However, as 10,000 catch rate estimates were resampled from the range of interviewed fishers' information, it is hoped that the actual levels of inter-annual variability in catches were also reflected within the survey data and, by extension, in the ranges of catch estimates described here. This bootstrapping approach is not capable of reflecting any longer-term trends in catch rates that might have been driven by changes in population abundance, environmental conditions or fishing behaviour. These estimated historical catches were combined with the annualised catches derived from the survey to generate continuous 58 year reconstructed time series of historical white shark catch estimates for commercial gillnet shark fishing in Western Australia (Figure 16).

Overall, estimates of annualised catches were highly uncertain (Figure 16) and the time series was broadly consistent with fishing effort (Figure 1). Annualised catches rose rapidly during the 1980s and peaked in 1988/89 at 98–143 (50th percentile) and 75–98 (50th percentile) sharks for method 1 and 2, respectively (Figure 16). Subsequently, catches declined throughout the 1990s and early 2000s which was driven by the reduction in fishing effort throughout the TDGDLF. An anomalous peak in catch occurred in 2005/06 which resulted from the high effort in that year relative to other subsequent years in Period 3 (Figure 1) and the fact that Period 3 catch rates were higher than in Period 2 (Figure 6). In 2012/13 the estimated catch was 27–34 (50th percentile) sharks for both methods.

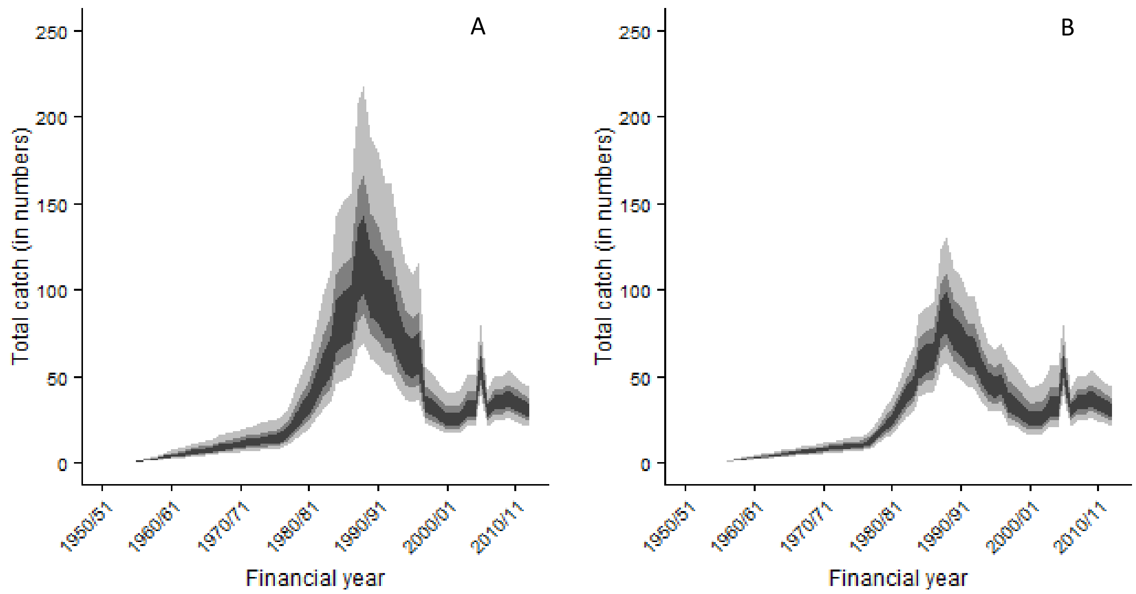

Figure 16. Reconstructed catch time series for white sharks in the Western Australian Temperate Demersal Gillnet and Demersal Longline Fisheries using (A) Method 1 and (B) Method 2. Fifty, 75 and 95% of the reconstructed catches are shown in progressively lighter shades of grey.

5.2 Commonwealth-managed South East Scalefish and Shark Fishery

Given the obvious similarities in geography, gear and target species (gummy and school sharks) of the South Australian component of the GHaT and the adjacent Zone 2 of the TDGDLF, Zone 2 catch rate estimates were considered to be the best-available proxy for white shark catch rates in the GHaT. Thus, catches were estimated according to the methods described above for the TDGDLF between 1975/76 and 2012/13; reported annual GHaT gillnet fishing effort and TDGDLF Zone 2 catch rates, estimated for corresponding periods. As available logbook, observer and anecdotal records suggest that gillnet catches of white sharks are and always were relatively minor off the Victorian and Tasmanian coasts, this estimation exercise only considered gillnet effort data from the South Australian part of the fishery after 1972/73, once gillnet effort became significant (Walker & Gason 2009). Due to changes in the way that data were reported by Commonwealth-managed gillnet fishers, relevant gillnet effort records were defined by State of landing (South Australia) prior to 2000 and from blocks west of the South Australian/Victorian border from 2000 onwards (Walker & Gason, 2009; recent data provided by ABARES). To use TDGDLF survey-derived catch rates, that are expressed in units of kilometre gillnet days, to estimate catches in the GHaT, it was necessary to assume that reported GHaT effort units of kilometre gillnet lifts are directly equivalent to the units used to describe TDGDLF effort.

Although Zone 2 catch rates were considered the best available proxy for white shark catch rates in the South Australian part of the GHaT, the abundance of white sharks has previously been reported to be higher off South Australia than off Western Australia. Malcolm et al. (2001) reported that gillnet catch rates of white sharks between Streaky Bay and the head of the GAB were approximately double those in Zone 2 in the TDGDLF. Therefore, two different scenarios of GHaT catches were estimated: one assuming that GHaT catch rates were equal to Zone 2 estimates and the second, assuming that they were double those of Zone 2 estimates. To account for uncertainty in both catch rate scenarios, catches were calculated using 10,000 catch rate estimates that were randomly sampled (with replacement) from separate lognormal distributions with means and standard deviations equal to the original bootstrapped Zone 2 estimates from methods 1 and 2 (see Chapter 3).

Estimates of annual catches were highly uncertain and the overall catch trend was fairly consistent with fishing effort (Figure 12). The estimated catch peaked in 1987/88 at between 121–239 and 454–777 sharks, respectively (50^{th} percentile, Figure 17 C3 and C2)). Current restrictions on the use of gillnets off South Australia (AFMA 2013) have led to a dramatic reduction in effort and the catch in 2012/13 was substantially less than in the 1980s and 1990s, with 50^{th} percentiles less than 30 sharks for all four scenarios.

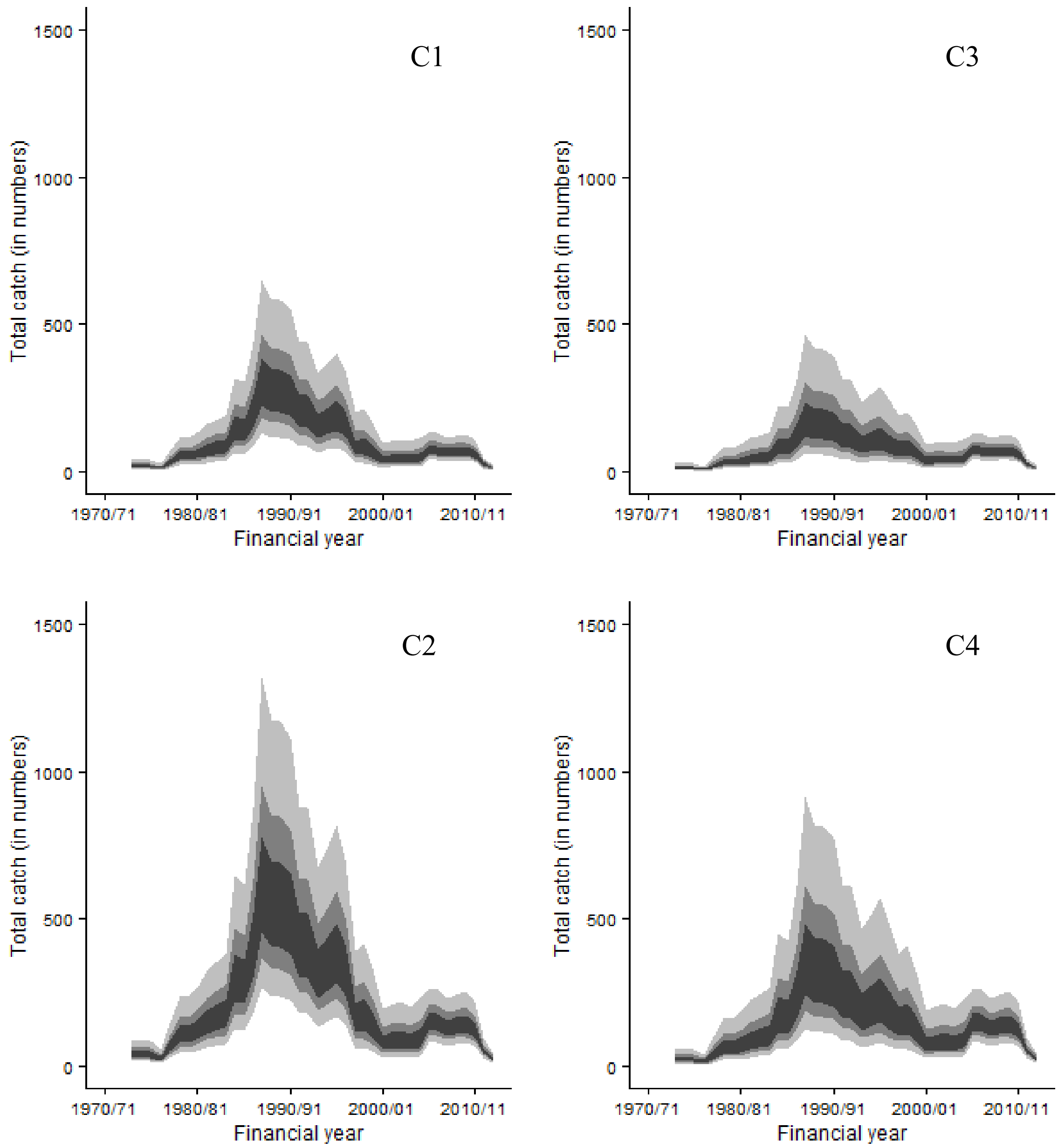

Figure 17. Reconstructed catch time series for white sharks in the Gillnet Hook and Trap Sector (refer to Table **5** for a description of the C1–C4 scenarios). Fifty, 75 and 95% of the reconstructed catches are shown in progressively lighter shades of grey.

5.3 South Australian Marine Scalefish Fishery

Fishing effort data for the MSF were first recorded in 1983/84, therefore this was assumed to be the first year of fishing. Due to the confidentiality of commercial fishing data from declining numbers of fishers, catches were only reported separately for gillnets and longlines until 2009/10. Therefore, the proportion of the total catch caught by gillnet and longline from 2009/10 onwards was assumed to be the same as in 2009/10. As units of effort in the MSF are reported as boat days, it was also assumed that all MSF gillnets were the maximum permissible 600m in length (Noell et al. 2006). However, unlike the TDGDLF and GHaT, longlining replaced gillnetting as the preeminent fishing method in the MSF during the mid-late 1990s. Because MSF longlines have been reported to catch white sharks (Malcolm et al. 2001), both gillnet and longline catches were considered in this analysis. Furthermore, while more recent management changes in the MSF have prohibited the use of wire trace of 2 mm or greater gauge in conjunction with fishing hooks size 12/0 of greater (Government of South Australia 2007), the death of a shark on a longline in 2010/11 (refer to Chapter 4) confirms that catches still occur using this modified gear.

To equate MSF longline effort to an equivalent unit of gillnet effort, a linear regression of annual longline and gillnet catch rate data was first performed. As recent annual gillnet catch rate values (2004/05 to 2012/13) were very high in comparison to earlier years and resulted from very low levels of fishing effort (Figure 15 (A)), the regression was based on the catch rate data from 1983/84 to 2003/04 (Figure 18 (B)). Equivalent annual longline effort (1983/84 to 2012/13) was then estimated by dividing the annual longline catch of whaler sharks by the product of the annual longline catch rate and 1.5656. This latter value was derived from the equation of the linear regression (Figure 18 (B)).

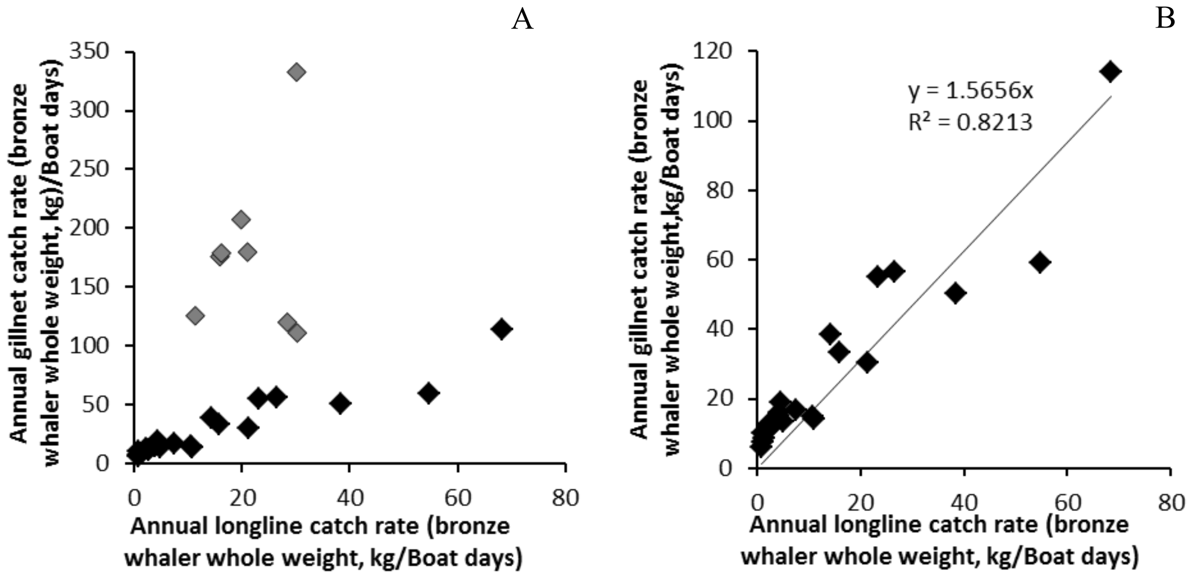

Figure 18. (A) Correlation between longline and gillnet bronze whaler catch rate data. Black diamonds are annual values between 1983/84 and 2003/04, grey diamonds are annual values between 2004/05 and 2012/13. (B) Regression between longline and gillnet catch rate data between 1983/84 and 2003/04.

As for the GHaT, due to the apparent similarities between MSF gillnets and those used in the TDGDLF, Zone 2 catch rates were taken to be the best available proxy for gillnet catch rates of white sharks in the MSF. Two catch rate scenarios were considered (equal to and twice the TDGDLF Zone 2 rates), with estimates drawn from separate lognormal distributions with means and standard deviations equal to the original bootstrapped Zone 2 estimates (see Chapter 3). According to these methods, estimated annualised catches were higher prior to the significant reduction in gillnet effort that commenced in 1996/97 (Figure 15(A)). The estimated catch peaked in 1994/95 at 37–63 sharks (50th percentile) for the highest catch scenario (Figure 19, C2).

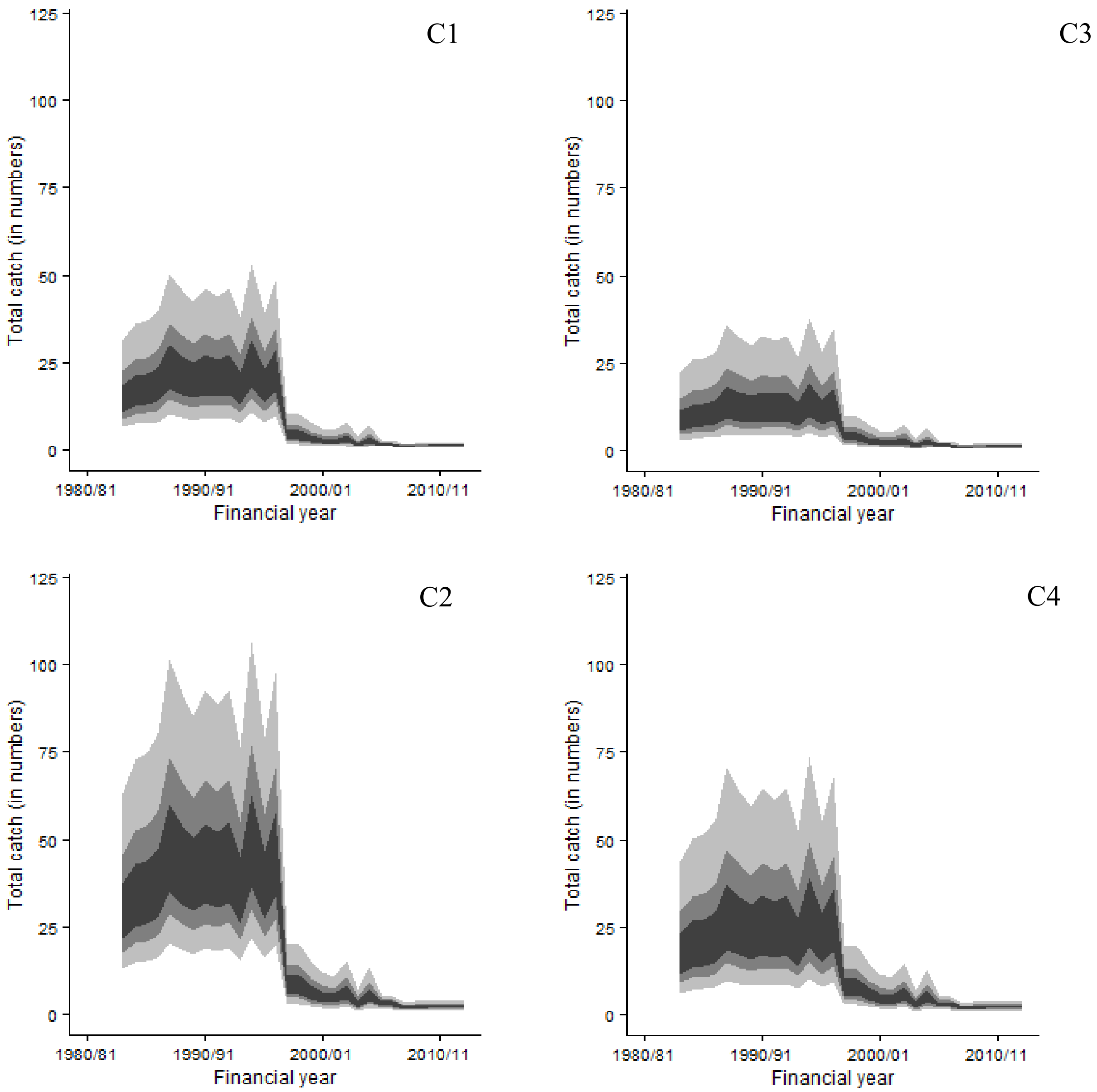

Figure 19. Reconstructed catch time series for white sharks in the Marine Scalefish Fishery (refer to Table **5** for a description of the C1–C4 scenarios). Fifty, 75 and 95% of the reconstructed catches are shown in progressively lighter shades of grey.

5.4 Western Australian 'wetline' fishing with float-hooks

Float hooks (officially recognised as 'droplines') usually comprised 12/0-14/0 straight shank shark or swordfish hooks or tuna circles and were intended to catch large sharks. Of the 30 TDGDLF fishers interviewed, seven reported catching white sharks using droplines. These fishers' mean reported catch rate of white sharks was 0.30 sharks per annum (S.D.=1.05). Furthermore, 21 white sharks were caught using nearly-identical gear during targeted fishery-independent tagging research in the area of the TDGDLF between 2012 and 2014 (DoF, unpublished data), and a single fishery-independent capture by a functionally-identical set-line occurred off Perth in 1996.

Because TDGDLF fishers used float-hooks in conjunction with their gillnets, float-hook effort of TDGDLF vessels was assumed to be indirectly proportional to the number of gillnet vessel days. As a crude basis for estimating these catches, it was arbitrarily assumed that 50% of TDGDLF fishing vessels that used gillnets of 3,000 m or longer (i.e. full-time shark fishers), used float hooks. As interviewed fishers reported that this practice began in the late 1980s and Department of Fisheries staff observed that most fishers had ceased using them by the end of 2002 (when pot-hooks were prohibited in the Western Rock Lobster Fishery), TDGDLF vessels' float hook catches were only estimated for the period 1988/89–2001/02, inclusive. Individual vessels' catch rates were randomly selected from a uniform distribution of between 0 and 1 shark per year and multiplied by half the number of vessels using 3,000m or more of gillnet. This procedure was repeated 10,000 times to represent uncertainty in the catch rates of this activity (Figure 20).

Given the similarity in gear type and areas fished, the same approach was used to estimate white shark catches by WCRL fishers who used to attach hooks to their pot floats. Individual vessels' catch rates were again sampled from a uniform distribution of between 0 to 1 sharks per year but in this case, it was assumed that 10% of WCRL fishing vessels operating in the fishery between 1988/89 and 2001/02 used this gear and therefore may have caught white sharks. According to these methods, the mean estimate of combined TDGDLF and WCRL fleets' catches of white sharks by float-hooks was estimated to be between 36 and 64 sharks per year between 1988/89 and 2001/02 (Figure 20).

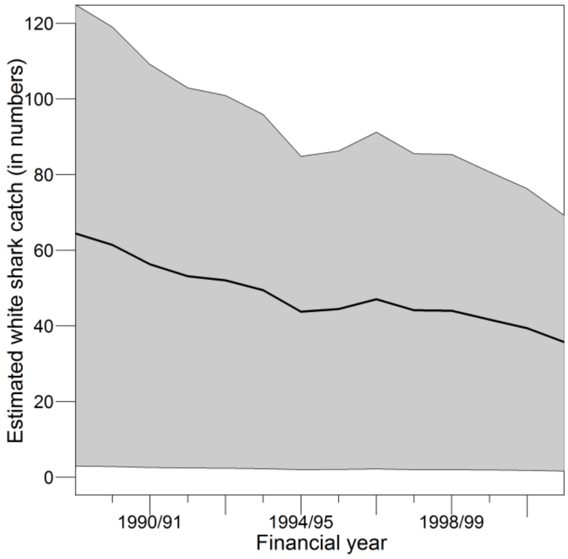

Figure 20. Reconstructed 'dropline' catch of white sharks by fishers in the Temperate Demersal Gillnet and Demersal Longline Fisheries and the West Coast Rock Lobster Fishery. Solid black line = mean, grey area = 95% of reconstructed catches.

Although Malcolm et al (2001) reported that some commercial fishers set droplines in the South Australian gulfs and caught white sharks for their jaws and meat, their study did not provide any basis for estimating those catches. As there are no other known sources of information about these catches, it is recognised that additional unquantified dropline catches may have occurred in South Australia and that the estimates for the TDGDLF and WCRL alone, may therefore under-represent catches by this method across the population's range.

5.5 Western Australian white shark catches at Albany whaling station

Based on the first-hand account of the targeted fishing associated with whaling activities around Albany in the 1970s (described in Chapter 3), an annual catch of 10 white sharks a year was assumed between 1970/71 and 1978/79 (Table 5).

5.6 South Australian recreational fishing

Game Fishing Club of South Australia fishing records documented 171 white shark landings between 1938 and 1990 (Bruce 1992). Therefore, an annual South Australian catch of 4 sharks yr^{-1} between 1938/39 and 1990/91 was assumed and included in the catch reconstruction. As fishing club catches peaked in the 1950s and declined down to only one shark a year in the late 1980s and early 1990s (Bruce 1992), no catches were considered after 1990/91.

Table 5. Summary of methods and assumptions used to reconstruct scenarios of historical white shark catches. TDGDLF=Temperate Demersal Gillnet and Demersal Longline Fisheries; GHaT=Gillnet Hook and Trap sector; MSF=Marine Scalefish Fishery. Refer to Chapter 3 for a description of the two methods used to estimate TDGDLF catch rates.

	Assumption			
Catch source	**C1**	**C2**	**C3**	**C4**
TDGDLF	Catch rate estimation method 1	Catch rate estimation method 1	Catch rate estimation method 2	Catch rate estimation method 2
GHaT	Catch rate equal to Zone 2	Catch rate twice that of Zone 2	Catch rate equal to Zone 2	Catch rate twice that of Zone 2
MSF	Catch rate equal to Zone 2	Catch rate twice that of Zone 2	Catch rate equal to Zone 2	Catch rate twice that of Zone 2
WA float-hooks	Catch rates of 0-1 sharks yr^{-1}; 50% TDGDLF vessels and 10% WCRLF vessels fishing between 1988/89 and 2001/02			
WA recreational	10 sharks yr^{-1} between 1970/71 and 1978/79			
SA recreational	4 sharks yr^{-1} between 1938/39 and 1990/91			

5.7 Discussion

Despite the lack of reliable, long-term white shark catch data from fisheries operating across the south-western Australian population's range, the survey of TDGDLF fishers in this study has provided a basis for estimating the magnitude of historical catches off Western and South Australia. Although the majority of the historical white shark catches were estimated to have originated from the southern Australian gillnet fisheries, a comprehensive analysis of other potential sources of mortality was undertaken to determine if their catch levels should be included in more detailed analyses.

The examination of multiple potential sources and the survey results confirmed that the majority of Western Australian catches occurred in the TDGDLF and the majority of those in Zone 2 of the JASDGDLF. Based on commercial fishers' recollections, the two approaches resulted in mean estimates between 1988/89 and 1996/97 of 59 and 81 sharks yr^{-1}. For the first period after protection (1997/98–2004/05), the estimated catch was 28 yr^{-1} and for the most recent period (2005/06–2012/13) it was 35 $yr^{-1}$for both approaches (Table 2). Not only were the Period 1 (1988/89–1996/97) catch estimates much higher than in subsequent periods associated with the high levels of effort that occurred during this period, but they were also much more variable due to the high variability in estimates for Zone 2. This was the region where most white sharks were caught but where the least (percentage of) effort was surveyed during Period 1. Because the most uncertain survey-derived catch rate estimates (i.e. from Zone 2 during Period 1) were used to hind-cast pre-1988/89 TDGDLF catches and as a proxy for catch rates in the Commonwealth (GHaT) and South Australian (MSF) gillnet and longline shark fisheries, similarly high levels of uncertainty were apparent in the cumulative historical catch estimates from all fishing activities.

Estimated total catches closely followed the trend in gillnet fishing effort across southern Australia, increasing rapidly during the 1970s and early 1980s before peaking in the late 1980s when gillnet fishing effort in the TDGDLF, GHaT and MSF was greatest (Figure 21). Despite the inclusion of additional Western Australian float-hook catches between 1988/89 and 2001/02, catches declined through the 1990s mainly as a result of the reduction in gillnet effort in these target-shark fisheries. The low catch rates derived for Period 2 of the survey (1997/98 and 2004/05) contributed to an even sharper decline in catches during the late 1990s, before reportedly higher TDGDLF catch rates during Period 3 led to a further moderate increase. The decline in 2011/12 and 2012/13 catch estimates was a direct result of measures to reduce Australian sea lion and dolphin bycatch in the GHaT (AFMA 2013). The introduction of these measures off the South Australian coast has both reduced the Commonwealth-managed gillnet effort and displaced South Australian based vessels to waters off Victoria and Tasmania, where white shark catch rates are known to be much lower (Malcolm et al. 2001).

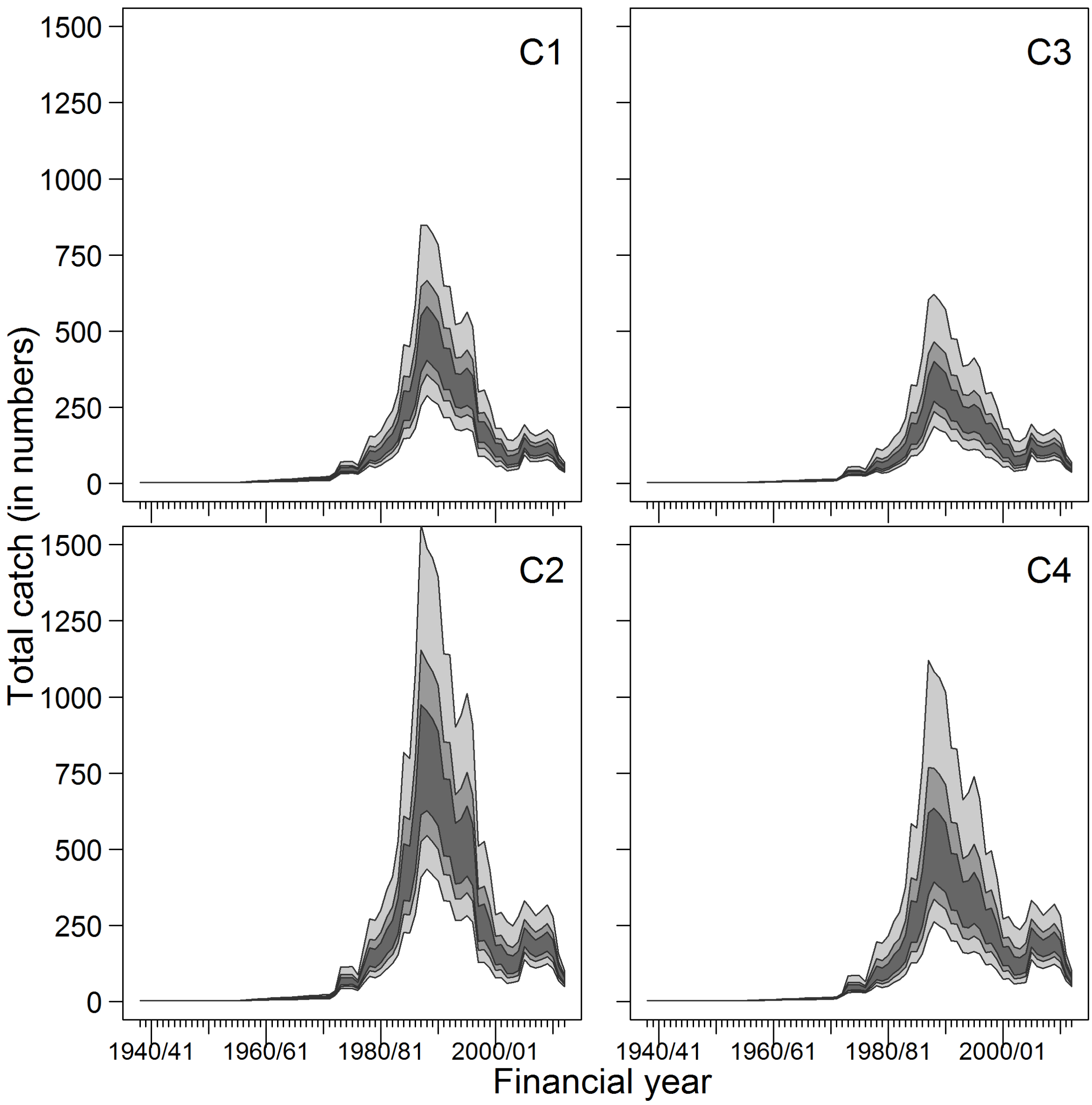

Figure 21. Reconstructed estimated total catch time series of white sharks from the south-western Australian population between 1938/39 and 2012/13 (refer to Table **5** for a description of the C1–C4 scenarios). Fifty, 75 and 95% of the reconstructed catches are shown in progressively lighter shades of grey.

6 White shark biology and ecology (Primary Author- Barry Bruce, CSIRO Hobart).

6.1 Species description

White sharks, also known as great white sharks or white pointers, are a close relative of mako and porbeagle sharks in the mackerel shark family Lamnidae (Last & Stevens 2009). They have a moderately stout and torpedo-shaped body; are coloured blue-grey to grey-brown on the upper surface and white below; have large serrated triangular teeth and a distinctive lateral keel along the body midline immediately before a crescent-shaped tail. White sharks are large apex predators that grow to at least 6 m in length and can weigh up to about 3,000 kg (Mollet et al. 1996; Last & Stevens 2009), although there are unverified reports of white sharks up to 7 m in length. A heat-exchanging circulatory system allows the shark to maintain a body temperature up to 14°C above that of the surrounding seawater, enabling it to tolerate a wide range of temperatures (Goldman 1997).

6.2 Life history

White sharks are long-lived, with recent longevity estimates, albeit from only a small sample size of four males and four females, ranging up to 70+ years in the North West Atlantic (Hamady et al. 2014) based on validation via bomb radio-carbon signatures in vertebrae. The smallest and largest male sharks in this data set were estimated at 9 and 73 years (223 & 493 cm FL) and females were estimated at 6 and 40 years (221 & 526 cm FL), respectively, suggesting considerable sexual dimorphism in size at age. These age estimates are at odds with previous results based on vertebral band-pair counts from the Pacific and Indian Oceans which estimated that similar sized sharks were between 3 and 23 years (Cailliet et al. 1985; Wintner & Cliff 1999; Malcolm et al. 2001; Kerr et al. 2006; O'Connor 2011; Tanaka et al. 2011), although these latter studies provide no validation of band-pair formation and may have underestimated age at length. The Hamandy et al. (2014) age estimates are also surprising in that the females were younger at corresponding sizes, whereas in other lamnid sharks, females are generally thought to be older.

White sharks have a relatively slow development and low reproductive rate with a long gestation period, estimated at up to 18 months matched with a possible 18 month resting period (Mollet et al. 2000; Mollet & Cailliet 2002). These characteristics imply a low reproductive potential which has implications for the vulnerability of white sharks to non-natural mortality and the rate at which populations can recover if depleted. The uncertainty in age estimation generated by results from the North West Atlantic suggest that if similar growth rates and longevity are applicable to the Pacific and Indian Ocean populations, white sharks are likely to be more vulnerable to sources of non-natural mortality than previously estimated. Age validation of white sharks in Australian waters thus remains a priority for research. Age-at-length estimates below follow analyses for Pacific and Indian Ocean studies but these may need to be further assessed in light of the Hamandy et al. (2014) results as further data relevant to the Australian region comes to hand.

6.3 Reproduction

Female white sharks nourish embryos via oophagy. During gestation embryos consume unfertilised eggs that the female continues to ovulate during the first periods of pregnancy (Mollet et al. 2000). Reported litter sizes are between 2 and 17 (Norman & Fraser 1937; Bigelow & Schroeder 1948; Paterson 1986; Uchida et al. 1987; Ellis & McCosker 1991; Bruce 1992; Fergusson 1996; Uchida & Toda 1996; Cliff et al. 2000; Malcolm et al. 2001), with the loss of aborted embryos probably responsible for at least some of the lower figures. However, the maximum number of near-term pups confirmed by dissection of pregnant females is 10 (Francis 1996). White sharks measure around 120 to 150 cm (Total Length, TL) at birth, up to 32 kg in weight and are believed to initially grow at a rate of approximately 30 cm yr^{-1} based on Pacific and Indian Ocean data, although this rate is likely to slow considerably as sharks reach maturity (Wintner & Cliff 1999, Malcolm et al. 2001). Males mature at between 3.6 and 3.8 m (7 to 9 years) and females between 4.5 and 5.0 m (12 to 17 years) (Francis 1996; Pratt Jr. 1996; Malcolm et al. 2001).

In Australia, neonate white sharks have most commonly been caught by commercial and recreational fishers in the western Great Australian Bight and Bass Strait (Malcolm et al. 2001; Bruce & Bradford 2012), suggesting these two areas hold likely pupping grounds. Pupping is generally believed to occur during spring or early summer which coincides with the period when Robbins (2007) reported the absence of female white sharks from the Neptune Islands. However, no pregnant white sharks have yet been reliably examined in Australian waters.

6.4 Diet

White sharks are versatile predators that feed primarily on finfish, rays and other sharks as juveniles (<3 m), prior to adding larger prey items to their diet. In Australia, white sharks of all sizes will continue to target elasmobranchs and finfish throughout life (Malcolm et al. 2001). The smallest white shark known from Australian waters to contain seal remains was a 2.7 m individual reported by Malcolm et al. (2001). White sharks first commonly appear at fur seal (*Arctocephalus pusillus doriferus* and *Arctocephalus forsteri*) and Australian sea lion (*Neophoca cinerea*) colonies in Australian waters by about 3.0 m in length and this probably indicates the size where such marine mammals are added to their diet. Relatively limited residency times at seal colonies (e.g. the Neptune Islands in South Australia), followed by extensive movements away from such areas (Bruce et al. 2006; Jorgensen et al. 2010; Sims et al. 2012; Domeier & Nasby-Lucas 2013; Francis et al. 2015) suggest that pinnipeds, although important, may be an overstated part of white shark diets compared to other prey species. These observations are consistent with some vertebral isotope analyses which indicate a dietary shift to include marine mammals by approximately 3.4 m (Estrada et al. 2006). However, similar analyses in the North East Pacific also indicate that not all white sharks transition their diets to include marine mammals and that some remain as generalist predators continuing to feed on finfish, cephalopods and other elasmobranchs throughout their life history (Kim et al. 2013). Species such as snapper (*Pagrus auratus*), mulloway (*Argyrosomus japonicas*), Australian salmon (*Arripis trutta*), school shark (*Galeorhinus galeus*), gummy shark and various ray species appear to be important components of white sharks' diet in Australian waters (Bruce 1992; Malcolm et al. 2001).

Adult, sub-adult and juvenile white sharks (including young-of-the-year sized individuals) have been observed to scavenge on floating whale carcasses (Carey et al. 1985; Curtis et al. 2006; Dicken 2008) and they may be particularly active around the site of whale strandings (Bruce & Stevens 2004). Other prey reportedly taken at times include: sea birds, ocean sunfish, tuna, sea otters and turtles (Ames et al. 1996; Fergusson et al. 2000; Kim et al. 2013).

Predatory strategies in white sharks have been the subject of a series of studies primarily based in California at the Farallon Islands (Ainley et al. 1985; Klimley et al. 1996, 2001; Pyle et al. 1996) and in South Africa (Martin et al. 2005). These studies deal specifically with predatory behaviour on pinnipeds and provide useful insights into behaviour in such habitats. However, the propensity for white sharks to spend considerable periods of each year in waters remote from pinniped colonies and undertaking very different predatory behaviours when doing so (Boustany et al. 2002; Bruce et al. 2006; Weng et al. 2007; Domeier & Nasby-Lucas 2008, 2013), as well as the likelihood that some white sharks may not transition to prey on pinnipeds even when these prey are accessible, suggest that their behaviour at pinniped colonies cannot necessarily be used to infer behaviour in other habitats and around other prey species. This may also apply to inferences about shark behaviour with respect to bites on humans.

6.5 Distribution

White sharks occur world-wide in coastal temperate and subtropical regions but they can also occur in tropical areas and, in some regions, may spend considerable periods in the open ocean (Compagno 2001; Weng et al. 2007; Bruce 2008; Domeier & Nasby-Lucas 2008). They are most frequently encountered off South Africa (Bonfil et al. 2005), southern Australia (Bruce et al. 2006), New Zealand (Duffy et al. 2012), northern California (Boustany et al. 2002), Mexico (Santana-Morales et al. 2012) and north eastern United States (Casey & Pratt Jr. 1985; Skomal et al. 2012). White sharks tagged at several world-wide locations intersperse coastal movements with extended offshore excursions (Boustany et al. 2002; Bonfil et al. 2005; Bruce et al. 2006; Bruce & Bradford 2012; Duffy et al. 2012) and have either been tracked across ocean basins or inter-continental movements have been inferred from historic genetic lineages (Gubili et al. 2011, 2012; Jorgensen et al. 2012). These movements suggest that occasional interactions occur between individuals from populations that are otherwise geographically widely separated. However, despite such long distance movements, genetic data worldwide suggests the existence of separate populations (Pardini et al. 2001; Gubili et al. 2011, 2012).

In Australia, white sharks have been recorded from central Queensland around the south coast to northwest Western Australia, but may occur further north on both coasts (Paterson 1990; Bonfil et al. 2005; Bruce et al. 2006; Last & Stevens 2009). White sharks are widely but not evenly distributed in Australian waters and appear to occupy some areas more frequently than others. These include waters in and around some fur seal and sea lion colonies such as the Neptune Islands (South Australia), areas of the Great Australian Bight as well as the

Recherche Archipelago and the islands off the lower west coast of Western Australia (Malcolm et al. 2001). Juveniles appear to aggregate seasonally in certain key areas including the 90 Mile Beach area of eastern Victoria and the coastal region between Newcastle and Forster in New South Wales (Bradford et al. 2012). Other areas such as the Portland region of western Victoria and the coast off the Goolwa region of South Australia and waters of the western Great Australian Bight are also areas reportedly frequented by juvenile white sharks at times.

Most research on white sharks has been conducted in and around the waters off South Australia, particularly at the Neptune Islands and Dangerous Reef (Bruce 1992; Bruce et al. 2005a, 2005b; Robbins 2007; Robbins & Booth 2012; Bruce & Bradford 2013; Huveneers et al. 2013; Semmens et al. 2013) and along the mid-north New South Wales coast (Bruce & Bradford 2012). Recent research has also focussed on recording the presence and movements of white sharks off the metropolitan Perth coast and off the South-West of the State (McAuley et al. 2016).

6.6 Habitat

White sharks can be found from close inshore around rocky reefs, surf beaches and shallow coastal bays to outer continental shelf and slope areas (Pogonoski et al. 2002; Bruce et al. 2006; Last & Stevens 2009). However, they also make open ocean excursions, can cross ocean basins and both adults and juveniles have been recorded diving to depths of 1,000 m (Bonfil et al. 2005; Weng et al. 2007; Bradford et al. 2012). Most white shark movements and activity in Australian waters occurs between the coast and the 120 m depth contour (Bruce et al. 2006; Bruce & Bradford 2012). However, the importance of offshore and high seas habitat cannot be dismissed, although unlike sharks tracked off the western coast of North America (Weng et al. 2007; Domeier & Nasby-Lucas 2008) there is no evidence thus far that white sharks in Australia utilise oceanic habitats other than for transit between temporary sites of continental residency.

White sharks do not live in one specific area or territory but travel great distances between sites of temporary residency (Bruce 2008). White sharks appear to be highly mobile off the Western Australian coast and individual displacements between listening station arrays exceeding 1,000 km were reported within a few weeks or months (McAuley et al. 2016). There is also mounting evidence for common movement pathways between some areas of temporary residency in Australian waters with transit paths common over depths between 60 and 120 m (Bruce et al. 2006). These depths hold reef structures associated with relic coastlines that may provide navigation cues and opportunistic feeding opportunities (Bruce & Bradford 2012) and coastal habitats in close proximity to these depth zones may show a higher rate of reported encounters with the species (Werry et al. 2012).

Distinct coastal nursery areas have been located in various localities worldwide although the spatial scale of these varies between regions. Juveniles occupy broad areas of the coast in the central Californian Bight (Weng et al. 2007a, Lyons et al. 2013) over a 400 km stretch of coast whereas Bruce and Bradford (2012) have documented a geographically discrete nursery area with a coastal footprint of only 60 km off Port Stephens in central New South Wales, eastern Australia and a second nursery area along 90 Mile Beach and in the vicinity of Corner Inlet in southeast Victoria with a coastal footprint of approximately 100 km. Individual juveniles between 1.7 and 2.8 m TL revisit these two eastern Australian nursery areas on an annual basis for up to 5 consecutive years after tagging, with several recorded moving between the two on a seasonal basis.

6.7 Movement patterns

White sharks are known to travel widely over distances of 1000s of kms which can include travel associated with shelf waters and offshore excursions. Cross-ocean basin travel has been documented between South Africa and northwest Australia (Bonfil et al. 2005). Open ocean excursions have also been recorded for sharks from the Farallon Islands (California) and those tagged at Guadalupe Island (Mexico). In both cases, sharks have been recorded moving to the same offshore region of the central eastern Pacific with some individuals moving as far west as Hawaii (Boustany et al. 2002; Domeier & Nasby-Lucas 2008; Weng & Honebrink 2013). Return of sharks to their site of tagging on a seasonal, or in some cases more frequent, basis has been a feature of most of these studies. Both males and females have been recorded making such offshore excursions although the timing of movements may differ between the sexes in some areas (Domeier & Nasby-Lucas 2008). The reasons for these broad scale offshore movements are unclear, but it is presumably related to feeding opportunities and/or reproductive activities, however, not all sharks undertaking such movements are adults (Bonfil et al. 2005; Bruce et al. 2006; Bruce & Bradford 2012).

In Australia, coastal movements have been documented from the Neptune Islands, South Australia to North West Cape in Western Australia (Bruce et al. 2006; McAuley et al. 2016) and from the Neptune Islands to Rockhampton (Queensland) and return (Bruce et al. 2006). Extensive movements of white sharks have been documented north and south on the east coast of Australia between eastern Tasmania and the southern Great Barrier Reef (Bruce & Bradford 2012; Figure 22). No individuals have been observed to travel up both west and east coasts of Australia. The deployment of acoustic receivers in many areas of coastal and shelf waters of Australia may enable tagged sharks to be tracked for far longer periods than currently available using other electronic tagging technologies. Not all movements appear to be this extensive with white sharks also recorded to move regularly between the Neptune Islands and the central and western regions of the Great Australian Bight (Malcolm et al. 2001; Bruce et al. 2005b). Some sharks have been recorded returning to the Neptune Islands on a highly seasonal basis, sometimes within a few days of their date of arrival the previous year, while others were more frequent in their visits (Bruce et al. 2005b). These patterns of site fidelity are similar to those reported for white sharks in Californian and South African waters (Klimley 1985; Cliff et al. 1996; Long & Jones 1996; Bonfil et al. 2005).

White sharks are not known to form and defend territories and are only temporary residents in areas they inhabit. However, their ability to return on a highly seasonal or more regular basis implies a degree of site fidelity that has implications for repeat interactions with site-specific threats and encounters. Recent tagging in New Zealand waters has also demonstrated movements from the Chatham Islands and Stewart Island to New Caledonia and Tonga as well as to the southern Great Barrier Reef (Duffy et al. 2012). Records of 2.1 m juvenile and 3.2 m sub-adult white sharks crossing the Tasman Sea from NSW to New Zealand indicates that large scale movements are not restricted to adults (CSIRO unpublished data).

Acoustic and satellite telemetry studies indicate that temporary residency of white sharks at particular sites can vary from days to weeks. Bruce and Bradford (2013) used acoustic tags and listening stations to investigate the number of days that tagged white sharks were detected within the vicinity of the Neptune Islands and at Dangerous Reef in South Australia. Most visits at the three locations were between one and six days duration, although some individual sharks remained active in these areas for up to 90 days. Similarly, most tagged whites sharks detected off Western Australia were only present for short periods (days to weeks) and there was minimal evidence of sharks spending extended periods in particular areas off the South-West of the State (McAuley et al. 2016).

Bruce and Bradford (2012) used satellite telemetry to identify periods of residency of juvenile white sharks at aggregation sites in central NSW and eastern Victoria. Some juveniles remained resident in these areas for periods up to 70 days and showed evidence of fidelity to particular regions of individual beaches. Juveniles travelled extensively after departing the central NSW region moving as far north as Fraser Island, south to eastern Bass Strait and northern Tasmania and across the Tasman Sea to New Zealand.

6.8 Seasonal movements

The satellite tracking reported by Bruce et al. (2006) and Bruce and Bradford (2012) suggest relatively limited mixing of white sharks between waters to the west and those to the east of Bass Strait. In general, white sharks appear to move north along the east coast from autumn to spring and return south during summer. This pattern is supported by the capture of white sharks by shark control programs in New South Wales and Queensland. Historical catches (1950–1993) show highest catch rates occur in New South Wales from May to November with a peak from September to November (Reid & Krogh 1992). Of the 100 white sharks caught by the NSW shark control program since 1990/91, 57 were caught in September and October (Green et al. 2009). Catches similarly peak in the Queensland program during September and October (Paterson 1990).

In Western Australia, tagged white sharks have moved north along the coast as far as North West Cape during winter and spring and sometimes return south during spring and summer (Bruce et al. 2006; Figure 23). However, coastal movements are more complex than simple seasonal migrations north and south along both coasts. Movements of individuals are not synchronous, with some sharks moving north while others move south during the same period (Bruce & Bradford 2012; Gallen et al. 2013) and white sharks can be recorded in some northern localities at any time of the year. Pooled tag detection data revealed that white sharks may be encountered off metropolitan Perth and the South West coasts of Western Australia at any time of year and few clear patterns in seasonal movement directions were observed (McAuley et al. 2016). However, northerly movements along the west coast, particularly by a small proportion of sharks that travelled as far as Ningaloo Reef, were most frequently observed during spring and summer, with southerly return movements during late summer and autumn (McAuley et al. 2016).

Despite the recorded movements of some individuals across the Tasman Sea to New Zealand (Bruce et al. 2006; Bruce & Bradford 2012) most white sharks tracked in Australian waters have made extensive coastal movements where they have remained in coastal Australian waters. This is in contrast to the regularity of movements by tagged white sharks into open ocean and international waters from California, Mexico, New Zealand and to some extent, South Africa (Boustany et al. 2002; Bonfil et al. 2005; Weng et al. 2007a; Domeier & Nasby-Lucas 2008, 2013; Duffy et al. 2012). Hence it is unlikely that a high proportion of individuals of the south-western Australian population regularly venture offshore and are captured in open ocean fisheries.

6.9 Depth-swimming behaviour

White sharks show complex patterns in their swimming behaviour that are dependant, in part, on what habitat they are in and presumably what prey species they are targeting. There have been various separate reports of different swim behaviours and this is likely to be a result of the short-term nature of many such studies that do not obtain data for individuals over all occupied habitats. The deployment of relatively long-life satellite and acoustic tag technology has recently provided more multi-habitat data series that more adequately illustrate the complexities in behaviour. Bruce et al. (2006) noted that white sharks around pinniped colonies in South Australia showed a diel signature in behaviour with sharks occupying shallow water during the day close to the colony and deeper swimming, away from the colony at night. One shark rapidly switched behaviour within days of departing the Neptune Islands and entering the adjacent Spencer Gulf, where it changed to bottom oriented swimming with no diel difference and where it was believed to be feeding on finfish and bottom dwelling rays. The same shark then showed highly repetitive dive-surfacing behaviour after leaving Spencer Gulf and rapidly heading west into the Great Australian Bight, a behaviour noted by other authors to assist in navigation (e.g. Klimley et al. 2002).

Off-shelf and open ocean movements generally see adult and sub-adult white sharks diving to common depth zones of between 400 and 600 m (Boustany et al. 2002; Weng et al. 2007a; Domeier & Nasby-Lucas 2008; Bradford et al. 2012) or between 800 and 1,000 m (Bonfil et al. 2005). These depths are also similar to those commonly reached by juvenile white sharks off eastern Australia and when crossing the Tasman Sea (Bruce & Bradford 2012). Overall, these studies have documented a wide range of behaviours in white sharks including prolonged periods at the surface or at depth, oscillatory or “yo-yo” ascents and descents, short regular intervals at the surface and depth, diel periodicity, deep dives at dawn and dusk, and periods of highly erratic swimming behaviour (Bruce et al. 2006).

6.10 Sexual segregation

Sexual segregation has been recorded in a wide variety of sharks. The seasonal, sex-specific occurrence of individually identified white sharks was studied at the South Farallon Islands, California between 1987 and 2000 by Anderson and Pyle (2003). Individual males were sighted every year, whereas individual females showed a biennial occurrence pattern, being recorded every other year at most. The authors suggested that female sharks may travel significant distances to give birth, whereas copulation may occur closer to the South Fallon Islands, allowing males to return annually. These results support a two-year behavioural cycle in females that is similar to estimates of gestation periods (Mollet et al. 2000). More recently, Domeier and Nasby-Lucas (2013) have demonstrated that some adult female white sharks tagged at Guadalupe Island undertake offshore excursions of up to 16 months as part of a two-year migration cycle — again consistent with a biennial presence at the island. During their offshore phase mature males and mature females remained spatially segregated.

The seasonal visitation of white sharks to the Neptune Islands, South Australia was studied by Robbins (2007) and compared between sexes. This study reported that male sharks were more common in the Neptune Islands in all months except for April and May and that males generally preferred cooler water temperature than females between 2001 and 2004. In 2003 the observed water temperature was lower throughout the year and this corresponded with an absence of females, prompting the suggestion that females preferred warmer water that may be beneficial for the development of young (Robbins 2007; Robbins & Booth 2012). Sex ratios appear to vary at the Neptune Islands and other island groups in South Australia over time. Malcolm et al. (2001) reported a female dominated sex-ratio (58:20, numbers observed) between August 1999 and August 2000 at the Neptune Islands and Bruce (1992) noted that the female-biased sex ratio observed at Dangerous Reef during 1990 and 1991 was contrary to the high incidence of males historically reported from that area. These observations suggest a more complex pattern of spatial dynamics between the sexes than water temperature cues alone.

Sexual segregation can occur over fine spatial scales. Kock et al. (2013) reported the autumn and winter presence of both male and female white sharks in waters around Seal Island, False Bay in South Africa. However, during spring and summer females were recorded almost exclusively along the coast inshore whereas males were rarely detected. This coincided with the presence of migratory teleosts and other elasmobranchs in inshore waters.

6.11 Population structure

Genetic analyses suggest some sub-structuring of populations world-wide (Pardini et al. 2001; Gubili et al. 2011, 2012). Various other world-wide genetics-based projects are currently underway and these may lead to higher resolution results than has previously been possible. Both tagging data and genetic data suggest that two populations of white sharks exist in Australian waters separated east and west by Bass Strait (Blower et al. 2012; Bruce & Bradford 2012; Figure 24).

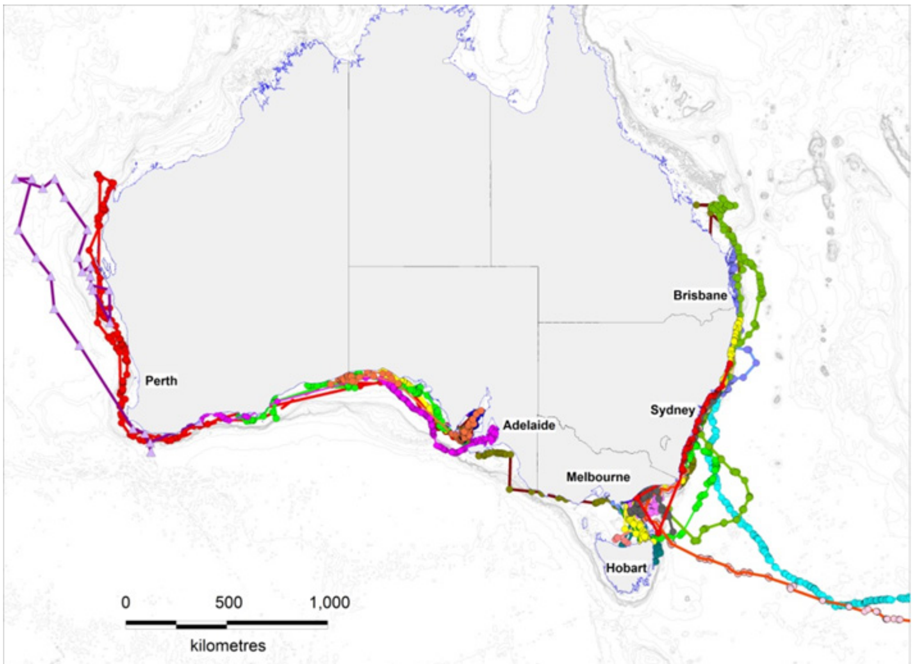

Figure 22. Tracks of white sharks tagged with fin-mounted satellite tracking tags in Australian waters (source CSIRO).

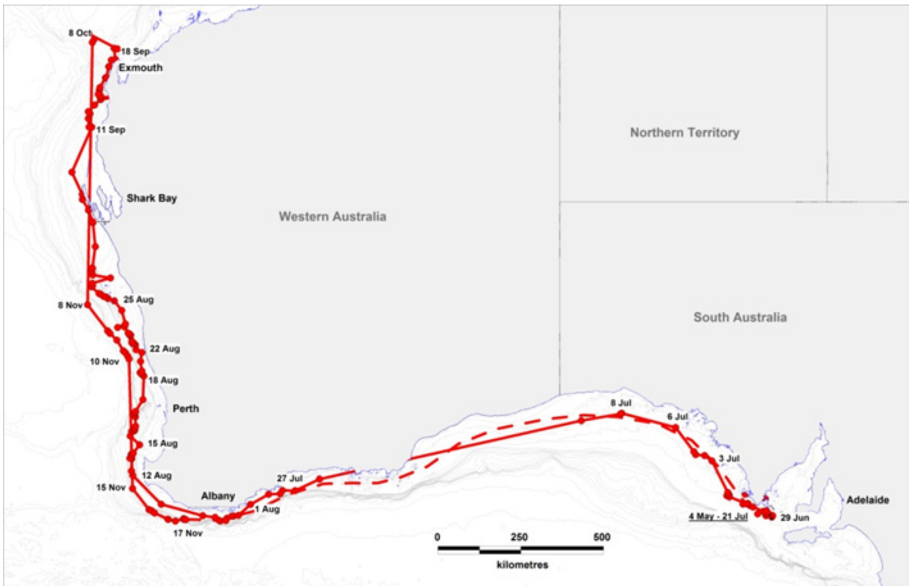

Figure 23. One-year track of a 3.6 m female white shark tagged at the Neptune Islands, South Australia in June 2006 (Source CSIRO). Solid lines indicate linear trajectories between satellite fixes and may not necessarily indicate the actual track taken by the shark. The dotted line indicates an assumed shelf-based trajectory over an extended period from the last received satellite fix in August 2006 and the first resighting of the shark at the Neptune islands with satellite tag still attached in May 2007.

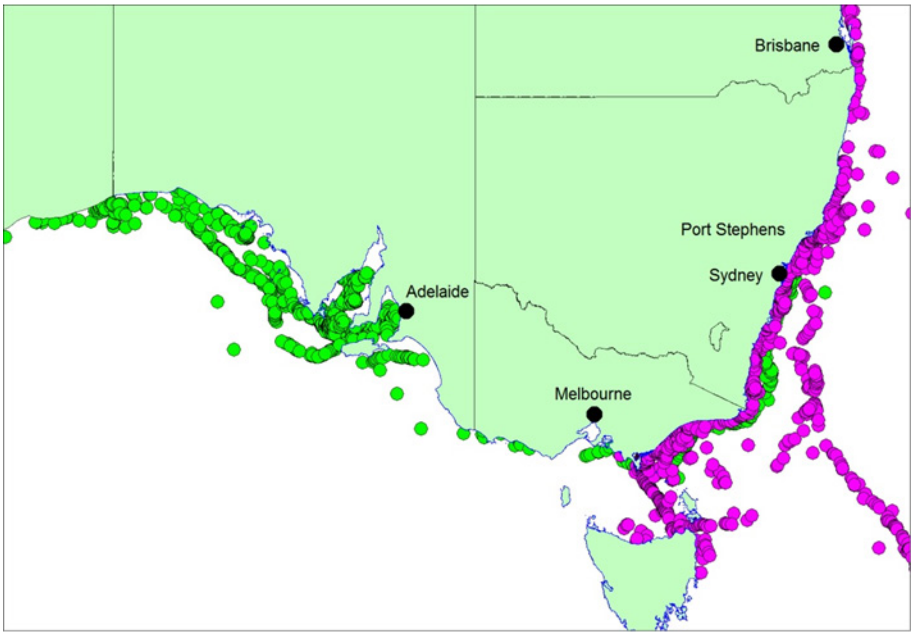

Figure 24. Satellite derived positions for white sharks tagged in eastern Australia (pink-filled circles) and for sharks tagged west of Bass Strait (green-filled circles) indicating limited movements across Bass Strait (Source CSIRO).

7 Quantifying uncertainty in the productivity and population trajectory of white sharks

7.1 Introduction

As outlined in Chapter 1 one of the factors that may have contributed to the increased rate of white shark attacks and encounters over the past decade within Western Australia is an increase in the abundance of the south-western Australian population of white sharks (Curtis et al. 2012; Sprivulis 2014). This chapter examines the possible effects to this population from the various changes to fisheries management arrangements over the past 90 years, but especially focuses on the period since 1997 when full protection of this species was established.

Determining productivity and reconstructing population trajectories of protected shark species is, however, challenging as the data necessary for quantitative assessments are generally uncertain and incomplete (e.g. McPherson & Myers 2009). This information is not only required for achieving natural resource management and conservation objectives but is also needed for informing government policy and social debate.

For the south-western Australian population, the information required for estimating specific population sizes and trends (e.g. time series of fishing exploitation rates and relative abundance levels) is not available. In the absence of this information, demographic models can be used to estimate the productivity and susceptibility of shark species to additional sources of mortality, such as fishing (Simpfendorfer 2005; McAuley et al. 2007). Previous demographic analyses for white shark populations elsewhere (Smith et al. 1998; Mollet & Cailliet 2002; Au et al. 2008; Ward-Paige et al. 2012) used limited deterministic approaches that ignored uncertainty in life history parameters, which for white sharks is substantial. Also, these studies either did not consider the anthropogenic impacts of fishing (Mollet & Cailliet 2002) or ignored age-specific rates of reproduction and mortality (Smith et al. 1998; Au et al. 2008; Ward-Paige et al. 2012).

In this chapter, estimates of catch from the reconstructions undertaken in Chapter 5 were combined with life-history parameters currently available for white sharks (including key uncertainties) presented in Chapter 6 to generate a series of potential population trajectory scenarios for the south-western Australian population. These scenarios allowed for an examination of the uncertainties associated with each of the model inputs by using two life history strategies (low and high productivity) from the latest information on population biology outlined in Chapter 6, the four versions of reconstructed catch histories as outlined in Chapter 5, three arbitrary levels of post-capture mortalities (PCM, 0%, 50% and 100%) and a distribution of assumed initial (unexploited) population sizes. This information was used in a simulation model to estimate the potential range of current abundance levels and trajectory histories for the south-western Australian population of white sharks. The variations in these values among scenarios will provide valuable information for determining which input variables and parameter assumptions have the largest effect on the outcomes and therefore where future research programs should be focussed to reduce the uncertainty in population estimates by the largest amount.

7.2 Methods

7.2.1 Demographic analysis

A probabilistic age-structured matrix model (Caswell 2001) was used to estimate key population productivity parameters (finite rate of population increase, λ , and population doubling time, T_D) while accounting for uncertainty in life history (LH). A probability distribution was defined for the biological parameters (10,000 Monte Carlo simulations) to draw samples from these distributions and construct posterior distributions of population productivity parameters and their corresponding medians and confidence intervals (2.5th and 97.5th percentiles). Life-history parameter values were obtained from the most recent published estimates. Two LH scenarios were considered (Table 6); the first scenario (LH1) was based on published life history information and the assumptions made in previous demographic analyses (Smith et al. 1998; Mollet & Cailliet 2002; Au et al. 2008; Ward-Paige et al. 2012). The second scenario (LH2) was based on expert judgement of newly emerging LH information.

Longevity estimates used in previous demographic analyses were between 36 (Smith et al. 1998) and 60 years (Mollet & Cailliet 2002) based on growth studies of white sharks from the Indian and Pacific Oceans. Until recently, the maximum number of vertebral growth bands observed was 23 (Francis 1996), so Smith et al. (1998) and Mollet and Cailliet (2002) used theoretical estimates of longevity derived from available age and growth information. In the present study, for LH1 longevity had a triangular distribution (Cortés 2002) with a mode of 40 and lower and upper bounds of 40 and 60 years, respectively (Figure 25). Natanson and Skomal (2015) recently showed that counts of vertical growth bands can underestimate the age of older individuals. Based on more recent attempts to validate age via bomb radio-carbon signatures, the maximum age of north-west Atlantic white sharks was estimated at 40 and 73 years for females and males, respectively (Hamady et al. 2014). These longevity estimates are higher than those from previous studies, and longevity could possibly be even higher as the Hamady et al. (2014) estimates were based on a sample of four females and four males, which were all smaller than the maximum reported sizes of this species. These authors suggested a lifespan of at least 70 years because in exploited populations longevity is generally higher than the observed maximum age. Whether white sharks live significantly longer in the north-west Atlantic than elsewhere or whether longevity has been underestimated in previous studies cannot currently be resolved. To account for this in LH2, uncertainty around longevity was broadened by using a mode of 70 and lower and upper bounds of 40 and 91 years (130% maximum age observed, as per Cortés 2002, Figure 25).

Female age at maturity is also uncertain. Based on published length at age estimates, Bruce (2008) reported a female age-at-maturity range between 12 and 17 years while Smith et al. (1998) used a range between 9 and 10 and Mollet and Cailliet (2002) set maturity at 15 years. Hence, for LH1 age at maturity had a triangular distribution with a mode of 13 and lower and upper bounds of 9 and 17 years, respectively (Table 6). Age-at-maturity values used in previous white shark demographic analyses were approximately 25% of longevity. However, age-at-maturity for other mackerel sharks (shortfin mako, bigeye thresher (*Alopias superciliosus*), pelagic thresher (*A. pelagicus*), common thresher (*A. vulpinus*), salmon shark (*Lamna ditropis*), porbeagle (*L. nasus*)) was between 25 and 64% longevity (Cailliet & Goldman 2004; Natanson et al. 2006; Goldman & Musick 2008). Age-at-maturity for LH2 was set at 38% longevity which was the mean across the studies on mackerel sharks and a value more consistent with validated estimates for other sharks with low productivity (McAuley et al. 2007). Age-at-maturity was sampled from a triangular distribution with a mode of 25 and lower and upper bounds of 15 and 35 years, respectively (Figure 25). Age at first reproduction was set to one year after the age at maturity for both LH scenarios.

The von Bertalanffy growth function (VBGF) was used to transform the relationships at total length (TL) to relationships at age. There is considerable variability in published growth estimates of white sharks. For example, Tanaka et al. (2011) reported a k value of 0.159 y^{-1} for female sharks from Japan whereas Cailliet et al. (1985) and Wintner & Cliff (1999) reported k values of 0.058 y^{-1} and 0.065 y^{-1} for females collected in California and South Africa, respectively. As a result, only the growth findings of O'Connor (2011) for southern Australia were used. A two parameter version of the VBGF (2 VBGF) was used as this provided the best fit (O'Connor 2011). Growth parameters are co-dependent so a multivariate normal distribution with means of 7.19 m (L_∞), 0.056 y^{-1} (k) and 1.40 m (L_0) was used to draw samples of L_∞ and k (Figure 25). Parameter samples were constrained to feasible values (i.e. k >0 and L_∞< 7.5 m). O'Connor (2011) did not report the variance-covariance matrix (VCM) for the estimated parameters, which is needed for drawing multivariate samples. The VCM was thus calculated by re-fitting the 2 VBGF to the data used by O'Connor (2011). The same samples of growth parameter values were used for both LH scenarios.

Embryo sex ratio (E_{sr}) has been observed to be 1:1 so a 0.5 factor was used to obtain the number of female embryos per female. Reported litter size (*Lit*) ranged between two and 17 pups per female. However, only a few pregnant females have been reliably examined with verifiable records for Japan and New Zealand (Bruce 2008). Although 17 pups have been reported in the literature, this figure has not been verified and the maximum number of near-term pups confirmed by dissection of pregnant females is 10 (Francis 1996). Based on this, for LH1 a triangular distribution with a mode of 10 and lower and upper bounds of two and 10 pups was used (Figure 25). For LH2, a uniform distribution with upper and lower bounds at two and 10 pups, respectively, was used to account for uncertainty in the reproductive strategy.

Information on the proportion of females in mature condition is only available at length (Francis 1996). Constructing an age-at-maturity curve from length-at-maturity information would be misleading given the recent maximum age findings. Hence, knife-edge maturity was assumed by setting *Lit* equal to 0 for all ages < age-at-maturity.

The frequency of white sharks' reproductive cycle (R_c) is still uncertain. Movement information from the north-eastern Pacific showed that mature females undertake a two-year reproductive migration (Domeier & Nasby-Lucas 2013), whereas Mollet et al. (2000) and

Mollet & Cailliet (2002) proposed a three-year cycle (a gestation of 18 months followed by a resting period of 18 months). As a result, for both LH scenarios samples of R_c between three and one years were drawn with an arbitrarily decreasing probability (Figure 25). Natality at age (N_a), the first row of the Leslie Matrix, was calculated as

$$N_a = \frac{E_{sr} Lit}{R_c}$$

There are no direct estimates of natural mortality (M) for white sharks so indirect methods were used. No single indirect method is preferred as all methods have accuracy and bias issues (Kenchington 2014), so mortality at age (M_a) was estimated from LH parameter information using a range of indirect age-independent (Pauly 1980; Hoenig 1983; Jensen 1996) and age-dependent (Peterson & Wroblewski 1984; Lorenzen 1996; Gislason et al. 2010) methods. Chen and Watanabe's estimator (1989) was not considered because it can produce unstable estimates (Kenchington 2014). Sea surface temperature values, required for Pauly's (1980) method, were derived from Reynolds & Smith (1994). Finally, population productivity for the unfished condition was determined by estimating λ, T_D and the reproductive value of each age class.

Table 6. List of scenarios and assumptions made for modelling uncertainty about the productivity and population trajectory of white sharks in the south-western Australian population. For the growth parameters, only the mean values used in the multivariate normal distribution are presented. Assumptions made for modelling the catch trajectories are shown in Table **5**.

Quantity	Assumption				
Life history	**LH1**			**LH2**	
Maximum age (year)	triangular(40, 40, 60)			triangular(40, 70, 91)	
Age at 50% maturity (year)	triangular(9, 13, 17)			triangular(15, 25, 35)	
Litter size	triangular(2, 10, 10)			uniform(2, 10)	
Reproductive period (year)	decreasing probability between 3 and 1			as LH1	
Embryo sex ratio	1:1			as LH1	
Size at birth (cm)	140			as LH1	
Growth coefficient (k, year^{-1})	0.056			as LH1	
Asymptotic total length (L_{inf}, cm)	719			as LH1	
Unexploited population size (N_0, females)	**1500**	**3000**	**5000**	**7500**	**10000**
Post-capture mortality (post 1997)	**0%**		**50%**	**100%**	
Selectivity	**Sel1**			**Sel2**	
Size composition	derived from interviews with commercial fishers, official logbooks and onboard observers			broader size composition used	

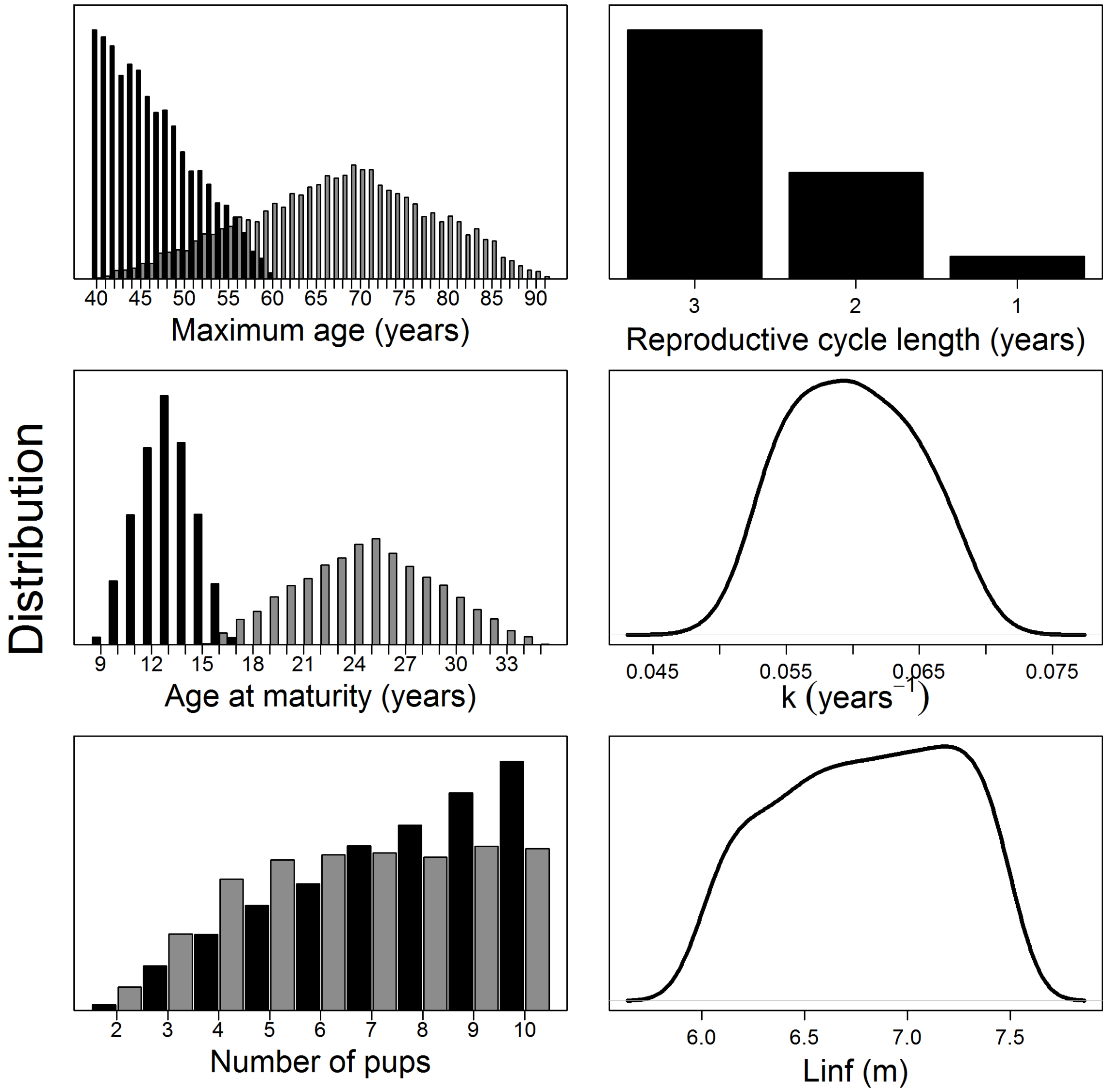

Figure 25. Probability distributions for the life history parameter inputs. For maximum age, age at maturity and number of pups, life history scenarios LH1 and LH2 are shown in black and grey, respectively. Reproductive cycle lengths of 3, 2, and 1 year were given a probability of 0.70, 0.25, and 0.05, respectively.

7.2.2 Population trajectory simulations

Population trajectories were simulated between 1938/39 (the assumed first year when white sharks from the south-western Australian population were caught in a fishery, refer to Chapter 5) and 2012/13 (financial years were used as they reflect commercial catch reporting procedures). This required values for unexploited population size (N_0) (females only, all age classes) and fishing mortality (F) in addition to the biological information described above. For each set of LH, N_0 and F scenarios, 1,000 simulations were performed to obtain a sample of possible population trajectories.

Results are presented for all female size classes and for females > 3 m TL to investigate whether there were differences in trajectories for the size component of the white shark population that has been identified as the size responsible for most attacks on humans. To quantify the number of females > 3 m, the age corresponding to a 3 m female was determined from the inverse of the von Bertalanffy growth curve based on the growth parameters simulated in each iteration.

As empirical measures of N_0 and F do not exist, assumed N_0 values and reconstructed fishery catches (refer to Chapter 5) were used to derive hypothetical time-series of F. A range of N_0 values was considered, with a minimum bound that, on average, avoided population extinction by 2012/13 for the most optimistic scenarios, and maximum bound above which fishing mortality had negligible effect. Estimates of the genetic effective population size (N_e, i.e. the size of a theoretical population with the same assumed rate of genetic drift as the population being examined, Wright 1931) were used to refine the range of N_0 values. Blower et al. (2012) reported a current (2012) genetic effective population size (N_e) of 693 individuals for the south-western Australian population. These estimates correspond to the effective population size but not the census population size (N_c, the size of the total population). Hence, assumptions were made on the male to female ratio of the breeding part of the south-western Australian population (between 1:1 and 3:1) and the N_e/N_c (between 1 to 0.25) to calculate a range of 2012 N_c values. An iterative search was then completed to estimate the N_0 values that yielded the 2012 N_c values given the assumed scenarios of life history, catch and selectivity. This process yielded a range of N_0 values (all age classes) between ~1,500 and 20,000 females (which equates to a range in total population size of 3,000–40,000 individuals- males and females). Hence, five N_0 scenarios were considered within this range (Table 6). Values of N_0 larger than 10,000 females showed negligible impacts from the reconstructed catches so they were not tested.

To investigate the range of hypothetical population responses to the assumed sources of fishing mortality the following population projection model was used:

$$N_{t+1} = \mathbf{MH}N_t$$

where N_t was the numbers-at-age vector in year *t*; $\mathbf{M}$ was the Leslie population projection matrix calculated from the LH parameters assuming a birth-pulse population and a post-breeding census; $\mathbf{H}$ was the exploitation matrix, i.e. a diagonal matrix with h_a elements corresponding to the proportion of individuals of age a surviving exploitation (Caswell

2001). The $\mathbf{H}$ diagonal elements were calculated based on F and fishing gear selectivity (Aires-da-Silva & Gallucci 2007).

Time series of F were derived from the annual exploitation rate, which was calculated as catch divided by estimated population size. The approach used to estimate the catches and their uncertainty is outlined in Chapter 5. These catches spanned between 1938/39 and 2012/13 and included: 1) incidental white shark catches in the TDGDLF, the GHaT (for South Australia only) and the MSF; 2) recreational catches at the Albany whaling station in Western Australia; 3) recreational catches by game fishers affiliated with the GFCSA in South Australia; and 4) Western Australian 'wetline' fishing with float-hooks. The catch samples (in number of individuals caught) were then used in each model iteration (Figure 21).

Three post-capture mortality (PCM) scenarios were considered (Table 6). It was assumed that prior to listing all caught individuals died because of the potential monetary value of the species' teeth and jaws and the lack of any obvious incentive for releasing live white sharks. The PCM of white shark post-protection is unknown. As PCM can only range between 0–100%, three scenarios were considered (0%, 50% and 100%) for sharks caught following their protection.

Fishing gear selectivity represented the capture probability for a shark of age a (S_a), calculated following Malcolm et al. (2001) as

$$S_a = \sum S_l P_{l|a}$$

where S_l was the capture probability for a shark of length l given by the proportion captured at length; $P_{l|a}$ was the conditional probability that a shark was of total length l given that it was of age a, which was calculated from a lognormal distribution with mean predicted by the 2 part VBGF and an assumed coefficient of variation of 0.3. For LH1, information on the proportion captured at length was derived from interviews with commercial TDGDLF fishers, observed TDGDLF catches, fishery-independent dropline catches in Western Australian waters and from GHaT fishery logbooks, catch disposal records and observer programs (Malcolm et al. 2001; refer to Chapter 3 and 4) . The observer and fishery-independent data provided individual measurements and estimates of total length for most sharks while most interviewed fishers did not keep a record of the size of the individuals captured so the reported length was the average size of the individuals caught. For LH2, a broader selectivity curve was used to allow for the capture of larger individuals (Figure 27). As relative S_a were used in the analysis, S_a was divided by the maximum S_a value.

The mean stable age distribution was used to initiate the population projection. The model was initiated in 1838, as a burn-in period of 100 years was required to allow the simulated population to stabilise at equilibrium conditions. To relax the assumption of time invariant survival and reproductive rates (Cortés 1998; Aires-da-Silva & Gallucci 2007) vital rates were allowed to vary in each projection time step (Aires-da-Silva & Gallucci 2007).

To avoid continuous exponential population growth, compensatory mechanisms were simulated through density-dependent survival. Following Taylor & Gallucci (2005), in each time step the survival probability of the age 1 class was multiplied by $e^{(-\alpha N_t)}$, where α was a density-dependent parameter estimated through an iterative search so that $\lambda(N_0) = 1$. All simulations were undertaken using the statistical package R (R Development CoreTeam 2011).

7.2.3 Additional Sensitivity Analyses

To further guide future research directions and priorities, in addition to the broad examination of using different sets of life history, differing levels of PCM and different catch reconstruction histories as outlined above, a set of more detailed sensitivity analyses were also undertaken to test the relative effects of varying some of the key values used in the model. The variables that were specifically tested were catch level, selectivity, natural mortality, maximum age, reproductive cycle length and litter size.

When undertaking sensitivity analyses in standard stock assessments, the effects of changing input values are generally compared against a defined base case. In this study, there was no base case because of the levels of uncertainty surrounding each of the quantities tested (as described above). Hence, three scenarios (minimum, average and maximum values) were defined for each of the assumed catch time series, S_a, maximum age, R_c, Lit, and M_a (Table 7) and tested quantities were maintained at average values except when the effect of that particular quantity was tested.

Using the values shown in Figure 26 and Figure 27, sensitivity analyses were undertaken for each of the assumed N_0 values. As the sensitivity analysis used averaged values, the specific population outputs generated are not directly comparable to the simulated population trajectories; however, it is the level of relative difference in trajectories amongst these values that is most informative and important.

Table 7. Sensitivity analysis conducted for guiding future research efforts. Minimum, average and maximum refer to the minimum, average and maximum value, respectively, across all possible values considered in the analysis.

Scenario	Catch	S_a	Maximum Age	R_c	*Lit*	M_a
Minimum	Minimum across years over C1, C2, C3, and C4	Minimum across age classes over Sel1 and Sel2	Minimum over LH1 and LH2	Minimum over LH1 and LH2	Minimum over LH1 and LH2	Minimum across age classes over LH1 and LH2
Average	Average across years over C1, C2, C3, and C4	Average across age classes over Sel1 and Sel2	Average over LH1 and LH2	Average over LH1 and LH2	Average over LH1 and LH2	Average across age classes over LH1 and LH2
Maximum	Maximum across years over C1, C2, C3, and C4	Maximum across age classes over Sel1 and Sel2	Maximum over LH1 and LH2	Maximum over LH1 and LH2	Maximum over LH1 and LH2	Maximum across age classes over LH1 and LH2

Table 8. Values of maximum age, reproductive cycle length and number of pups used in the sensitivity analyses.

	Maximum age	Reproductive cycle length	Number of pups
Minimum	40	1	2
Average	56	2	6
Maximum	90	3	10

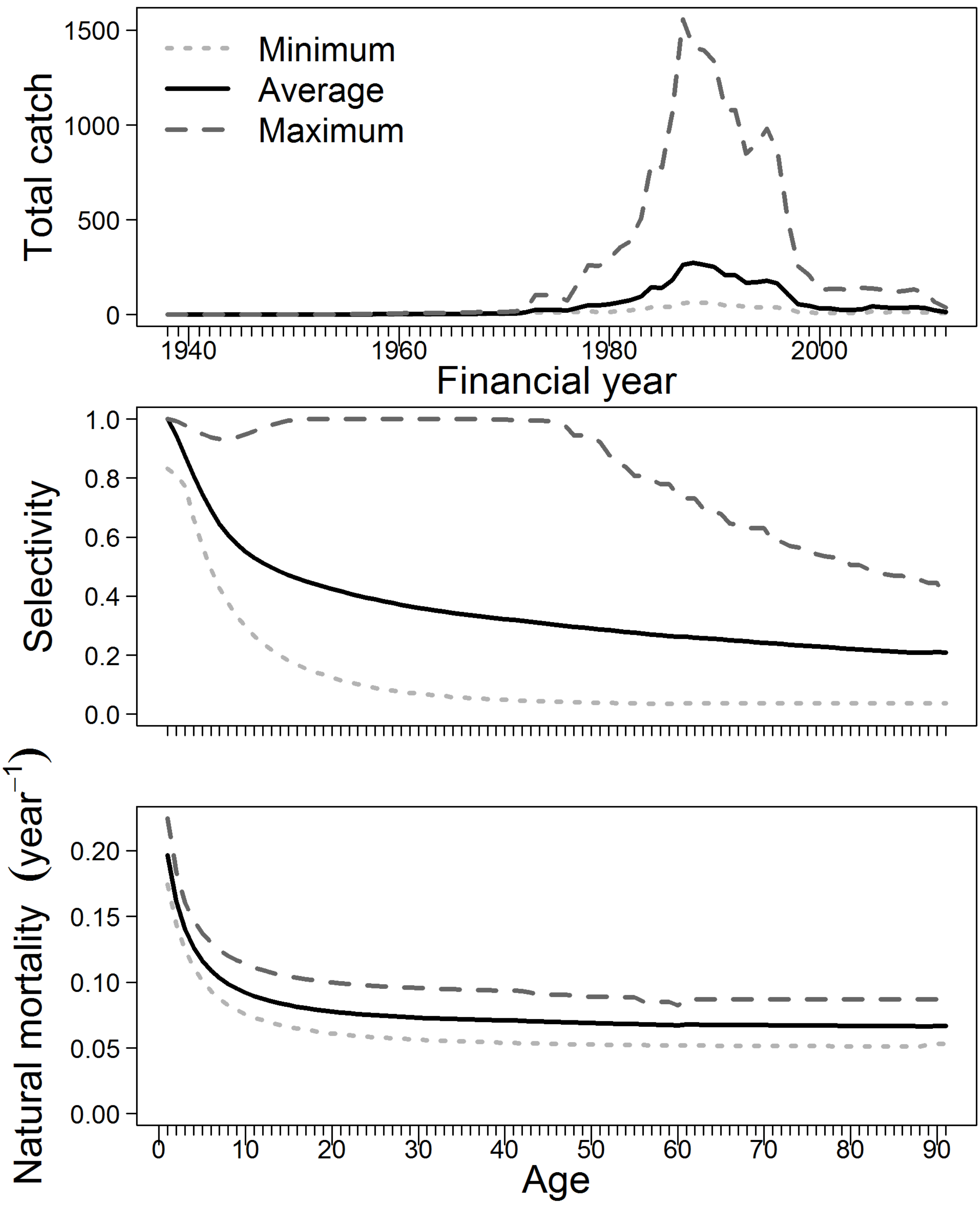

Figure 26. Values of total annual catch, selectivity and natural mortality at age used in the sensitivity analyses.

7.3 Results

7.3.1 Natural mortality

Natural mortality schedules declined approximately exponentially with age (Figure 27). The combination of uncertainty in vital rates and the use of age-independent and age-dependent methods yielded median M_a values ranging from 0.075 to 0.204 year^{-1} for LH1 and from 0.059 to 0.189 year^{-1} for LH2. For the age-independent methods, Jensen's (1996) method, which relies on age at maturity, yielded higher M values than the other methods for LH1. Pauly's method (1980), which relies on growth parameters and water temperature, yielded higher M values than the other methods for LH2. For the age-dependent methods and the two LH scenarios, Gislason et al.'s (2010) method yielded higher M_a values up to approximately age class 10 after which Peterson & Wroblewski's (1984) method yielded slightly higher M_a values.

7.3.2 Demographic analysis

The demographic analysis was sensitive to the assumptions made on the parameter values used in the LH scenarios (Figure 28). For LH1, median λ and T_D were 1.07 (95% CI: 1.02–1.13) year^{-1} and 10.88 (95% CI: 5.71–43.13) years, whereas for LH2, median λ and T_D were 1.02 (95% CI: 1.00–1.06) year^{-1} and 31.08 (95% CI 11.66–431.58) years. The higher uncertainty for LH2 was mostly given by the assumed uniform distribution for litter size where low and high litter size values were given equal probability. Note that some of the very low litter size values for LH2 (two and three pups) yielded negative population growth under no fishing (i.e. $\lambda < 1$) so these values were discarded and the biological parameters resampled. Hence, for LH2 litter size values of two and three had lower probability. The unrealistic λ values could have resulted from combining these litter size values with unrealistic values of other life history parameters. The 15–27 and 29–35 age classes had the highest reproductive value for LH1 and LH2, respectively (Figure 28).

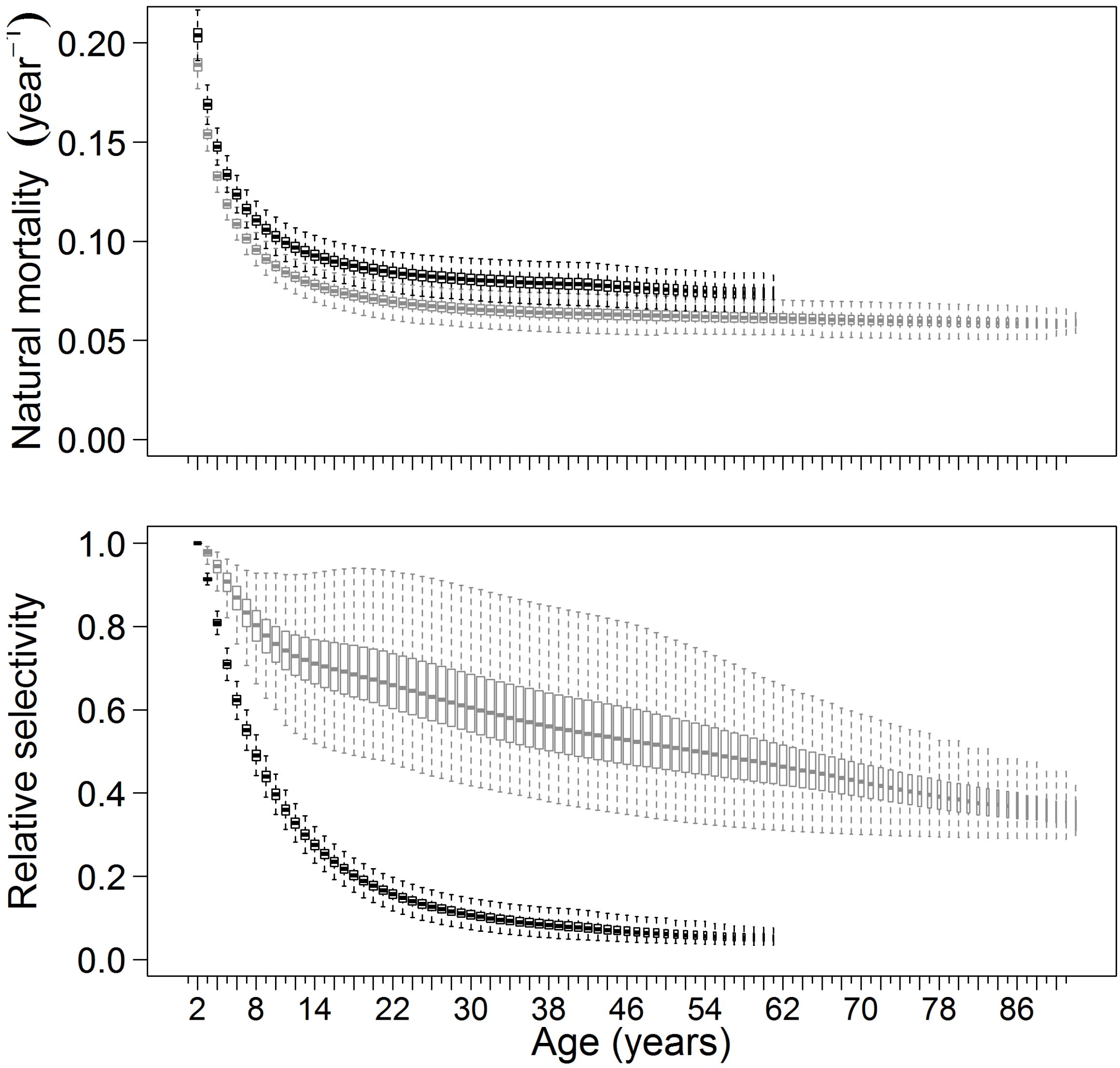

Figure 27. Natural mortality and selectivity-at-age box plots. Scenarios 1 and 2 are shown in black and grey, respectively. Boxes' widths are proportional to the square-roots of the number of observations in each age class.

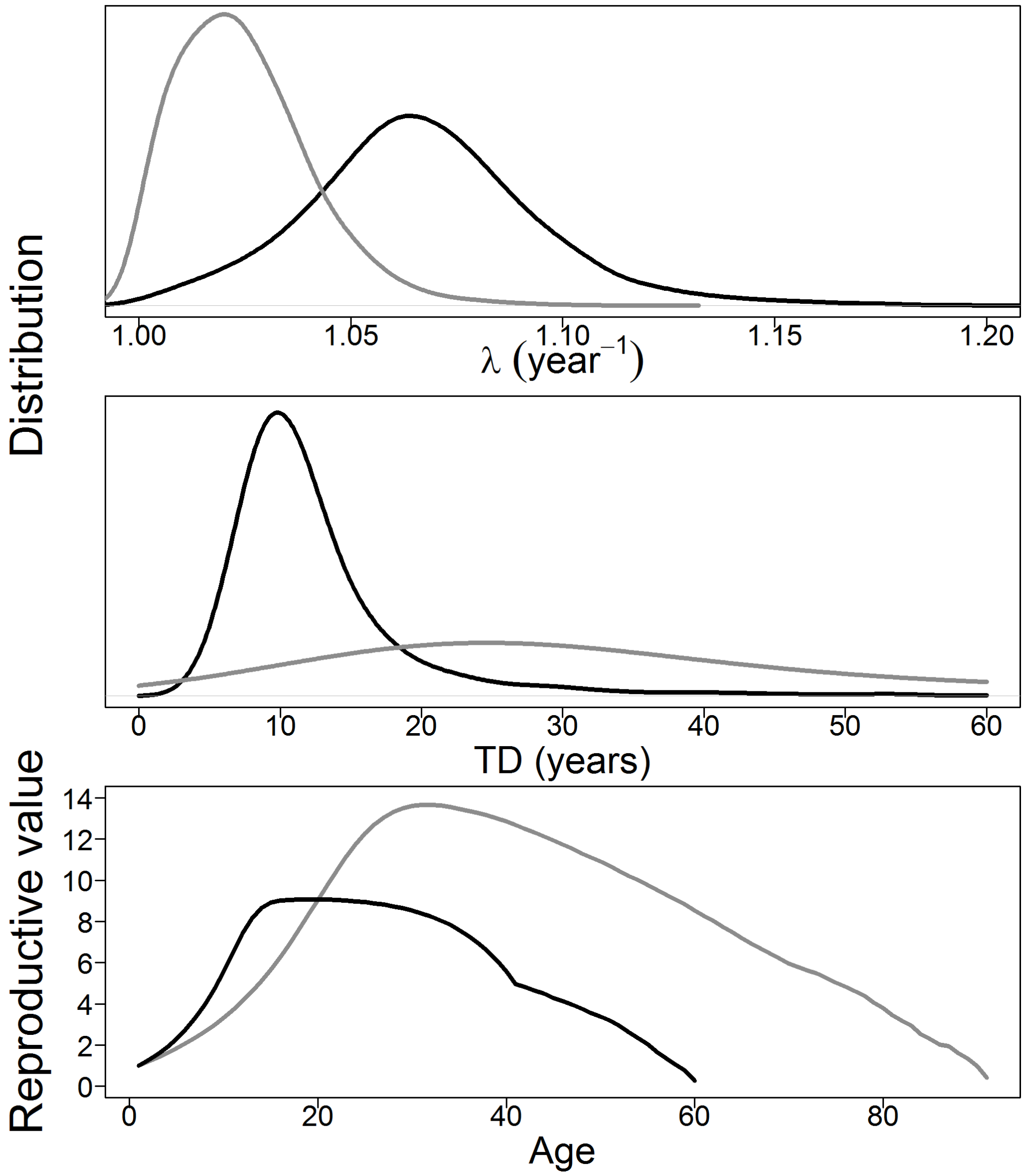

Figure 28. Probability distributions for an unfished white shark population: finite rate of population growth (λ , top), population doubling time (TD, middle) and reproductive value (bottom). Life history scenarios 1 and 2 are shown in black and grey, respectively.

7.3.3 Population trajectory simulations

The simulated population trajectories for the assumed N_0, LH, catch and PCM scenarios ranged between population extinction and a slight reduction in population size since 1938/39. Overall, both the total population and larger size category were less affected by the reconstructed catches under the LH1and 0% PCM conditions (Figure 29 to Figure 34). The following provides more details on the outcomes of the model for each of the scenarios for total population changes and for sharks > 3m TL. This includes outlining the relative level of change for each of the scenarios since protection was legislated in 1997.

Total Population

100% PCM Scenarios

For the 100% PCM and LH1 scenarios, the N_0 of 1,500 females (3,000 individuals) became extinct (median trajectory) before 2000 under C2 conditions and declined considerably under C4 and C1 conditions (Figure 29). For larger N_0 values, the population was less affected, with N_0 > 7,500 (15,000 individuals) showing minimal declines in population size under all catch scenarios.

For the 100% PCM and LH2 scenarios, a N_0 of 1,500 females (3,000 individuals) became extinct (median trajectory) before 2000 under all catch scenarios. A N_0 of 3,000 (6,000 individuals) became extinct under C2 conditions and declined considerably under C4 and C1 conditions. For larger N_0 values, the population trajectories were less affected.

For the 20 LH1 scenarios with 100% PCM, nine scenarios either (1) became extinct or (8) showed negligible population decline since 1938/39 whereas 11 scenarios showed a population decline of >10% since 1938/39 but did not go extinct. For these 11 scenarios, five showed no increase in population size since protection and six scenarios showed an increase of <10% (Table 9A).

Out of the 20 LH2 scenarios with 100% PCM, five scenarios became extinct whereas 15 scenarios showed a population decline of >10% since 1938/39. For these 15 scenarios, none showed any increase in population size since protection (Table 9A).

50% PCM Scenarios

Similar overall patterns, though progressively more optimistic, were found under the assumption of 50% PCM (Figure 30) and 0% PCM (Figure 31) since protection.

Out of the 20 LH1 scenarios with 50% PCM, 12 scenarios either (1) became extinct or (11) showed negligible population decline since 1938/39 whereas eight scenarios showed a population decline of >10% since 1938/39. For these eight scenarios, one scenario showed no increase in population size since protection, five scenarios showed an increase of <10% and two scenarios showed an increase of between 10 and 20% since protection (Table 9A).

Out of the 20 LH2 scenarios with 50% PCM, five scenarios became extinct whereas 15 scenarios showed a population decline of >10% since 1938/39. For these 15 scenarios, 11 scenarios showed no increase in population size since protection and four scenarios showed an increase of <10% (Table 9A).

0% PCM Scenarios

Out of the 20 LH1 scenarios with 0% PCM, 13 scenarios either (1) became extinct or (12) showed negligible population decline since 1938/39 whereas seven scenarios showed a population decline of >10% since 1938/39. For these seven scenarios, four scenarios showed an increase of between 10 and 20% in population size since protection and three scenarios showed an increase of between 20% and 30% (Table 9A).

Out of the 20 LH2 scenarios with 0% PCM, five scenarios became (4) extinct or showed negligible population decline (1) since 1938/39 whereas 15 scenarios showed a population decline of >10% since 1938/39. For these 15 scenarios, 11 scenarios showed an increase of <10% in population size since protection and four scenarios showed an increase of between 10 and 20% (Table 9A).

Sharks larger than 3 m

Similar to the range of total population numbers, depending upon the life history and other model inputs used, the simulated population trends for larger sharks (females > 3m TL) also ranged between extinction and just a slight reduction in their abundance since 1938/39 (Figure 32 to Figure 34).

Females > 3m TL showed similar variations in the patterns of population change for the period since protection was legislated in 1997. In comparison to the whole population, however, there were fewer scenarios that showed declines in their abundance during this period and the relative levels of potential increase were greater (about double) than those calculated for the total population. Consequently, out of the 120 scenarios, there were 16 scenarios which showed increases > 10%, 7 scenarios with increases > 20% and two scenarios with increases > 40% (Table 9B).

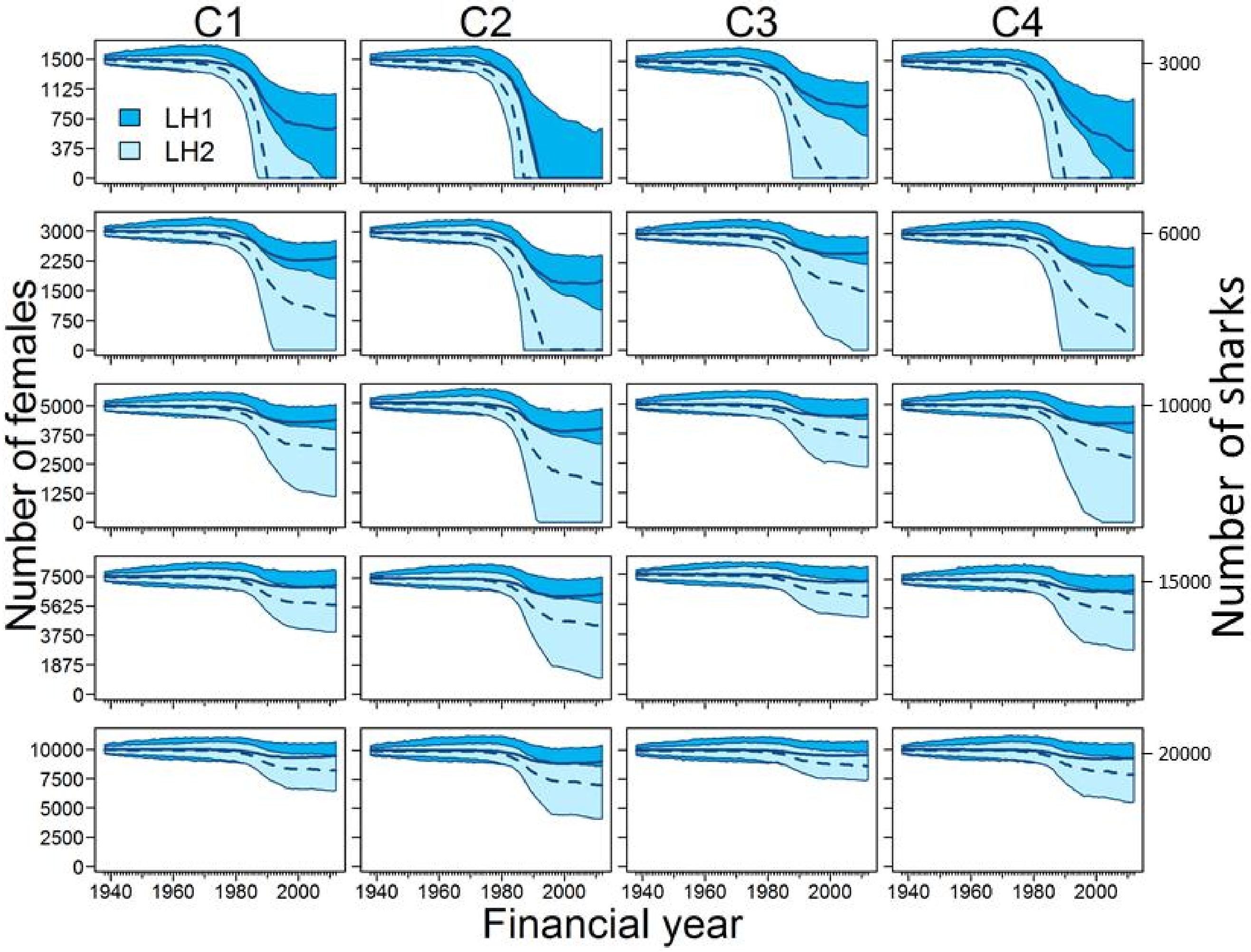

Figure 29. Total Population; PCM 100%: Simulated stochastic population trajectories for the 100% post capture mortality (PCM) scenario under the assumed N_0, LH, and catch scenarios. The median trajectory is shown as a solid (LH1) or broken (LH2) line and 95% of the simulated trajectories are shaded dark (LH1) or light (LH2) blue. The left axis shows the number of females in the population and the right axis shows the total number of sharks in the population.

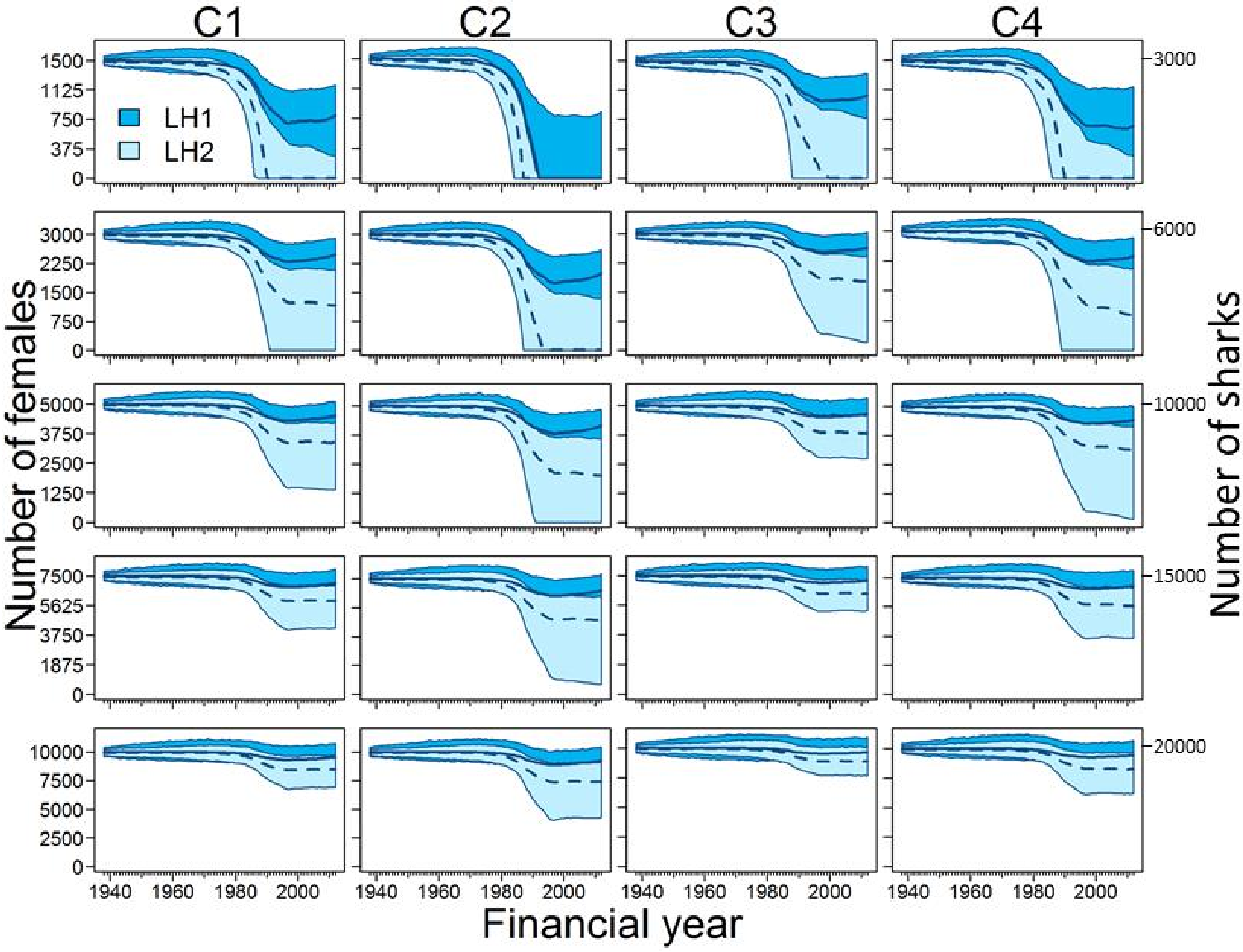

Figure 30. Total Population; PCM 50%: Simulated stochastic population trajectories for the 50% post capture mortality (PCM) scenario under the assumed N_0, LH, and catch scenarios. The median trajectory is shown as a solid (LH1) or broken (LH2) line and 95% of the simulated trajectories are shaded dark (LH1) or light (LH2) blue. The left axis shows the number of females in the population and the right axis shows the total number of sharks in the population.

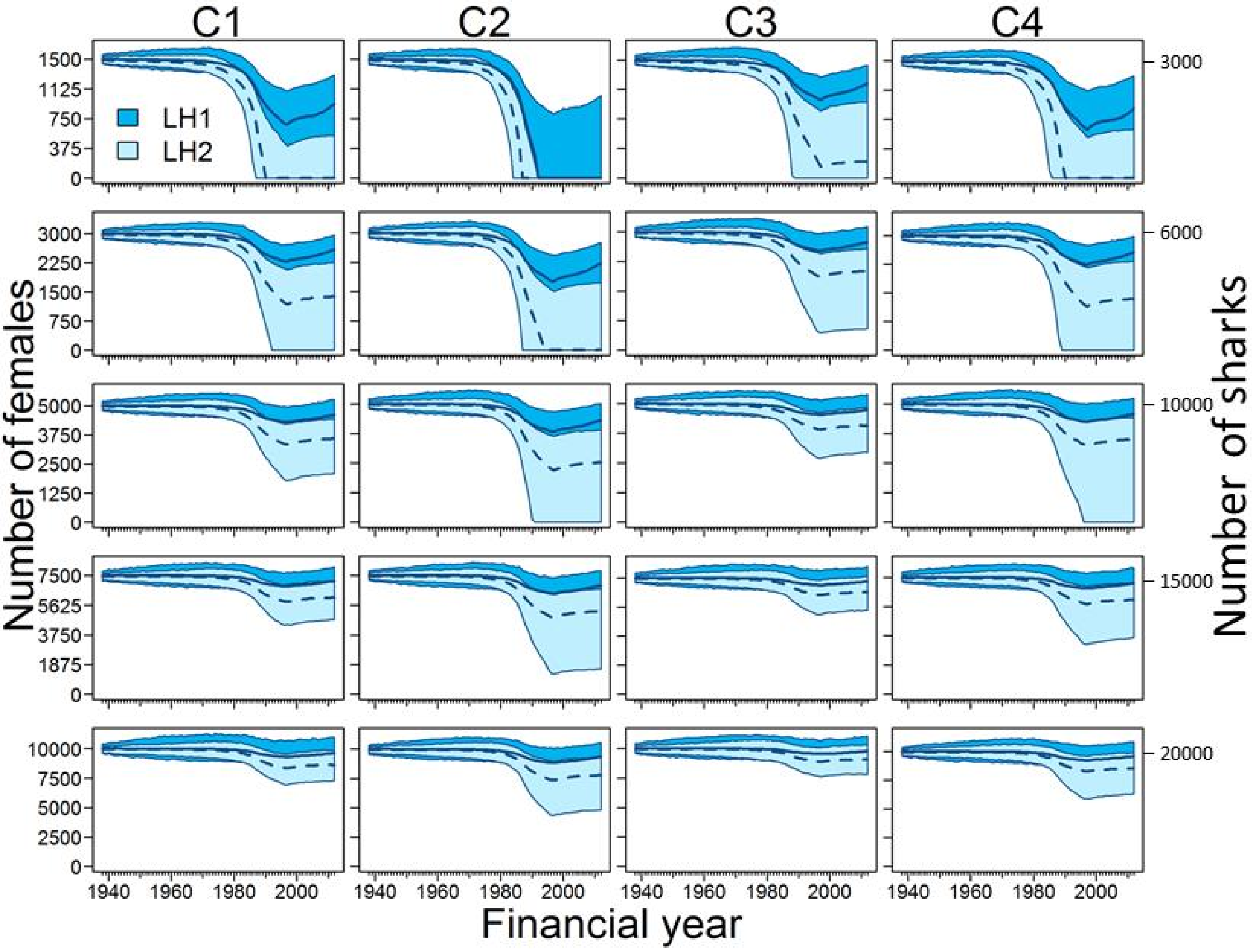

Figure 31. Total Population; PCM 0%: Simulated stochastic population trajectories for the 0% post capture mortality (PCM) scenario under the assumed N_0, LH, and catch scenarios. The median trajectory is shown as a solid (LH1) or broken (LH2) line and 95% of the simulated trajectories are shaded dark (LH1) or light (LH2) blue. The left axis shows the number of females in the population and the right axis shows the total number of sharks in the population.

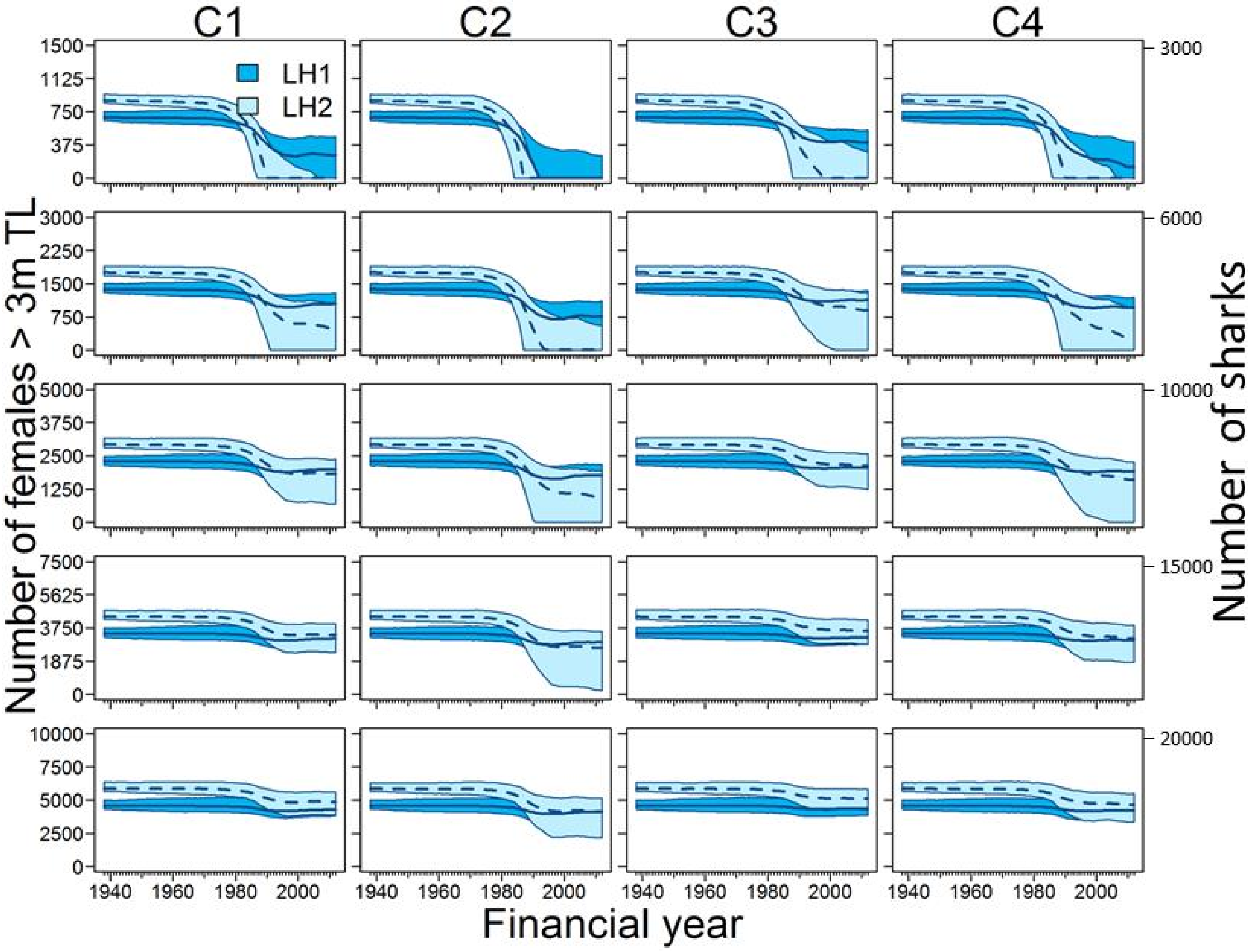

Figure 32. Large (> 3m TL) Sharks; PCM 100%: Simulated stochastic population trajectories for females > 3 m TL under the 100% post capture mortality (PCM) scenario. The median trajectory is shown as a solid (LH1) or broken (LH2) line and 95% of the simulated trajectories are shaded dark (LH1) or light (LH2) blue. For comparative purposes, the y-axis scale is the same as for Figure 29. The left axis shows the number of females > 3m in the population and the right axis shows the total number of sharks > 3m in the population.

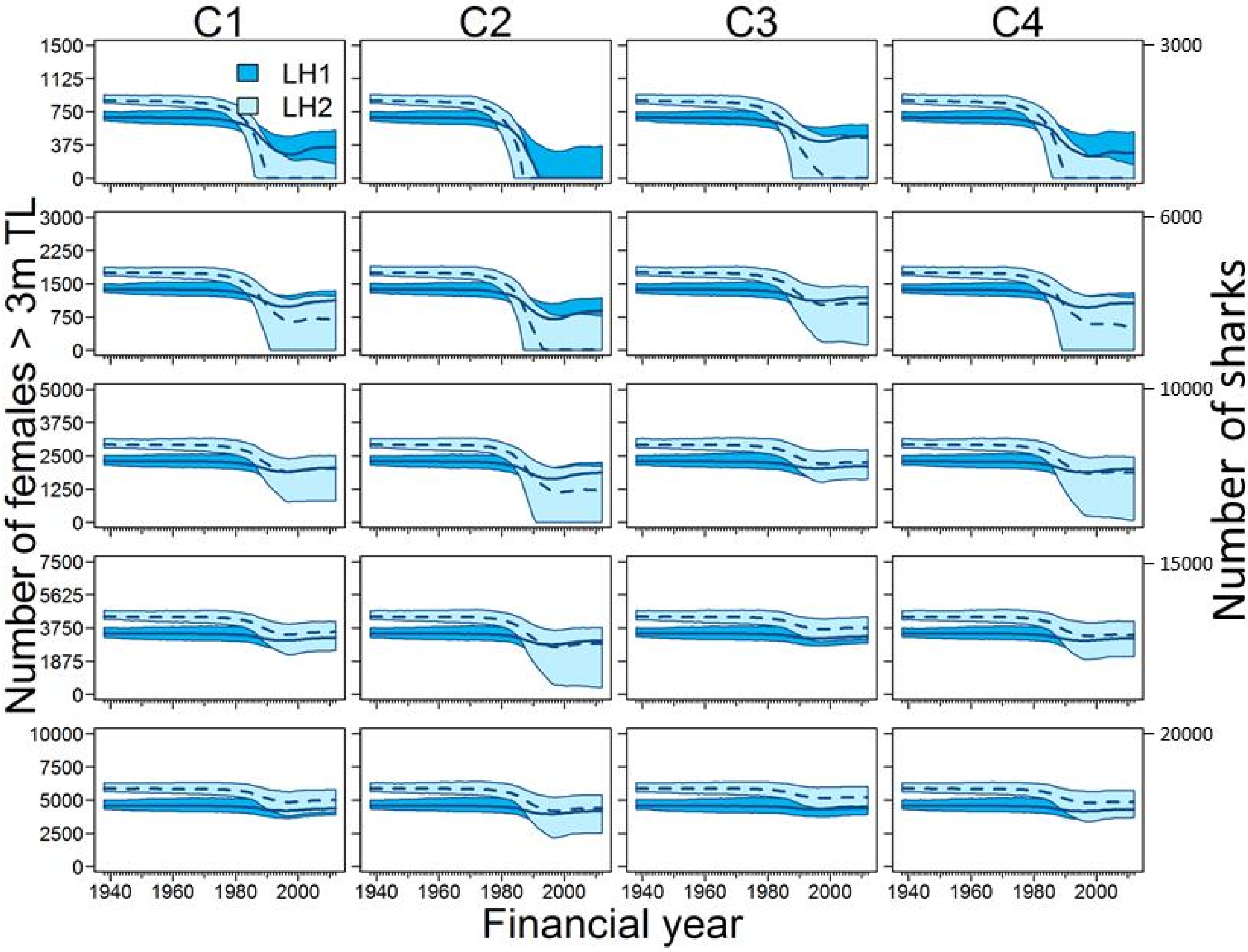

Figure 33. Large (> 3m TL) Sharks; PCM 50%: Simulated stochastic population trajectories for females > 3 m TL under the 50% post capture mortality (PCM) scenario. The median trajectory is shown as a solid (LH1) or broken (LH2) line and 95% of the simulated trajectories are shaded dark (LH1) or light (LH2) blue. For comparative purposes, the y-axis scale is the same as for Figure 30. The left axis shows the number of females > 3m in the population and the right axis shows the total number of sharks > 3m in the population.

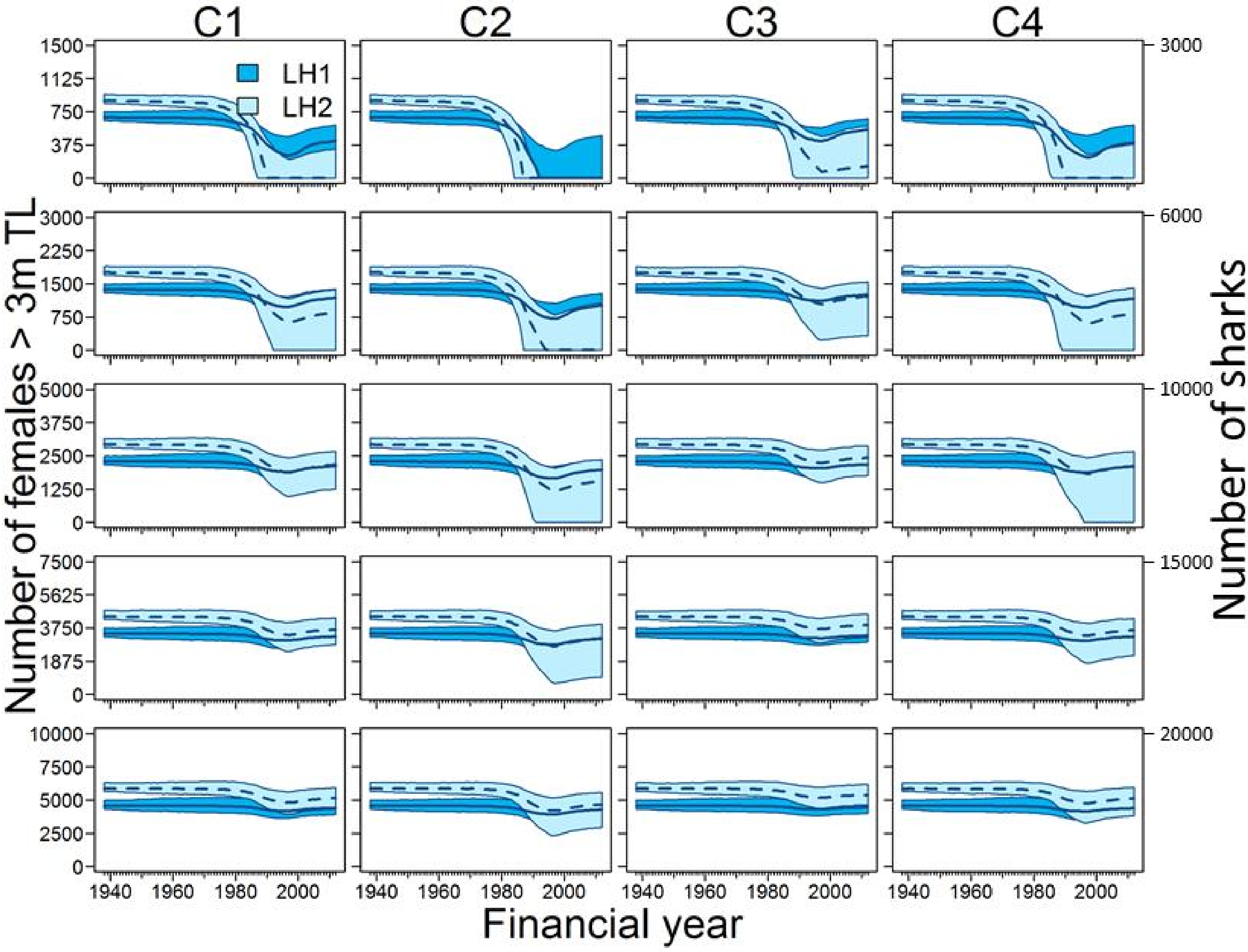

Figure 34. Large (> 3m TL) Sharks; PCM 0%: Simulated stochastic population trajectories for females > 3 m TL under the 0% post capture mortality (PCM) scenario. The median trajectory is shown as a solid (LH1) or broken (LH2) line and 95% of the simulated trajectories are shaded dark (LH1) or light (LH2) blue. For comparative purposes, the y-axis scale is the same as for Figure 31. The left axis shows the number of females > 3m in the population and the right axis shows the total number of sharks > 3m in the population.

Table 9. Median rate of population increase (in %) between 1998/99 and 2012/13 for the assumed N_0, LH, catch and PCM scenarios. A) Entire female population; B) females > 3 m TL. PCM_100=100% post capture mortality; PCM_50=50% post capture mortality; PCM_0=0% post capture mortality. A population increase of 0.0 implies either extinction of the white shark population in the simulation or no increase since protection.

A)

PCM	Catch	1500 LH1	1500 LH2	3000 LH1	3000 LH2	5000 LH1	5000 LH2	7500 LH1	7500 LH2	10000 LH1	10000 LH2
PCM_100	C1	0.0	0.0	3.8	0.0	2.8	0.0	1.8	0.0	1.5	0.0
PCM_100	C2	0.0	0.0	0.0	0.0	4.0	0.0	3.2	0.0	2.5	0.0
PCM_100	C3	0.0	0.0	0.9	0.0	0.8	0.0	0.6	0.0	0.6	0.0
PCM_100	C4	0.0	0.0	0.0	0.0	1.0	0.0	0.9	0.0	0.8	0.0
PCM_50	C1	10.0	0.0	8.1	0.0	4.9	0.1	3.1	0.5	2.4	0.6
PCM_50	C2	0.0	0.0	11.3	0.0	8.2	0.0	5.6	0.0	4.1	0.5
PCM_50	C3	7.1	0.0	4.3	0.0	2.8	0.0	1.8	0.0	1.3	0.0
PCM_50	C4	0.0	0.0	6.1	0.0	4.0	0.0	2.8	0.0	2.1	0.0
PCM_0	C1	26.2	0.0	12.4	11.7	6.8	6.3	4.6	4.0	3.4	2.8
PCM_0	C2	0.0	0.0	21.0	0.0	11.8	10.1	7.5	6.5	5.4	4.7
PCM_0	C3	17.8	11.0	7.8	7.4	4.5	4.1	3.0	2.7	2.2	2.0
PCM_0	C4	24.6	0.0	12.8	10.9	7.4	6.5	4.8	4.2	3.5	3.1

B)

PCM	Catch	1500 LH1	1500 LH2	3000 LH1	3000 LH2	5000 LH1	5000 LH2	7500 LH1	7500 LH2	10000 LH1	10000 LH2
PCM_100	C1	0.0	0.0	8.1	0.0	5.0	0.0	3.3	0.5	2.5	0.7
PCM_100	C2	0.0	0.0	7.4	0.0	8.0	0.0	5.3	0.0	4.0	0.0
PCM_100	C3	0.0	0.0	2.8	0.0	2.0	0.0	1.3	0.0	1.1	0.0
PCM_100	C4	0.0	0.0	1.1	0.0	2.1	0.0	1.6	0.0	1.3	0.0
PCM_50	C1	25.5	0.0	13.5	4.6	7.5	5.9	4.8	4.2	3.6	3.2
PCM_50	C2	0.0	0.0	22.6	0.0	13.2	4.2	8.3	6.1	6.0	5.2
PCM_50	C3	14.9	0.0	7.3	2.0	4.3	2.6	2.8	1.9	2.1	1.6
PCM_50	C4	6.7	0.0	10.9	0.0	6.3	1.9	4.1	2.3	3.1	1.9
PCM_0	C1	49.3	0.0	19.2	26.1	10.2	13.3	6.5	8.2	4.7	5.9
PCM_0	C2	0.0	0.0	36.1	0.0	18.0	23.5	11.0	14.7	7.9	10.2
PCM_0	C3	28.5	23.8	11.7	15.9	6.5	8.4	4.2	5.3	3.2	4.0
PCM_0	C4	43.7	0.0	19.8	23.9	11.0	14.2	6.8	8.8	5.0	6.3

7.3.4 Additional Sensitivity Analyses

As seen in Figure 29 to Figure 34, the model outcomes have already been shown to be highly sensitive to the assumed N_0, PCM and LH values. The outputs from the more detailed sensitivity analyses are displayed below (Figure 35) for an assumed N_0 value of 3,000 females (6,000 individuals). As similar patterns were observed for the other assumed values of N_0, the outputs from these analyses are not shown.

The outputs identified that the model was highly sensitive to which of the four time series of reconstructed catches was used and also to the assumed selectivity at age. Similarly, for the life history parameters, the outputs showed that the model was more sensitive to the assumed values of number of pups and natural mortality than to the assumed values of maximum age and reproductive cycle length (Figure 35).

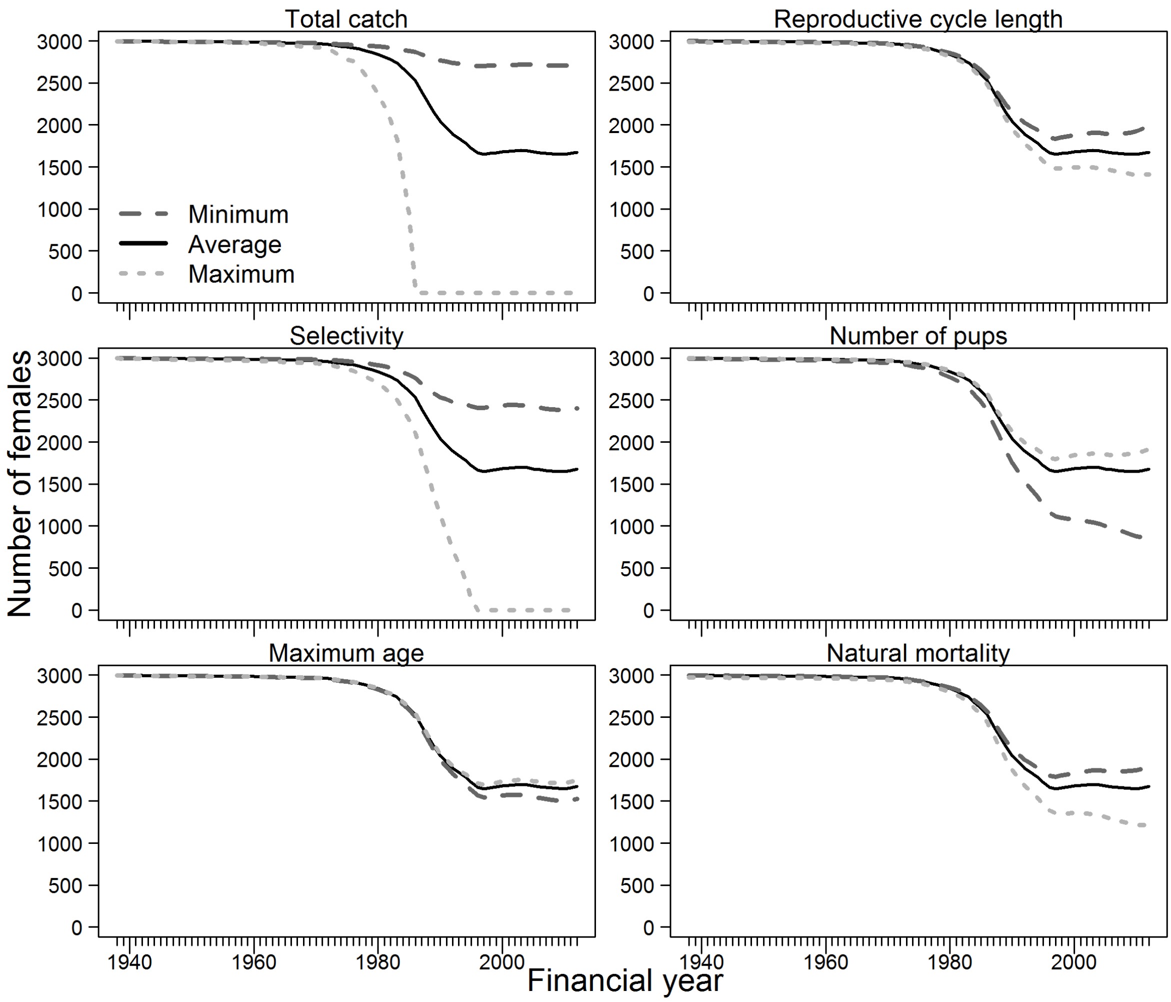

Figure 35. Sensitivity analysis testing the effect of varying different model input quantities for an assumed N_0 of 3,000 females.

7.4 Conclusion

The different input levels used for each of the four key parameters (LH, PCM, Catch, and N_0) resulted in significant differences to the modelled outputs for both current population size (N_0, Catch) and/or current trajectory (PCM, LH). As additional information may reduce the level of uncertainty associated with these parameters this could reduce the set of plausible scenarios. Further discussion of the potential to improve the level of understanding for each of these parameters is undertaken within Chapter 8 to help develop future management and research priorities.

8 Discussion and Conclusions

8.1 Catch Reconstruction

The lack of an accurate catch history has frequently been identified as a key deficiency in the ability to determine estimates of the current abundance and trajectory history for the south-western Australian population of white sharks (e.g. DEWHA, 2009). Within this report, the additional surveys and analyses used to estimate the historical levels of annual captures of white sharks are the most detailed yet undertaken for this population. While Malcolm et al (2001) provided survey-derived estimates of catches at about the time of this species' EPBC Act listing, the current study is the first to use time-series of fishing effort to describe historical patterns in these catches (Figure 21).

Given the data sources available it was not feasible to precisely account for every possible source of mortality or generate exact historical levels of catches for this population. The detailed analysis of all available information on the levels of captures of white sharks from the south-western population since 1938/39 included the collection of additional first-hand catch and catch rate information from fishers which was combined with a re-analysis of effort data from these key fisheries plus an examination of all other known potential sources of mortality. Based on current understanding of the distribution and movements of the south-western Australian white shark population we believe we have identified which activities were most likely to have generated significant levels of mortality and which were most likely to have generated negligible levels of mortality over the past 90 years. Should new information emerge, such as data that suggest open-ocean movements are more extensive than currently assumed, and that these could have led to frequent encounters with offshore fishing activities (e.g. WTBF, Indian Ocean Tuna Commission fleets), our estimated catches would need to be refined.

To account for the uncertainties in the data, rather than pick a single option, the combinations of datasets that were available for the three main fisheries examined (GHaT, TDGDLF and MSF) were combined with different sets of assumptions to generate a series of estimates of the historical levels of annual white shark catches since 1938/39. As these estimates were based on different assumptions, the potential levels of annualised catch show high uncertainty. Importantly, however, the overall patterns for the annual catches by each of these series were similar and were largely consistent with the changes in total levels of fishing effort over this period (Figure 21).

Catches were comparably low prior to the early 1980s when a rapid increase in commercial fishing effort resulted in a rapid increase in annualised catches. Catches peaked in the late 1980s with catch values of up to 270–401 and 627–975 white sharks a year (50th percentile) under the lowest (C3) and highest (C2) catch scenarios, respectively (Figure 21). Following the catch peak, reconstructed catches declined to much lower levels for all catch scenarios. The estimated catch in 2012/13 was between 45–56 and 61–79 sharks (50th percentile) for C3 and C2, respectively. As these fisheries are still operating, there may be some scope to decrease the uncertainty in these estimates by gathering more precise data on current catches which can then be used to potentially tune the historical data series.

The calculated estimates of white shark catches by commercial ‘wet-line’ fishing activities in Western Australia had relatively large levels of variation. This was due to a combination of uncertainties including what proportion of the large numbers of fishers who potentially may have undertaken the specific fishing activities that could result in the retention of white sharks, the widespread area over where this type of activity may have occurred, the diversity of fishing methods used, and different targeting behaviours. Given that the specific methods to capture white sharks by this sector have not been permissible for some time now, it is unlikely that any further improvements to the quantification of the historical catch levels by this method could be achieved. The impact of this uncertainty on future population modelling will, however, diminish through time.

In addition to the uncertainty in the magnitude of catches, a lack of information on the size/age composition of catches across multiple regions, gear-types and decades affects the assessment of historical fishing impacts on this population. Survey results were imprecise as to the sizes of sharks caught and any regional or temporal trends in their size composition. Operators in the JASDGDLF reported catching sharks of between 1 and 5m long, while WCDGDLF fishers reported lengths generally in excess of 4m. Thus two arbitrarily-defined scenarios of size-selectivity were assumed in these assessments. The sex composition of catches across the range of these fisheries is similarly unclear, with authors variously suggesting female (Robbins 2007) and male (Bruce 1992; Malcolm et al. 2001)–dominated abundance at South Australian aggregation sites. Limited, unpublished data show a slight female bias in the white sharks tagged off the coast of Perth in spring and a higher number of male sharks off the south coast during winter. The size and sex composition data that are currently being collected by white shark tagging programs in South and Western Australia may eventually provide a more precise and reliable basis for assessing catch selectivity.

Sensitivity analysis showed that the potential overall population declines were most sensitive to the reconstructed catch values and the assumed selectivity schedules. The collection of more accurate catch statistics would assist in evaluating conservation and management issues for white sharks. However, it was also apparent from survey responses that, despite the defences afforded to TDGDLF operators by virtue of the fisheries accreditation as an approved Wildlife Trade Operation (WTO) under the EPBC Act (1999), there remain considerable disincentives to report white shark catches accurately. While the survey did not attempt to identify these, fishers expressed concerns about catches being perceived as being “too high”, leading to introduction of further restrictions of fishing activities. Relying solely on commercial fishing returns to provide accurate information on white shark catches for future assessments is likely to remain a challenge. Alternative methods for monitoring catches could enable improved validation of white shark catch statistics but policies and activities designed to directly reduce the sensitivities of fishers to accurately report should also be explored.

8.2 Population Trajectories

There was considerable difference among scenarios for the simulated population sizes and trajectories for the south-western Australian population of white sharks. Depending upon the combination of inputs, the changes in simulated population levels since 1938/39 have varied from essentially no change in their population abundance, moderate declines, through to the population having already declined to extinction.

Forty percent of the 120 scenarios for the entire population were at one extreme (negligible abundance change since 1938/39) or the other (extinction has occurred). For the remaining 60% of scenarios where there was at least a moderate (> 10%) decline in their total population abundance since 1938/39 (but not to extinction), depending upon the combination of model inputs, there was substantial variations in their population trajectories since protection in 1997 (Figures 29-31, Table 9A). These population trajectories after protection have varied from continued declines, no measurable change, through to varying levels of increase.

The examination of the modelled changes in abundance after 1997 for the larger sized sharks (> 3m TL) found fewer of these scenarios have had declines since protection than for the total population abundance (Figures 32-34). Most of the scenarios showed increases in abundance for this size category since protection and these increases were approximately double the percentage increase found for the total population size. Consequently, the largest modelled increases in abundance over this period were close to 50% (Table 9B).

The marked differences found in both the current population levels and recent abundance trajectories among these alternative scenarios would clearly generate very different longer term management and policy strategies. To decrease this level of uncertainty, additional information is required and further analyses of other data sources undertaken in order to reduce the number of plausible alternative scenarios. To assist with the identification of how this can be done in the most cost effective manner, each of the inputs to the model has been examined in detail to identify their relative impact on the model outputs and outline what other possible actions can be undertaken to reduce the levels of uncertainty – both individually and collectively.

8.3 Initial Population Size

In order to quantify the potential population-level impacts of the assumed catch schedules, size-selectivity, sex ratio and PCM rates, it was necessary to assume a range of initial (unfished) population sizes (N_0) from which sharks were removed. The starting values ranged from 1,500 females (3,000 individuals) up to 10,000 females (20,000 individuals). As outlined above, the simulated outcomes for overall population change to the white shark population since 1938/39 (first year of assumed fishing mortality) ranged from only minimal change (i.e. < 10% reduction) in their abundance levels through to complete population extinction.

The broad range of population outcomes generated from the different scenarios by the modelling suggest that the range of initial population sizes, which encompassed the estimate of population numbers generated from other studies in Australia (Blower et al., 2012), was appropriate. While the estimates of other white shark population sizes for California (Chapple et al. 2011; Burgess et al. 2014) and South Africa (Towner et al. 2013) were not directly considered here because of probable differences in the exploitation histories and geographic scales of different populations and general productivity of the coastal waters, these estimates were still encompassed within the range that was used.

Within this broad range, it is clear that the south-western Australian white shark population is still 'extant'. Consequently, for the smallest N_0 initial value tested (1,500 females; 3,000 total) to be plausible, the modelling suggests that the less pessimistic combinations of catch, life history and PCM assumptions would be required. Whereas, if the larger starting values of N_0 (5,000 females; 10,000 total) are accurate, most of the different combinations of catch and life history could be applicable. Moreover, in most of these cases there would have been minimal change in the white shark population during the entire period.

In terms of gaining better estimates of total population numbers of white sharks for this population, the method most likely to generate more precise levels is from continued use of genetic based approaches (Dudgeon et al. 2012). Genetic sampling and analysis could eventually lead to more precise estimates of current and historical effective genetic population sizes, better understanding of the relationship(s) between Ne and Nc and potentially other indirect methods for assessing and monitoring the status of this population. It is strongly recommended that all opportunities to collect genetic samples are expanded. Continuing the collection and analyses of genetic samples is both feasible and low-cost.

8.4 Post Capture Mortality

The level of post capture mortality (PCM) had one of the greatest levels of impact on the type of population trajectory there may have been since 1998/99 (Figures 29-34; Table 9). Using the 100% PCM level, many of the low productivity (LH2) scenarios continued to show declines during this post-protection period. The 50% and 0% PCM scenarios generated increasingly more optimistic scenarios, with the latter scenario resulting in significant levels of increase, particularly for sharks > 3m TL (Table 9).

The PCM rate of white sharks was intended to be reduced as a consequence of their listing as a protected species. Retention of incidentally-caught white sharks almost certainly did decline once their possession was prohibited under various States' and Commonwealth legislation. In the absence of any empirical data to more accurately quantify PCM rates, this study covered the entire range - from 0%, 50% and 100% PCM. It is recognised that neither of the extremes is likely because white shark mortality and releases have been reported in several of the fisheries examined in this report since the species was protected. Furthermore, white sharks are obligate ram-ventilating species with higher metabolic demands than many other shark species (Sepulveda et al. 2007; Ezcurra et al. 2012) and are physiologically-similar to the shortfin mako which have high PCM risk score when caught by equivalent GHaT gear (Braccini et al. 2012).

Because the reconstructed trajectories were highly sensitive to any improvements in the values of PCM it would be extremely valuable for the rates of PCM to be quantified experimentally. This could involve either a tagging and/or biochemical research program, preferably in collaboration with the fishing industry.

8.5 Life History and Population Productivity

Under unfished conditions, the south-western Australian population's finite rate of increase (λ) and doubling time (TD) were dependent on the assumptions about life history (LH). Previous deterministic studies used different input parameter values. Yet the median estimate of λ was similar to the estimate of Mollet & Cailliet (2002) under LH1 assumptions and it was lower but close to the estimates of Smith et al. (1998), Au et al. (2008) and Ward-Paige et al. (2012) under LH2 assumptions. Though our findings are consistent with the range of point estimates obtained in previous analyses, those studies did not consider the uncertainty in the estimation of λ and TD. The present study has included the most likely range of possible life history parameters, and it has demonstrated that the current uncertainty in the life history of white sharks causes substantial differences in their estimated levels of their biological productivity and capacity to recover from differing levels of depletion.

With the current levels of available life history information generally lacking for the south-western Australian population, no single life history scenario was assumed to be more realistic than the others; instead the 'true' values are likely to be within the ranges of assumed values. Hence the collection of population-specific information on the biological and other life history characteristics for white sharks from southern and western Australia are required for improved estimates of their productivity.

Collection of biological samples and data from white sharks is a universally difficult task due to the species' rarity and its large size and consequently there is likely to remain substantial uncertainty in most aspects of the life history of white sharks for some time to come, including for the south-western Australian population. Even before their protection, commercial TDGDLF fishers did not retain whole specimens due to the difficulties associated with getting them on board their vessels, storage, vessel-stability, commercial considerations and logistics of disposing of carcasses once they were brought ashore. Since their protection throughout Western Australian waters in 1997, there have been additional disincentives to fishers retaining accidentally-caught sharks. Thus, local opportunities to obtain biological samples (in addition to just genetic samples) from white sharks in Western Australia have been limited to eight individual sharks since 1994 and all but two of these were immature females.

Currently-available methods for quantifying age, growth and reproductive rates require samples from dead sharks, which survey results suggest may be limited to as few as 35 per year in Western Australian fisheries and fewer than 100 per year across all fisheries within the south-western Australian population. Even if a reasonable proportion of incidentally-caught sharks could be sampled, accurate estimation of the population's life history parameters (e.g. size and age at maturity, litter size, reproductive frequency) would still not be possible in the short term.

Based on the level and reliability of all available data it will remain unclear which of the two life history scenarios more accurately represents this population's biological characteristics or even whether its biology differs from those used in the defined distributions. The stochastic demographic modelling approach we have used in this study has provided a useful framework for demonstrating how the current lack of reliable biological data affects our understanding of the potential impacts of fishing (Figure 29.). With the exception of the smallest initial (female) population size of 1,500, the LH1 life history scenarios resulted in more moderate reductions in population abundance followed by stability or increases in more recent years. In contrast, with the LH2 constraints on the population's productivity, a considerable proportion of population trajectories reached very low levels and even extinction. While there is currently minimal opportunity to directly determine which of these life histories is correct, continued monitoring and analysis of all other possible data sources could, in the short to medium term, assist in determining which of these life history scenarios is more likely.

8.6 Conclusions

The purpose of this study was to improve our understanding of the potential changes in the abundance of white sharks in Western Australian waters that may have been generated from changes in fishing and other management arrangements that have affected the levels of annual mortalities. As outlined in the introduction, given the uncertainties in the quantitative data that are available on the levels of catch and the paucity of information available on the biological productivity of white sharks generally, and especially for this population, it was not expected that this study would generate a definitive estimate of the current population size or its recent abundance trajectory. We have, however, undertaken the most detailed examination of potential sources of mortality for this population which has enabled the generation of a series of plausible historical catch reconstructions which can now be used as the basis for undertaking future modelling and population assessment studies for this population.

Using these reconstruction histories in combination with the most up-to-date descriptions of the biological and productivity characteristics of white sharks, a series of modelled abundance trajectories were generated for both the total and larger sized (> 3m TL) individuals for the south-western Australian population of white sharks. Despite not being able to identify which of these is the 'true' approximation for this population, the differences observed in modelled population levels and abundance trajectories among the various scenarios are informative. The 120 different scenarios can be broadly grouped into the following five categories:

(1) **Negligible (< 10%) overall decline in total abundance since 1938/39.**
Scenarios that had high initial population levels plus some with moderate initial levels when combined with a high productivity life history.

(2) **Total abundance had declined by more than 10% before protection, but may have been increasing slowly from this level since protection in 1997(< 10%**

increase in total population or <20% increase in white sharks > 3m TL since 1997).

Scenarios that had small or moderate initial population levels (with high productivity) when also combined with high PCM.

(3) Total abundance had declined by more than 10% before protection, but may have been increasing significantly from this level since protection in 1997(> 10% increase in total population or > 20% increase in white sharks > 3m TL since 1997).

Scenarios that had small or some moderate initial population levels when also combined with low to moderate PCM.

(4) Total abundance had declined by more than 10% before protection and may have declined further from this level since protection in 1997.

Scenarios that had small (with high productivity) or moderate (with low productivity) initial population levels when combined with high PCM.

(5) Total abundance declined and became extinct before 2012 (noting that this category is not plausible)

Scenarios that had low initial population levels when combined with low productivity or the highest catch level.

Whether the current population trajectory for white sharks is declining, steady, increasing slowly or increasing significantly has major implications for management and the development of appropriate public policies. Given that scenarios with different input combinations had similar population trajectory patterns, the range of potential current population sizes within each of the four plausible categories was wide and often overlapping. Consequently, even if an estimate of the current abundance of white sharks is generated through a genetic-based or other technique, this may still not resolve which of these population trajectory categories is correct. Until this aspect can be resolved, the policy implications of these different categories and their relative likelihoods should continue to be considered. Furthermore, any strategy should be sufficiently agile to enable the rapid inclusion of additional scientific information that assists in refining which of these categories, and potentially which specific scenario in that category, was more likely.

To assist in reducing the levels of uncertainty and thereby narrowing the range of plausible scenarios for the current abundance and population trajectories for this population of white sharks a number of lines of investigation could be pursued. By comparing among these scenarios and by undertaking additional sensitivity testing we have identified which of the key model inputs has the biggest impact on model outputs for both abundance levels and recent trajectories and therefore where future studies should best be directed (see below).

8.7 Recommendations for Further Studies

The inherent difficulties that are associated with studying a large, relatively rare species in difficult oceanic conditions have been outlined above. Consequently it must be recognised that successfully progressing any of these additional investigations will require ongoing government, fishing industry and community commitment. This includes shifts in the attitudes towards the capture and examination of specimens and/or the development of innovative non-lethal sampling methods. Based on the above discussion there are a number of lines of investigation that could be pursued to assist in reducing the levels of uncertainty and thereby narrowing the range of plausible scenarios for both the current abundance and current population trajectories for this population of white sharks. Each of these is outlined briefly below.

Catch Reporting: The collection of more accurate data on catches by commercial fisheries would assist in reducing uncertainty in current abundance and population trajectories. Given the benefits from the data that could be collected from white sharks that are accidentally caught, efforts to accurately record incidental capture and release details including size, sex and condition upon capture should be continued and be improved. This additional information could be used to tune the historical data series and potentially reduce the uncertainty for the entire time series. These improvements could involve adopting alternative methods for monitoring catches rather than relying on logbooks.

Post Capture Mortality: White sharks captured by commercial operators could be fitted with archival satellite pop-up tags which have provided information on the behaviour and ultimately the fate of sharks up to 6 months after their release (e.g. Campana et al. 2009). As physiological responses to capture stresses can be observed through changes in blood chemistry (e.g. French et al. 2015) the collection of blood samples from captured white sharks could also assist in evaluating PCM. The cost of the tags, training of observers and/or fishers in tagging or obtaining blood samples, and the requirement for a representative sample of sharks would need to be considered.

Biology: The collection of relevant biological data (e.g. number of pups, timing of the reproductive cycle, vertebrae for ageing, size-at-maturity) would assist in further refining the two LH scenarios used in this study. These could be obtained from those white sharks that were caught by commercial fishers and subsequently died and/or by undertaking specific research sampling surveys. The practicalities involved in dealing with large white sharks at sea are challenging and the legal (and social) implications of commercial fishers or trained observers and researchers obtaining samples from dead specimens would also need to be considered.

Genetics: It is strongly recommended that opportunities to collect genetic samples are maintained or expanded as continuing the collection and analyses of genetic samples is both feasible and low-cost. Analyses of this material could eventually lead to more precise estimates of current and historical effective genetic population sizes, better understanding of the relationship(s) between Ne and Nc and potentially other indirect methods for assessing and monitoring the status of this population.

Additional Modelling and Weight of Evidence framework: The scenarios developed in this study show very different population trajectories through time. If new and more accurate information became available from the recommendations mentioned above, the modelling could be updated which would refine the number of plausible scenarios for the population levels and abundance trajectories.

In the interim, the relative likelihoods of the four categories of population trajectories could be examined using a risk-based, weight of evidence framework (Fletcher, 2015; Wise et al. in prep) using other relevant quantitative and qualitative data sources.

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10 Appendix

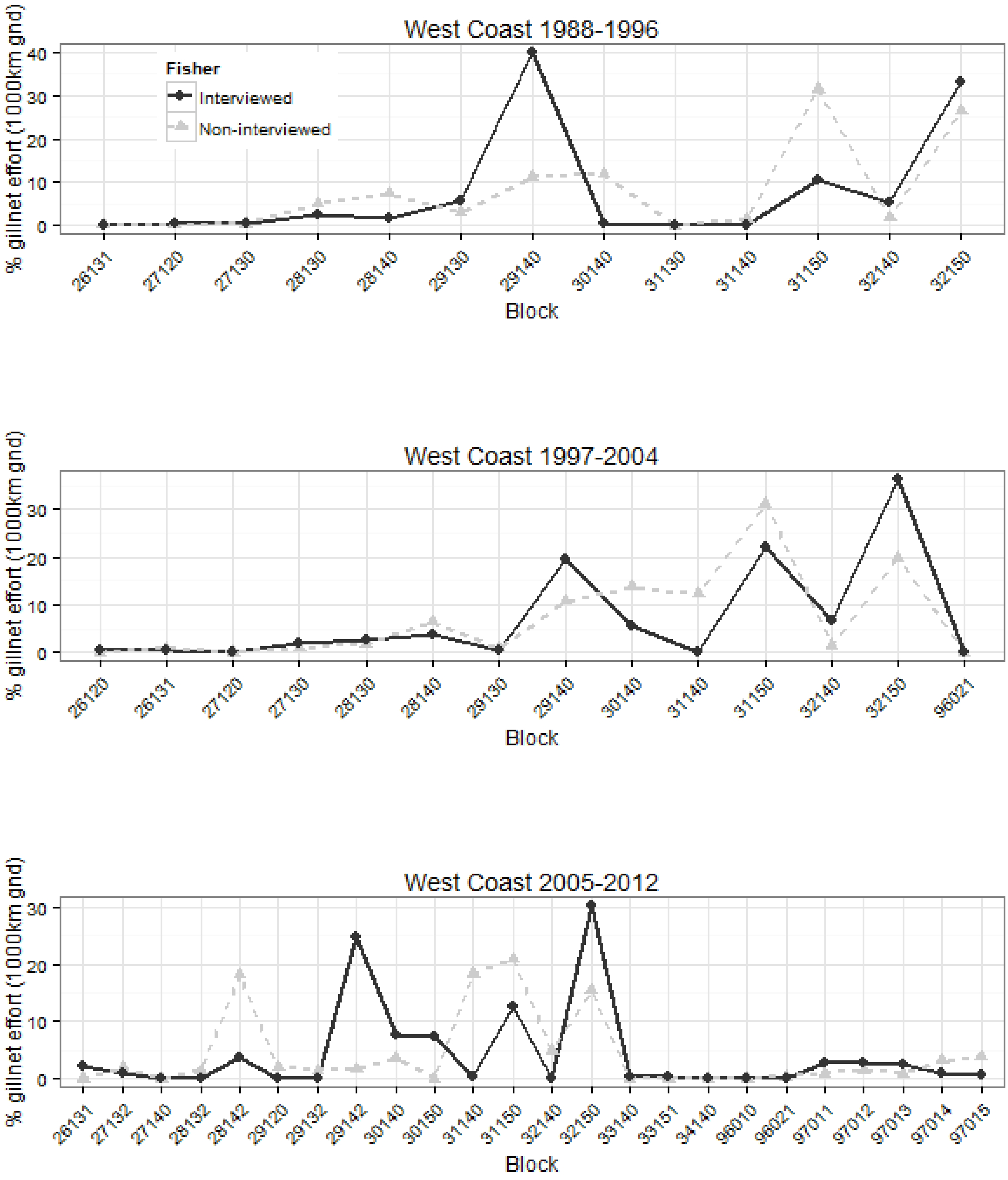
Appendix A. Checking process for verifying data obtained from commercial fishers during interviews.

		Boating information		White shark catch information			Outcome	
Fisher ID	Verification code	Exact match for number of boats?	Dates for each boat ± 3 years?	Recall whether white sharks caught in each time period?	Catch of white sharks partially verified?	Verification type	Use in white shark catch expansion	Use attitudinal data
1	Good	✔	✔	✔	✔	1	✔	✔
2	Good	✔	✔	✔	✔	4	✔	✔
3	Good	✔	✔	✔	✔	1	✔	✔
4	Good	✔	✔	✔	✔	2	✔	✔
5	Good	✔	✔	✔	✔	1, 2, 3	✔	✔
6	Adequate	✔	✖	✔	✔	2	✔	✔
7	Adequate	✔	✔	n/a	n/a		✔	✔
8	Good	✔	✔	✔	✔	2	✔	✔
9	Adequate	✔	✔	✔	✖		✔	✔
10	Inadequate	✖	✖	✖	✖		✖	✔
11	Inadequate	✖	✖	✖	✖		✖	✔
12	Good	✔	✔	✔	✔	2	✔	✔
13	Good	✔	✔	✔	✔	1,5	✔	✔
14	Good	✔	✔	✔	✔	1	✔	✔
15	Good	✔	✔	✔	✔	4	✔	✔
16	Adequate	✖	✖	✔	✔	1	✔	✔
17	Inadequate	✔	✖	✖	✔	4	✖	✔
18	Good	✔	✔	✔	✔	1,3	✔	✔
19	Adequate	✔	✔	✔	✖		✔	✔
20	Adequate	✔	✔	✔	✖		✔	✔
21	Adequate	✔	✔	✔	✖		✔	✔
22	Adequate	✖	✖	✔	✔	1,2	✔	✔
23	Good	✔	✔	✔	✔	6	✔	✔
24	Adequate	✔	✖	✔	✔	4	✔	✔
25	Adequate	✖	✖	✔	✔	1	✔	✔
26	Adequate	✖	✖	✔	✔	1	✔	✔
27	Good	✔	✔	✔	✔	4	✔	✔
28	Good	✔	✔	✔	n/a		✔	✔
29	Good	✔	✔	✔	✔		✔	✔
30	Good	✔	✔	✔	✔	1	✔	✔

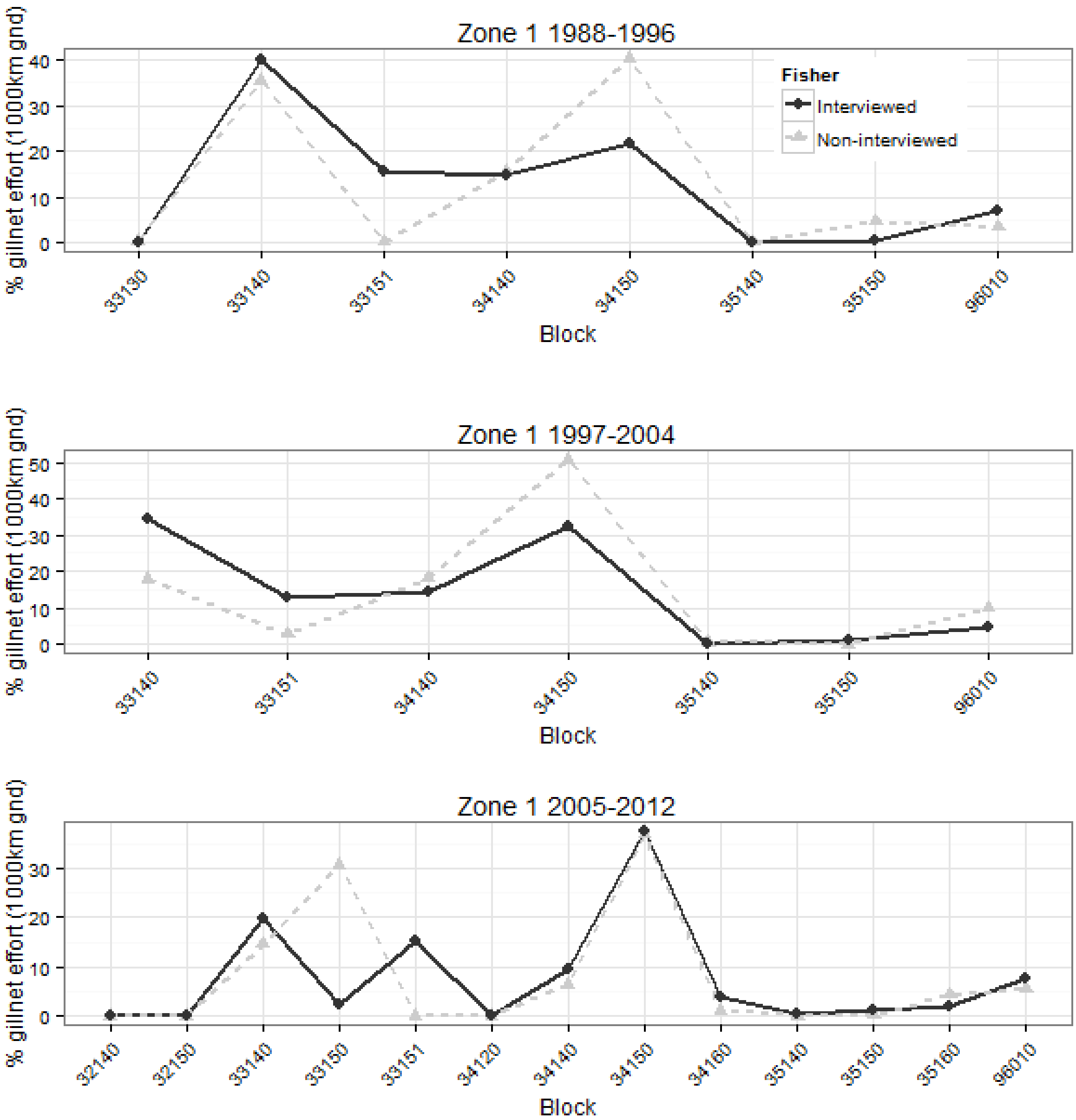
Each Fisher Id number represents an individual fisher. Presence/absence of one or more white sharks partially verified by: 1=reporting in daily logbook (2005/06 onwards), 2= Research log or observer program, 3=newspaper article, 4=photo/jaws sighted by the PI, 5=camera/video recording, 6=personal fisher log cited by the PI.

Appendix B. Gillnet fishing effort (% 1000km gn.d) by block for interviewed fishers and non-interviewed fishers for (A) West Coast, (B) Zone 1 and (C) Zone 2.

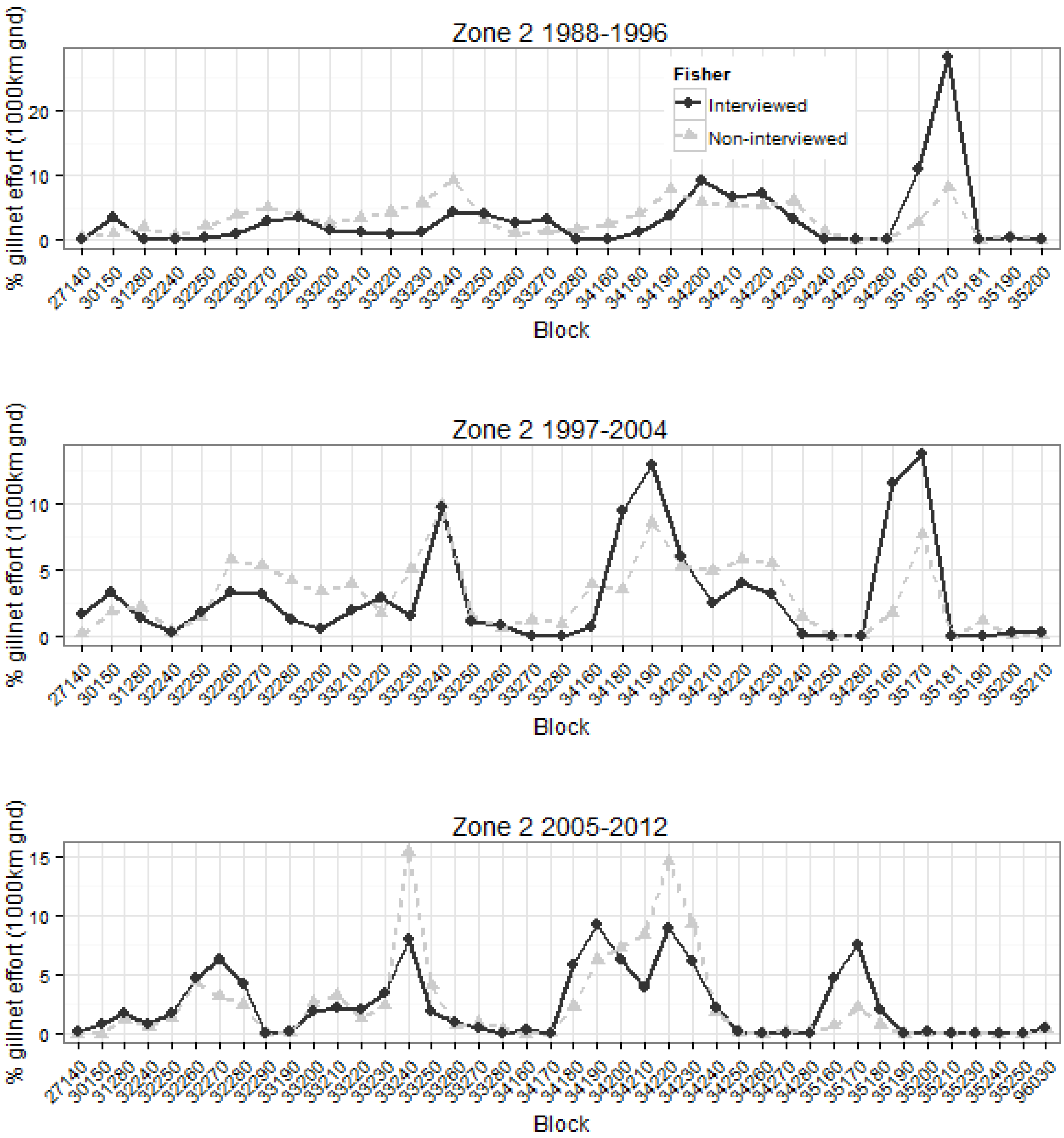
A



B


Zone 1 1988-1996
% gillnet effort (1000km gnd)
0
10
20
30
40
Fisher
Interviewed
Non-interviewed
33130
33140
33151
34140
34150
35140
35150
96010
Block
Zone 1 1997-2004
% gillnet effort (1000km gnd)
0
10
20
30
40
50
33140
33151
34140
34150
35140
35150
96010
Block
Zone 1 2005-2012
% gillnet effort (1000km gnd)
0
10
20
30
32140
32150
33140
33150
33151
34120
34140
34150
34160
35140
35150
35160
96010
Block

C



Zone 2 1988-1996
Fisher
Interviewed
Non-interviewed
% gillnet effort (1000km gnd)
Block
Zone 2 1997-2004
% gillnet effort (1000km gnd)
Block
Zone 2 2005-2012
% gillnet effort (1000km gnd)
Block