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Evaluation of passive acoustic telemetry approaches for monitoring and mitigating shark hazards off the coast of Western Australia

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Executive Summary

Shark attacks are rare but traumatic events that involve complex and dynamic interactions between sharks' ecology and human demographics and behaviours. To better understand the biological and ecological factors contributing to the series of incidents of white shark (*Carcharodon carcharias*) attacks off Western Australia, sharks were fitted with acoustic transmitters ('tags') that emit unique identification codes every 50 to 150 seconds. Tagged sharks were monitored by up to 143 acoustic receivers off the metropolitan Perth coast since 2009, by another 149 receivers around the South-West of the State since 2012 and by up to 42 off Ningaloo Reef. Between December 2007 and July 2015, 50 white sharks were tagged between Perth and Israelite Bay (approximately 200km east of Esperance) in Western Australia and 151 were tagged by collaborators in South Australian waters. Acoustic tags were surgically-implanted into 30 of the sharks[1] tagged in Western Australia, potentially allowing their movements to be monitored for up to a decade. Another 55 large bronze whaler sharks (*Carcharhinus brachyurus*) and 70 tiger sharks (*Galeocerdo cuvier*) were also internally-tagged with acoustic transmitters so that their presence at key coastal locations can be monitored.

Across the more than 183 acoustic receivers, collectively known as the Shark Monitoring Network (SMN) plus another 151 compatible receivers located around the Western Australian coast by collaborating partner organisations, more than 22,000 detections of 64 tagged white sharks; 150,000 detections of 46 tagged bronze whaler sharks and 7000 detections of 21 tiger sharks have been recorded up to July 2015. In addition to recording the presence and movements of tagged sharks around more than 2,000 kilometres of coastline through 309 'passive' Vemco VR2W receivers which must be retrieved from the ocean floor to download detection data, 25 satellite-linked Vemco VR4Global (VR4G) receivers have provided continuous near-real-time monitoring off some of the State's most popular beaches. These receivers' communication capabilities have been used to develop a purpose-designed system for notifying public safety officials about the presence of tagged sharks in high-use coastal areas. This information is also published via social media and interactive web-based maps to inform the community of the whereabouts of tagged sharks, allowing water users to make more informed decisions about their safety. The detections of tagged sharks by the satellite-linked receivers has also enabled the Department of Fisheries to identify and advise the public about otherwise unobserved transient environmental conditions that attracted tagged and, potentially, untagged sharks close to water users.

The combination of detection data from both the VR2W and VR4G receivers has also provided the first set of detailed data on the locations and periods of tagged shark activity and movement patterns off the Western Australian coast. In the metropolitan region, white sharks were most commonly detected by receivers off the northern end of Garden Island and across Gage Roads, at detection rates of nearly 10 times those of beachside receivers. More than one third of the 36 tagged white sharks detected off the metropolitan coast were only recorded by

[1] Six more white sharks were internally-tagged in August 2015, after data for this report were compiled

receivers located West of Rottnest Island, indicating that many white sharks travelling past Perth do so too far offshore to pose a threat to the majority of water users in the region. Of the 23 white sharks that were detected closer to the coast, only five were detected for more than seven consecutive days. Only three white sharks have so far been detected again in the metropolitan region more than one year after their release or initial detections, suggesting that regular long-term returns to Perth by individual sharks may be uncommon[2]. This contrasts with the much more regular return behaviour exhibited by bronze whaler sharks. Greater numbers of white sharks were detected off Perth during spring and early summer (September–December) and, on average, those sharks spent longer in the region during those months (eight days per month in October), than at other times of year.

Off the South and South-West coasts, tagged white sharks were mostly detected in deeper offshore waters, with the majority (94%) of detections in depths of more than 50m and further than 10km off the mainland coast (88%). Although sharks appear to be more consistently active off the South and South-West coasts throughout the year, relatively more sharks were detected during late summer and autumn, with fewer detected in early winter than off the metropolitan coast. Movements of the sharks detected around the South and South-West coasts, were characterised by rapid transits (in both directions) between receiver arrays and there was minimal evidence of sharks spending extended periods in particular areas off the South-West of the State.

A total of 211 inter-regional movements[3], totalling 134,592km were recorded for 51 tagged white sharks. These included 54 movement events (i.e. movements between receiver arrays, release locations or locations of known mortalities) of over 1,000km and up to 3,375km. Cumulatively, individual sharks travelled distances of up to 6,542km (mean individual cumulative distance=2,639km). Estimated Rates of Movement (ROM) in excess of 3 km per hour (mean=1.8kmh^{-1}; max.=5.6kmh^{-1}) were common, even over distances of thousands of kilometres. Pooled tag detection data revealed that white sharks may be encountered off metropolitan Perth and the South-West coasts of WA at any time of the year. There was considerable variability in the direction and timing of individual sharks' movements and few clear patterns in seasonal movement directions were observed. 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.

By 1 July 2015, the satellite-linked VR4G receiver network had detected 73 different white, bronze whaler and tiger sharks, a total of 3,139 times. These detections resulted in 2,748 near-real time notifications of 920 individual potential "shark hazard events". An automated SMS and email system has been developed to rapidly notify public safety officials about detections of tagged sharks at key locations, enabling hundreds of pre-emptive public safety responses. Detections are also published via social media and interactive web-maps, to enable members of the public to make more-informed decisions about their water use. Unlike other

[2] Since data were extracted, 2 more sharks have been re-detected in a third consecutive year

[3] i.e. between receiver arrays; between release and first detection locations and between locations of last detection and known mortalities.

sources of shark reporting, the species and size (at release) of sharks detected by VR4G receivers are automatically validated; repeat detections of the same sharks can be identified and monitoring occurs 24h per day and year-round. The Warnbro Sound, Garden Island, Middleton Beach (Albany) and Meelup receivers have recorded the most tagged shark detections in the VR4G network, with notification rates about ten times greater than the median rate across the VR4G network of 7.3 notifications per 100 days.

Although some external tags are known to have remained attached to sharks for up to three years, results have been influenced by the relatively short-term retention of externally-fitted transmitters. Since 2012, there has been a greater emphasis on internal-implantation of transmitters, resulting in over 30 white sharks, 55 bronze whalers and 70 tiger sharks being permanently-fitted with acoustic tags. It may therefore be possible to collect decadal time series of movement data for these sharks, which might provide improved insights into their movement patterns. Nevertheless, it is hoped that this initial description of the ecological dynamics associated with white shark movements around Western Australia, may assist public safety agencies, Government and the community develop ways to potentially minimise the risks of human encounters.

Background

In response to an increasing number of encounters with white sharks (*Carcharodon carcharias*), including those resulting in injuries and death in Western Australian (WA) waters, the State Government's Shark Hazard Committee recommended that a "pilot research program of electronic shark tagging in relation to public safety and shark hazard mitigation" be undertaken (DoF, 2004). This recommendation was, in part, informed by early satellite tracking and archival tag data that showed tagged white sharks moving between South Australia (SA), southern WA and along the west coast as far as North West Cape (Bruce and Stevens, 2004, Bruce et al. 2006). Prior to this, the Committee had considered electronically-tagging sharks to be an unfeasible hazard mitigation strategy due to the lack of predictable tagging opportunities in WA waters. The emerging satellite telemetry data, however, suggested that it might be possible to monitor this species' movements through WA waters by fitting sharks with tags at predictable aggregation sites is SA, specifically at the Neptune Islands, off the Eyre Peninsula. Furthermore, successful tagging collaborations between CSIRO and cage-diving tourism operators, which already existed at these locations (Malcolm et al., 2001; Bruce et al., 2005), provided a proven opportunity to cost-effectively tag relatively large numbers of sharks outside of the State.

At the time, a number of electronic tagging technologies were considered, as white shark tracking data had already been successfully obtained from satellite positioning tags (SPOT/SPLASH), Popup Archival Transmitting (PAT) tags (Wildlife Computers^{TM}) and acoustic transmitters ('tags'). Each of these technologies was however, recognised as having particular individual strengths and weaknesses. For example, satellite positioning tags can provide accurate location data over large distances, almost anywhere on earth. However, these tags are expensive to buy (thousands of dollars each) and cannot communicate with satellites when submerged. As sharks usually only partially (and infrequently) break the surface, satellite tags need to be attached to the top of their dorsal fins to provide their best chances of satellite communication and position estimation. Fitting satellite tags therefore requires sharks to be captured and restrained, which can be logistically complex and expensive. Additionally, at the time that electronic tagging was first being considered, satellite tags' battery-life was limited to several months and white sharks were known to travel long distances without surfacing. Thus the potential use of this technology to monitor sharks' presence off any particular area of interest (e.g. off metropolitan Perth) or for periods long enough to provide information on underlying patterns of movement and habitat use, seemed limited. Pop-up Archival Transmitting (PAT) tags record depth, temperature and light data before releasing themselves and floating to the surface to remotely transmit the recorded data. These data can be used to provide an approximate retrospective daily estimate of the tag's location over the course of the shark's track (e.g. Abecassis et al., 2012; Duffy et al., 2012). Although PAT tags were considered as a potentially useful source of information about how frequently and how close sharks come to shore (indicated by depth data), as well as their temperature-related swimming behaviour, distribution and large-scale movements, due to the retrospective nature of their data, the Committee did not see their application for identifying real-time shark hazards.

Acoustic tags are small transmitters that emit unique identification signals either continuously, for manually tracking animals over limited distances and for short periods (Stevens et al., 2009; Pita and Freire, 2011; Werry et al., 2012) or at longer-intervals, which significantly lowers their power consumption thereby allowing much longer detection periods (now estimated to be up to ten years). Unlike satellite tags, acoustic tags transmit while submerged in water, allowing their detection without the need for sharks to break the surface. Because of this and their relatively small size, acoustic tags can either be fitted externally to sharks without the need to capture and restrain them (simple, cheap but impermanent) or they can be permanently implanted inside sharks to ensure their retention. Passive acoustic telemetry monitoring (sending and receiving acoustic data) also requires compatible acoustic receivers to detect, decode and record transmitters' presence. Given the low power output of the acoustic transmitters used to study fish, the detection range of these receivers is however typically only several hundred metres, which has historically limited acoustic telemetry studies to relatively small geographic scales. Also, because receivers traditionally had to be physically retrieved to download tag detection data, when first considered, passive acoustic telemetry technology was considered to have relatively limited potential to be used as a shark hazard monitoring tool.

By 2006 however, the major manufacturer and supplier of acoustic telemetry equipment for marine species research (Vemco) began development of a new generation of acoustic receivers that was capable of remotely reporting tag detections in near-to real-time. Given this technology's potential for providing rapid notifications of acoustically-tagged sharks' presence at key locations, WA Government Development and Better Interests Funding (DBIF) was sought and obtained in 2008 to examine whether acoustic telemetry approaches could be used to monitor the movements of tagged sharks off the Western Australian coast and, if detected at monitored beaches, mitigate the risks posed to the public. Before the results from this three-year feasibility trial could be reported however, an unprecedented sequence of five fatal white shark attacks between September 2011 and July 2012, led to a rapid and extensive expansion of acoustic monitoring infrastructure around the South-West of the State. As the Shark Monitoring Network project moved directly from a metropolitan-only feasibility trial between 2009 and 2011 (inclusive) to an operational data-provision system in 2012, this report is the first to evaluate the potential benefits of these acoustic telemetry approaches to shark hazard mitigation.

1 Introduction

1.1 Western Australian shark attack records

Shark attacks are very rare events that can nonetheless have traumatic consequences for those involved, their families, friends and affected communities. Despite being a very infrequent cause of injury and death in Australian waters, shark attacks receive disproportionately high levels of media attention and may have flow-on economic effects for tourism and other marine-related industries (Francis, 2011; Neff, 2012; Neff and Yang, 2012). The Australian Shark Attack File (ASAF)[4] has recorded a total of 120 injurious and fatal "shark attacks" in WA waters between March 1803 and June 2015, inclusive. Twenty six (26) of those incidents caused or are presumed to have caused fatal injuries to the people involved (West 2011; ASAF, 2015[5]). Although the annual frequency of WA shark attacks has been highly variable, there has been an increasing decadal trend since the 1970s (DoF, 2012; Figure 1A). Notwithstanding under-estimation of historical records due to a lack of organised data collection programs before the late 1980s, approximately half of all recorded shark attacks (n=64) and fatalities (n=12) in WA occurred between 1 July 1996 and 30 June 2015. Furthermore, there were eight fatal shark attacks in WA over the five years between July 2010 and June 2015 (inclusive).

[4] Although several shark attack databases exist, the authors consider the Australian and International Shark Attack Files (ASAF and ISAF, respectively) to be the most authoritative records of shark bite statistics available. All references to shark bite statistics in this report are therefore derived from those data sources.

[5] Australian Shark Attack File, http://taronga.org.au/conservation/conservation-science-research/australian-shark-attack-file.

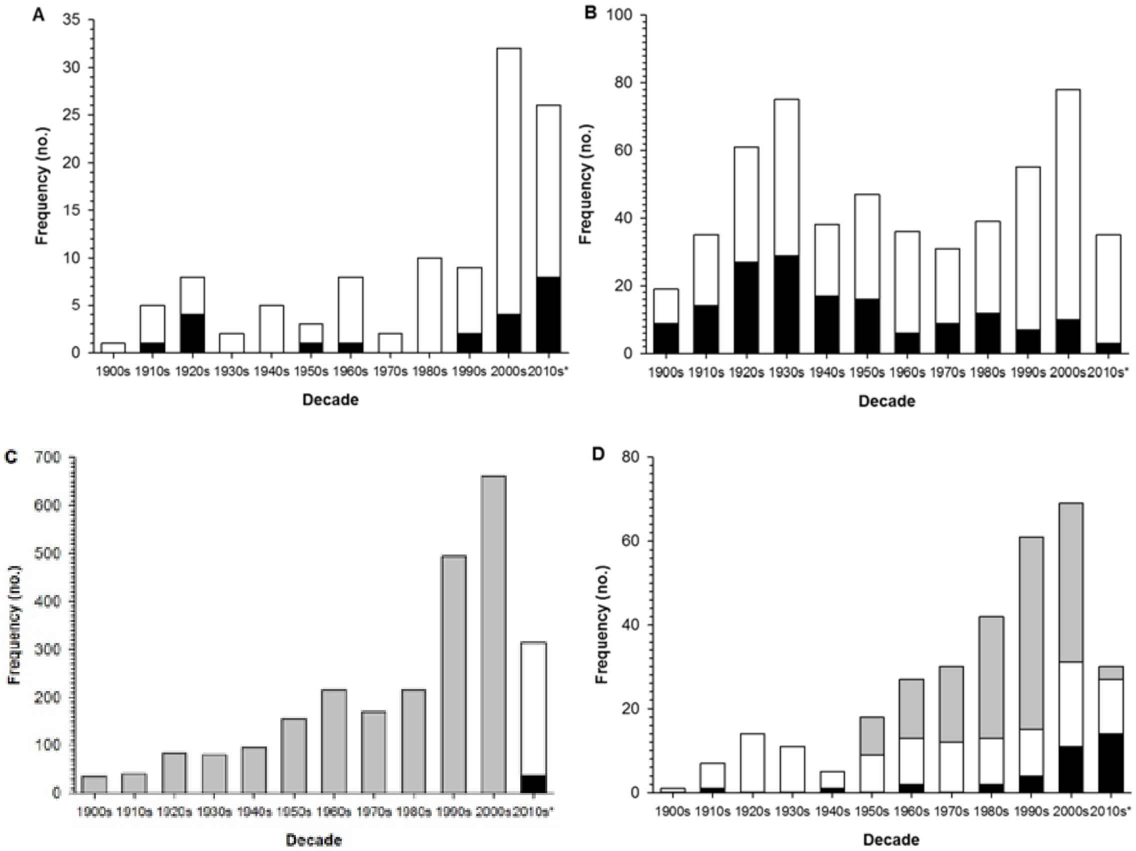

Figure 1. Frequency of recorded shark attacks in: A Western Australian waters (including Cocos Keeling and Christmas Islands; black=fatalities; white=injuries; ASAF, 2015); B the rest of Australia (i.e. excluding WA; black=fatalities; white=injuries; ASAF, 2015); C worldwide (grey=unspecified; black=fatalities; white=injuries; reproduced from ISAF, 2014) and D attributed to white sharks (black=WA, white=rest of Australia and grey=worldwide). *Data from the decade beginning 2010 are complete up to 30 June 2015 for WA and up to 1 January 2014 for other regions.

The increasing trend in shark attacks in WA over the last 40 years (DoF, 2012), is generally consistent with increasing trends elsewhere in Australia (Figure 1B) and internationally (Figure 1C). However, the increasing rate of fatalities in WA is in contrast to the relatively lower and more stable rates in other Australian jurisdictions. While there are several possible explanations for the observed differences in survival rates in different parts of the nation (e.g. proximity to medical care; species responsible; victims' activities; availability of records; etc.), an increasing number of incidents involving white sharks, particularly since 2000, has contributed to the increasing fatality rate WA (Figure 1D). In contrast, the number of attacks attributed to this species has remained lower and more consistent in other parts of Australia. Many hypotheses have been proposed to explain the reasons for the increasing frequency of white shark bites in WA. However, a paucity of reliable high-resolution information about this species' spatial distribution, movements, and behaviour around the State's coastline, has been one of the impediments to understanding the ecological factors contributing to encounters with this species and for testing commonly-held theories about the causes of attacks. Obtaining better data on the distribution, movements and habitat use by white sharks in Western Australian waters could therefore assist with improving hazard mitigation strategies.

1.2 White sharks' distribution, population structure and movements

White sharks occur in coastal temperate and subtropical regions around the world but they can also occur in tropical areas (Compagno, 2001; Last and Stevens, 2009). They are generally found in continental shelf waters and around oceanic islands, although in some regions they may spend considerable periods in the open ocean (Weng et al., 2007; Bruce, 2008; Domeier and 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, 1985; Skomal et al., 2012). White sharks tagged at several 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). Some individuals have been tracked crossing ocean basins and inter-continental movements have also been inferred from historic genetic lineages (Gubili et al., 2011; 2012; Jorgensen et al., 2012). These linkages suggest that there may be some interaction between populations that are otherwise geographically widely separated. However, despite such long distance movements, genetic data suggest that separate international populations exist (Pardini et al., 2001; Gubili et al., 2011, 2012).

In Australia, the species has been regularly recorded from central Queensland around the south coast to the North-West of Western Australia, but may occasionally 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 islands in the Recherche Archipelago 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 GAB are also areas reportedly frequented by juvenile white sharks at certain times. Most research on white sharks in Australia 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; Bruce and Bradford, 2015).

1.2.1 Population structure

Genetic analyses suggest some differentiation of and sub-structuring within white shark populations from different parts of the wold (Pardini et al., 2001; Gubili et al., 2011, 2012). Various genetics studies are currently underway and these may lead to higher-resolution understanding of the species' international and regional population structure(s) than has previously been possible. Recent genetic analyses of Australian white sharks (Blower et al., 2012) and electronic tagging data (Bruce et al., 2006; Bruce & Bradford, 2012), indicate evidence for functionally-separate populations, east and west of Bass Strait. This recent differentiation of populations has important implications for understanding historic trends and current status of Australian populations. For example, it would suggest that any inferences about population status derived from long-term New South Wales and Queensland shark control program data (Reid & Krogh 1992; Reid et al., 2011) are not directly relevant to the population distributed to the west of Bass Strait, which is referred to throughout this report as the south-western Australian population.

1.2.2 Sexual segregation

The seasonal, sex-specific occurrence of 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. The authors suggested that female sharks may travel significant distances to give birth, whereas mating may occur closer to the South Fallon Islands, allowing males to return annually. These results support a two-year reproductive cycle in females that is similar to estimates of gestation periods (Mollet et al., 2000). More recently, Domeier and Nasby-Lucas (2012) demonstrated that some adult female white sharks tagged at Guadalupe Island off the Pacific Coast of Mexico, 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. Sexual segregation has also been reported 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.

Patterns in seasonal visitations of male and female white sharks to the Neptune Islands in South Australia was studied by Robbins (2007). This study reported that male sharks were common around the Neptune Islands in all months except for April and May and that they generally preferred cooler water temperature than females. 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). However, more recent analyses based on a 14-year data record suggest that 2002-2004 was an anomalous period at the Neptune Islands where few sharks were present (Bruce and Bradford 2015). The analyses by these authors confirmed that there is a seasonal pattern in the presence of males and female sharks at this site with males arriving and departing year-round, whereas females visit almost exclusively from April to September, with the number of sharks recorded being inter-annually variable. These observations suggest that the spatial and temporal distributions of white sharks are far more complex than simple linear relationships with water temperature alone.

1.2.3 Habitat use

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 1,000m (Bonfil et al., 2005; Weng et al., 2007; Bradford et al., 2012). Most white shark movements and activity in Australian waters have been reported to occur between the coast and the 120m depth contour (Bruce et al., 2006; Bruce & Bradford, 2012). Although the importance of offshore and high seas habitat cannot be dismissed, unlike sharks tracked off the West 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). There is also mounting evidence for common movement pathways between some areas in Australian waters with transit paths common over depths between 60 and 120m (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). Thus, the species may be more frequently encountered in coastal habitats that are in close proximity to these depth zones (Werry et al., 2012).

Distinct coastal nursery areas have been located in various localities around the world, although the spatial scale of these varies between regions. Juveniles occupy broad areas of the central Californian Bight (Weng et al., 2007, Lyons et al., 2013) over a 400km stretch of coast whereas Bruce and Bradford (2012) have documented a geographically discrete nursery area with a coastal footprint of only 60km off Port Stephens in central New South Wales 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 100km. Individual juveniles between 1.7 and 2.8m 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.

1.2.4 Movements

White sharks are known to travel widely over distances of 1000s of kilometres, which can include travel associated with shelf waters and offshore excursions. Cross-ocean basin travel has also been documented between South Africa and North-West Australia (Bonfil et al., 2005). Open ocean excursions have also been recorded for sharks from the Farallon Islands (off California) and those tagged at Guadalupe Island (off the Pacific coast of 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). Sharks returning to their tagging site 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). 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 2.1m juvenile and 3.2m sub-adult white sharks crossing the Tasman Sea from NSW to New Zealand indicates that large scale movements are not restricted to adults (Bruce and Bradford 2012; Francis et al. 2015). The reasons for these broad scale offshore movements are unclear but are presumably related to feeding opportunities and/or reproductive activities (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 and from the Neptune Islands to Rockhampton (Queensland) and return (Bruce et al., 2006). Extensive north-south movements of white sharks have been documented on the east coast of Australia between eastern Tasmania and the southern Great Barrier Reef (Bruce & Bradford, 2012). No individuals have been observed to travel up both west and east coasts of Australia. 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 influences the probability of encounters with them at those locations.

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 receivers to investigate the number of days that tagged white sharks were detected within the vicinity of the Neptune Islands in South Australia. Most visits were between one and six days duration, although some individual sharks remained active in these areas for up to 90 days. 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 individual beaches. Juveniles travelled extensively after departing the central NSW region moving as far north as Fraser Island in southern Queensland, south to eastern Bass Strait and northern Tasmania as well as across the Tasman Sea to New Zealand.

1.2.5 Seasonal movement and distribution

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).

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 remained in coastal Australian waters where they made extensive coastal movements. 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, 2012; Duffy et al., 2012).

In Western Australia, satellite-tagged white sharks have moved north along the coast as far as North West Cape during winter and spring and returned south during spring and summer (Bruce et al., 2006). 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.

1.3 Legislated protection of white sharks

White sharks are listed as a protected species in several parts of their range, including in South Africa, Namibia, Israel, Malta, California and Florida. They are also listed under 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. These international listings recognise the cumulative international impacts that threaten this species and the need for international cooperation for its conservation.

In Australia, the white shark was initially declared a protected species under Tasmanian legislation in 1995/96, shortly before its listing under all State fisheries Acts and the Commonwealth Endangered Species Protection (ESP) Act, between 1997 and 1999 (Malcolm et al., 2001). In 1999, the ESP Act was replaced by the Environment Protection and Biodiversity Conservation (EPBC) Act, under which white sharks were designated as a ‘vulnerable’ species due to evidence of population decline, their conservative life history characteristics (longevity and low reproductive capacity), limited local distribution and abundance and, ongoing pressure from the Australian commercial fishing industry (Environment Australia, 2002). At the time of their protection under State and Commonwealth legislation, white sharks were notionally thought to constitute a single Australian population.

1.4 Objectives and scope of the current study

This study is one of a number of initiatives that have been funded by the Western Australian Government to improve understanding of and monitor the risks posed to the public by sharks. White sharks have been responsible for more shark bite injuries in Western Australia (49%) than any other species over the last decade and consequently, the primary objectives of this work have focussed on this species. However, as some objectives relate to the broader risks of encountering sharks (e.g. objectives ii and vii, below) and where appropriate, results for tiger and bronze whaler sharks are also reported and summarised[6]. All data reported in this publication were compiled and therefore current on 30 June 2015.

The Shark Monitoring Network (SMN) project has undergone two distinct phases in its development: a feasibility trial conducted between 2009 and 2011 (inclusive) and an operational data-collection phase (2012-2015, inclusive). The following evaluation of the project's "benefits", are therefore defined in terms of its feasibility-phase objectives to:

(i) collect information on the occurrence, movements and behaviour of white sharks off metropolitan beaches and the associated risks of human encounters and

(ii) evaluate the feasibility and public safety benefits (relative to aerial surveillance) of using communicating acoustic receivers as an 'early-warning' system for notifying public safety authorities of the presence of acoustically-tagged sharks' close to populated beaches

and operational-phase objectives to:

(iii) monitor movements and behaviour of tagged white sharks in the South West of the State (namely, the Capes and Albany regions);

(iv) obtain a more accurate understanding of white sharks' large-scale movements from South Australia (the core of the species' distribution) into the South West and lower west coast regions of WA;

(v) collect data for investigating what environmental conditions contribute to the apparently fluctuating abundance of white sharks off the lower West and South West coasts of WA;

(vi) collect data for investigating whether individual sharks repeatedly visit particular locations in the SW of the State and whether sharks tagged in the area are resident or temporary visitors to those areas and

(vii) provide a system for alerting public safety officials and the public, about risks of encountering tagged sharks (and sharks more generally) close to populated areas, beaches and surf breaks in the Capes and Albany regions.

The data reported here are the most current and comprehensive description of tagged white sharks' movements in Western Australia that may assist the WA public, safety authorities and Government decision makers to potentially develop ways to minimise the risks of human encounters around the State's extensive coastline.

[6] NB, although bull sharks are recognised as a potentially dangerous species, they are relatively uncommon in marine waters off southern Western Australia and none were encountered during tagging operations.

2 Methods

2.1 Tags and tagging

During the initial SMN feasibility trial phase, Vemco V16-6H acoustic transmitters ('tags') were externally-fitted to 83 white sharks around the North and South Neptune Island groups in South Australia and to 11 white sharks off the South and lower West coasts of Western Australia between 20 December 2007 and 1 September 2011 (Figure 2). Tags transmit unique identification signals at random intervals of between 50 and 130 seconds or 70 and 150 seconds. All of the tags deployed in SA during the project's feasibility phase were fitted to sharks by CSIRO staff or by cage-dive tourism operators, in accordance with CSIRO protocols (Bruce et al., 2005, Bruce and Bradford, 2011). Nine sharks were tagged by Department of Fisheries staff in WA prior to 2012 after they were located scavenging on whale carcasses off the metropolitan coast (n=4) and at Two People's Bay (n=5), while the other two were tagged during research fishing activities. External transmitters were attached via 1.6mm diameter 316 grade stainless steel wire rope tethers to sharpened, stainless steel anchors, which were embedded in sharks' dorsal musculature using applicator needles mounted on fiberglass hand-spears. Externally-tagged sharks' lengths (TL) were estimated to the nearest 10cm, their sex was determined (where possible) and the times, dates and coordinates of each tag deployment ('tag release metadata') were recorded.

Since 2011, an additional 69 white sharks have been tagged by the same external-attachment methods at the Neptune Islands and off the eastern tip of the Eyre Peninsula (SA), through various studies undertaken by the CSIRO (Bruce and Bradford, 2011), South Australian Research and Development Institute (SARDI; Huveneers et al., 2013; 2014) and the Fox Shark Research Foundation (FSRF; Robbins and Booth, 2012). Eight (8) white sharks have also been externally-tagged in Western Australia by Department of Fisheries' (DoF) research staff and Fisheries and Marine Officers during the SMN project's operational phase (2012 to 2015, inclusive). At the time of writing, a further 30 white sharks were caught by setlines during targeted DoF tagging activities off the WA coast since October 2012 (Figure 2). Captured sharks were secured in an inverted position alongside tagging vessels and V16-5L and V16-6L transmitters were surgically-implanted in their abdominal cavities according to standard techniques (e.g. Heupel and Hueter, 2001). Incisions were sutured; sharks were measured (to the nearest centimetre Fork Length, FL) and tagged with uniquely-numbered yellow Jumbo Rototags in their first dorsal fins for visual recognition, before being released. Of these 30 internally-tagged sharks, 22 were also tagged with external transmitters as per the methods described above, to collect data for estimating external tag shedding rates. Two of these dual-tagged sharks, as well as a third which had previously been externally-tagged at the Neptune Islands, were recaptured and re-tagged with new internal and external tags.

In addition to white sharks, 53 bronze whaler sharks caught during shark tagging activities were also tagged because of their relatively large size (>2m) and relevance to various agencies' public safety protocols. A further 55 bronze whaler sharks tagged in South Australia through various fishery research projects, were also included in the data that could be monitored by SMN receivers. Similarly, 70 tiger sharks (*Galeocerdo cuvier*) that were (internally) tagged during Department of Fisheries' research surveys, Western Australia Shark Hazard Mitigation Drum Line program trial (2014) and a University of Western Australia research cruise were also monitored. The release locations, size and sex compositions of all SMN-monitored sharks are given in Figures 2 and 3, respectively).

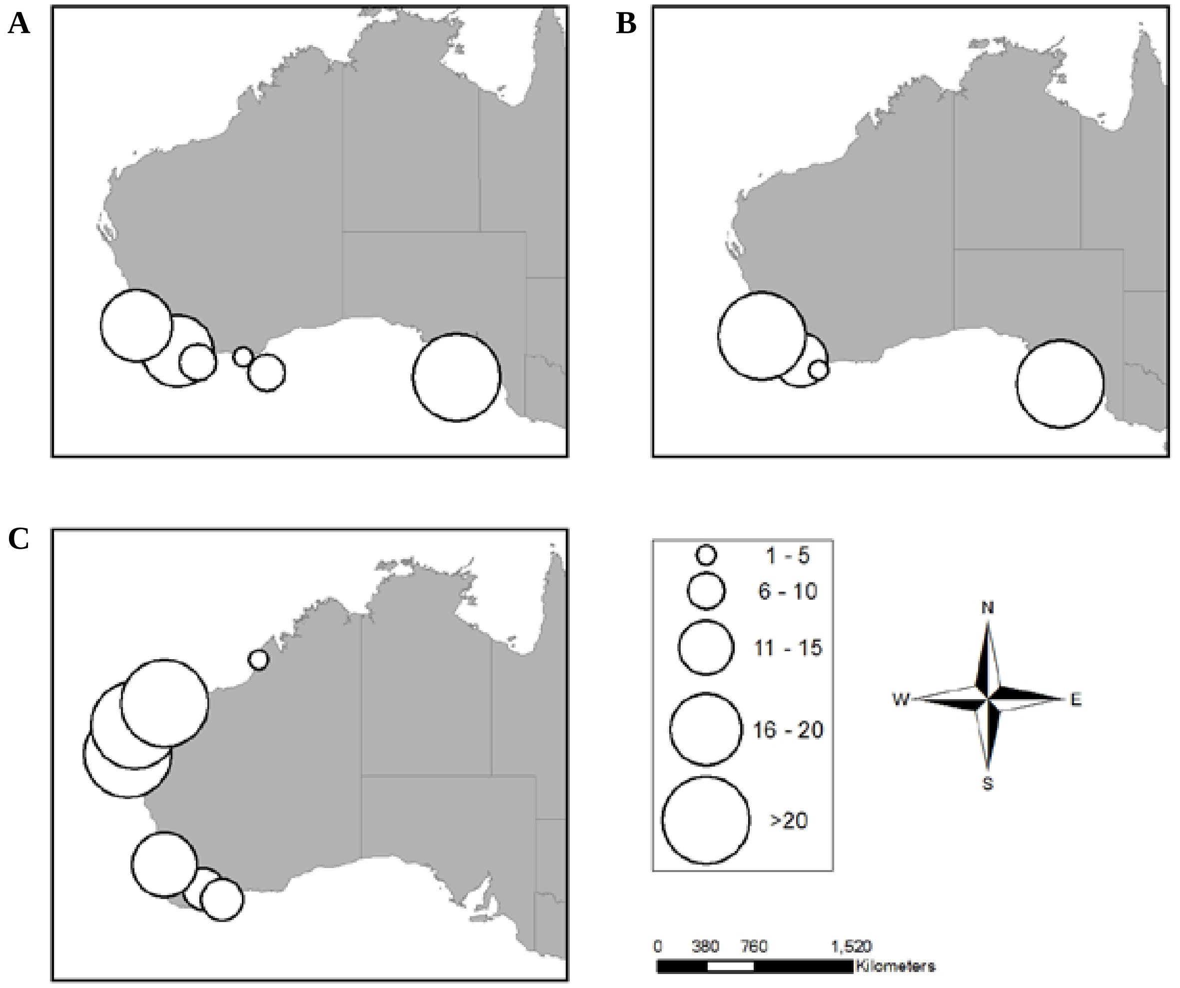

Figure 2. Release locations of (A) 201 acoustically-tagged white sharks (including 3 sharks that were re-captured and re-tagged), (B) 108 tagged bronze whaler sharks and (C) 50 tagged tiger sharks (locations of 20 tiger sharks tagged by the University of Western Australia are not included).

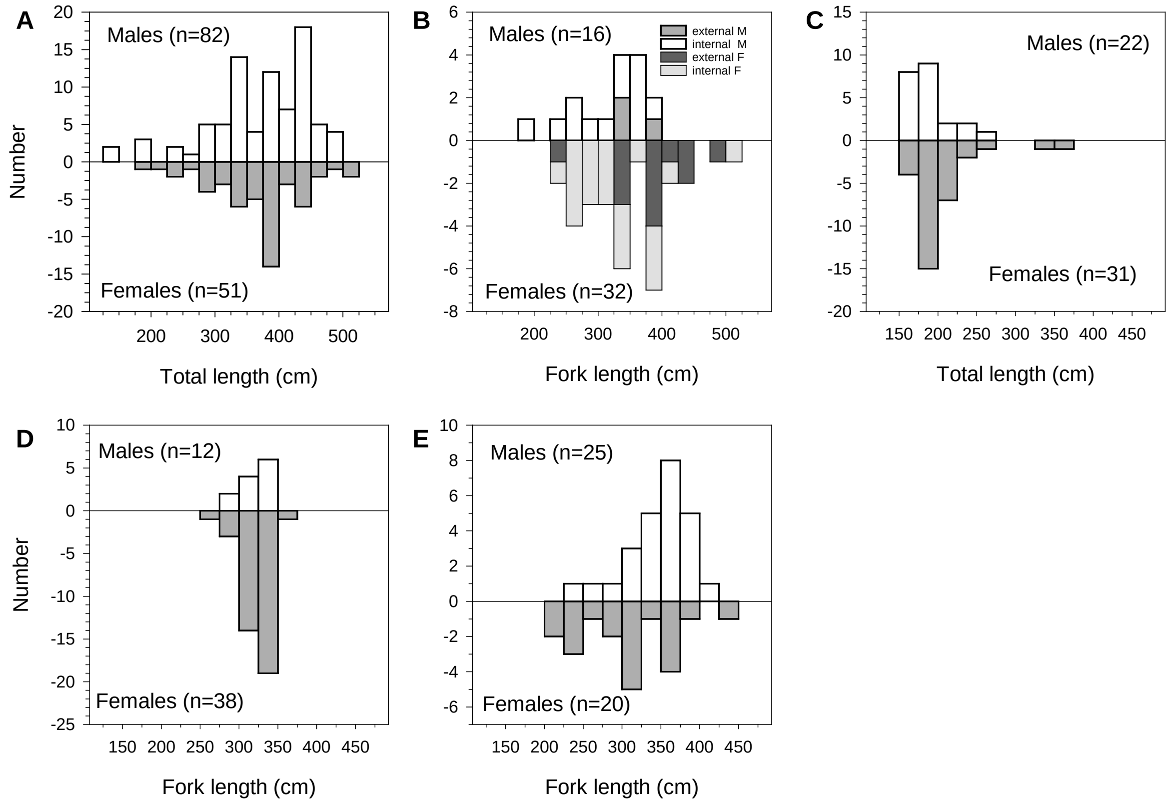

Figure 3. Size and sex compositions of (A) 133 South Australian (externally) tagged white sharks; (B) 48 Western Australian tagged white sharks (including 3 re-tagged sharks), (C) 53 South Australian (internally) tagged bronze whaler sharks; (D) 50 Western Australian (internally) tagged bronze whaler sharks; (E) 45 Western Australian (internally) tagged tiger sharks. NB as sexes and sizes were not recorded for all sharks, these sample sizes are not equal to the numbers of sharks tagged.

2.2 Acoustic monitoring

An array of 19 Vemco VR2W and 20 prototype satellite-linked VR4G acoustic receivers was installed along the Perth Metropolitan coast between January 2009 and May 2010, in what is known as the Shark Monitoring Network (SMN). Receivers were configured as disjunct inshore and offshore lines. The inshore line extends between Ocean Reef in the North and Fremantle in the South (diverted around Three Mile Reef between Mullaloo and Trigg; Figure 4A). The offshore line originally extended between Rottnest and Garden Islands (Figure 4A) and comprised four VR4G receivers and five VR2W receivers. Two of the VR4G receivers at Stragglers Reef in the centre of the offshore line were removed in April 2010 and December 2011 and relocated to Warnbro Sound and Mullaloo, respectively. Offshore SMN VR2W receivers were removed in January 2015. In early 2009, the SMN array was augmented by a cross-shelf array of 53 VR2W receivers, provided by the Canada Foundation for Innovation-funded international Ocean Tracking Network project (OTN; http://oceantrackingnetwork.org) and also by a Department of Fisheries' (DoF) demersal scalefish research array of (up to) 52 VR2W receivers, that extended across the top of and inside Cockburn Sound (Figure 4B). Receivers in the OTN array are located at 800m intervals, which theoretically provides a continuous detection 'curtain' across the continental shelf. In January 2015, the inshore component of the OTN line and offshore component of the SMN VR2W array were consolidated and relocated to 800m intervals between Rottnest and Garden Islands and between Garden Island and the mainland (Figure 4C).

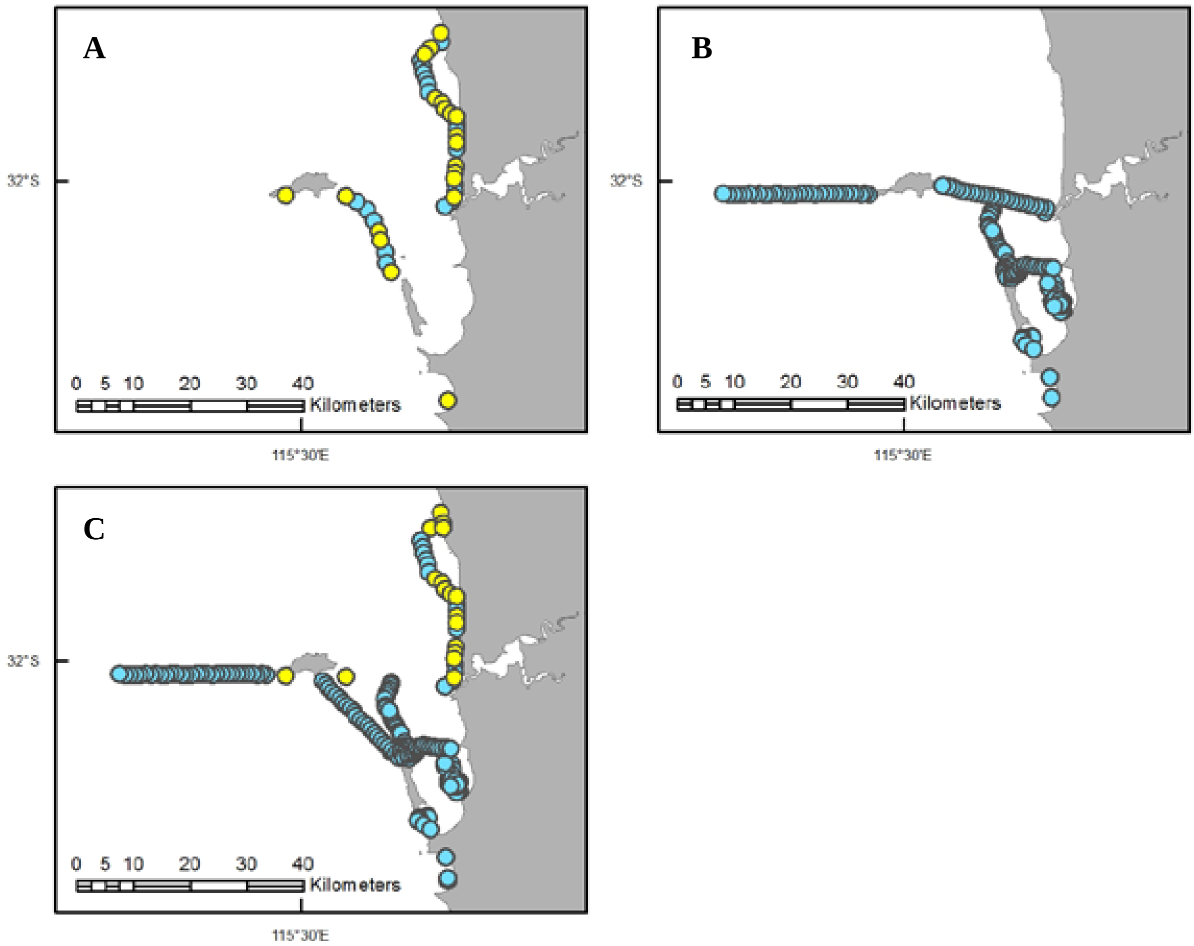

Figure 4. Locations and types of acoustic receivers in the original 2009 configuration of (A) the metropolitan SMN array; (B) associated OTN and DoF demersal scalefish research arrays and (C) consolidated arrays since 2015. Yellow and blue circles indicate VR4G and VR2W receivers, respectively.

Vemco VR2W acoustic receivers are submersible recording devices, which in the SMN, OTN and DoF scalefish research projects, are installed on moorings close to the seabed (Figure 5). When these receivers detect a compatible transmitter (‘tag’) within their approximately 400-500m detection range, the tag ID number and the detection time and date are recorded in receivers’ on-board memory. These receivers need to be retrieved so that their detection logs can be downloaded, batteries replaced, software updated and other maintenance performed. Receivers located in less than 30m depth are recovered and replaced by SCUBA divers and in depths greater than 30m, VR2W receivers are recovered using a combination of a Seabotix vLBV 300 Remotely Operated Vehicle (ROV) and Teledyne-Benthos 875-T and 875-TD acoustic releases (OTN array only). Deep-water OTN stations are gradually been replaced by ROV-serviced mooring assemblies, as the latter have proven to be a much more reliable method for securing and recovering receivers, with a realised 98% receiver recovery rate over three years.

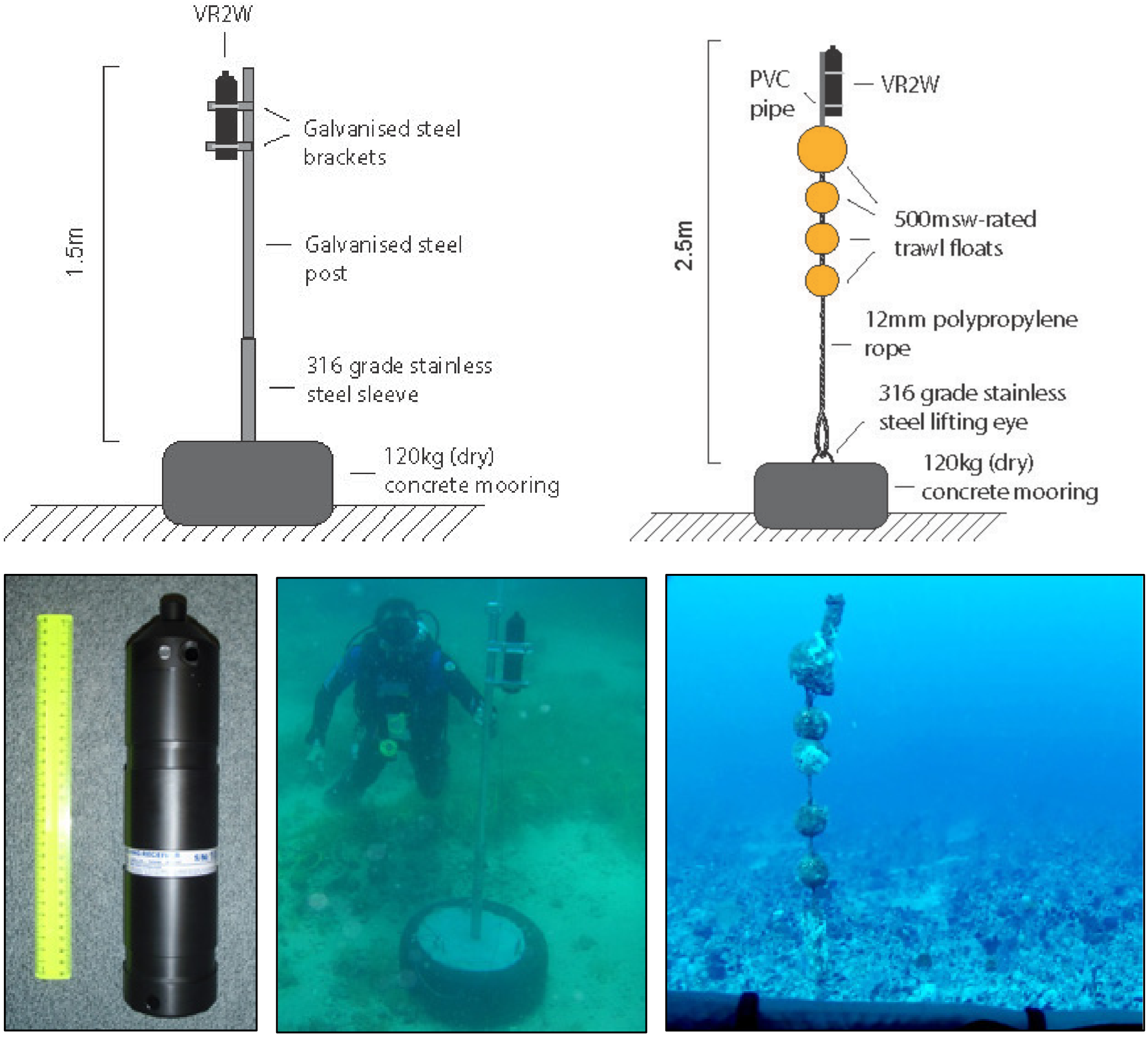

Figure 5. Diagrammatic views of diver-serviced (top-left panel) and ROV-serviced (top-right panel) VR2W installations; Vemco VR2W acoustic receiver (lower-left panel); diver-serviced VR2W mooring assembly (lower-centre panel) and deep-water (acoustic release) VR2W mooring assembly (lower-right panel).

Vemco VR4G receivers are equipped with Iridium satellite modems that enable remote transmission of detection data without the need for their recovery (Bradford et al., 2011). These receivers are effectively 2-piece devices, comprising a satellite modem and battery (surface) unit that is attached to a submerged hydrophone via a data cable. To enable satellite communication and to protect them from boat collisions, submersion and other damage, all but one of the VR4G receivers' surface units are installed atop modified Meridian Plus spar buoys (Fendercare Australia Pty. Ltd.), approximately 2m above the sea surface (Figure 6). Receivers' hydrophones are mounted at a depth of approximately 4m on galvanised steel sub-frames that attach buoys to their moorings. The data cables connecting hydrophones and surface modem units are run through internal conduits in the buoy and sub-frame to protect them from strain, abrasion and other damage. Mounting hydrophones at 4m depth is intended to reduce acoustic interference from turbulence in the surface layer, thereby maximising receivers' detection range. Based on limited initial range testing, VR4Gs detection range appears to be similar to that of VR2W receivers (400-500m). The initial 20 prototype VR4Gs have gradually been replaced with second-generation metal-cased units, which have required modifications of the buoys on which these later-generation (Mk2) receivers are installed. A single VR4G receiver is located off the Busselton foreshore in water that is too shallow (≈4m) for a buoyed installation. This receiver is instead mounted in a thermo-plastic piling with the hydrophone installed beside it on a modified VR2W mooring. As a result of these various modifications, there is now considerable variation in the appearance of VR4G installations throughout the network (Figure 6).

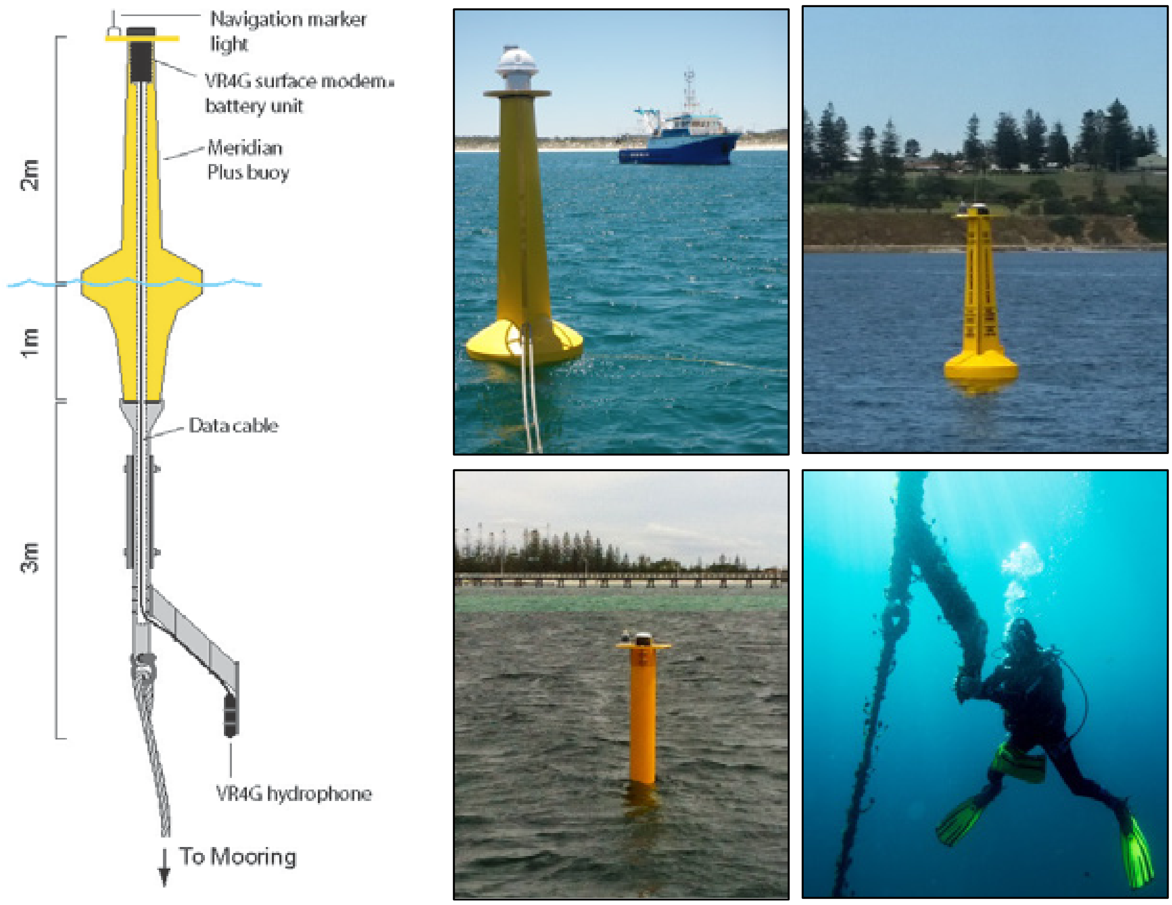

Figure 6. Cross-sectional diagrammatic view of a (third-generation) Meridian Plus VR4G receiver buoy (left panel, receiver components are coloured in black); prototype VR4G off Mullaloo Beach (upper-centre panel); Mk2 VR4G (in 3rd generation buoy) off North Cottesloe (upper-right panel); VR4G piling installation off Busselton (lower-centre panel) and diver inspecting hydrophone assembly on VR4G steel sub-frame (lower-right panel).

During the SMN project's expanded operational phase, an additional three cross-shelf lines, comprising 125 VR2W receivers were deployed around the South-West coast of WA in April-May 2012 (Figure 7). These receivers were installed at 800m intervals off Hamelin Bay (48 receivers); Chatham Island (44 receivers) and Bald Island (33 receivers). While these lines were notionally intended to span the entire continental shelf (i.e. to a depth of 200m), all three are between 3km and 5km short of the closest points of the 200m isobath. A fourth line of 18 VR2Ws was opportunistically-installed across 20km of continental shelf waters in the Recherche Archipelago in November 2014. Between October and December 2013, an additional three VR4G receivers were installed off Back Beach, Bunbury; the Busselton foreshore and Meelup beach in Geographe Bay and another 2 were installed at Frenchman's Bay and Middleton Beach in King George Sound, Albany. Following extensive logistic and environmental assessments, a VR4G was also installed off Smith's Beach, Yallingup in December 2014. With the consolidation of the metropolitan VR4G array to 19 receivers in December 2011, 25 VR4G receivers were operating in the SMN at the time of writing.

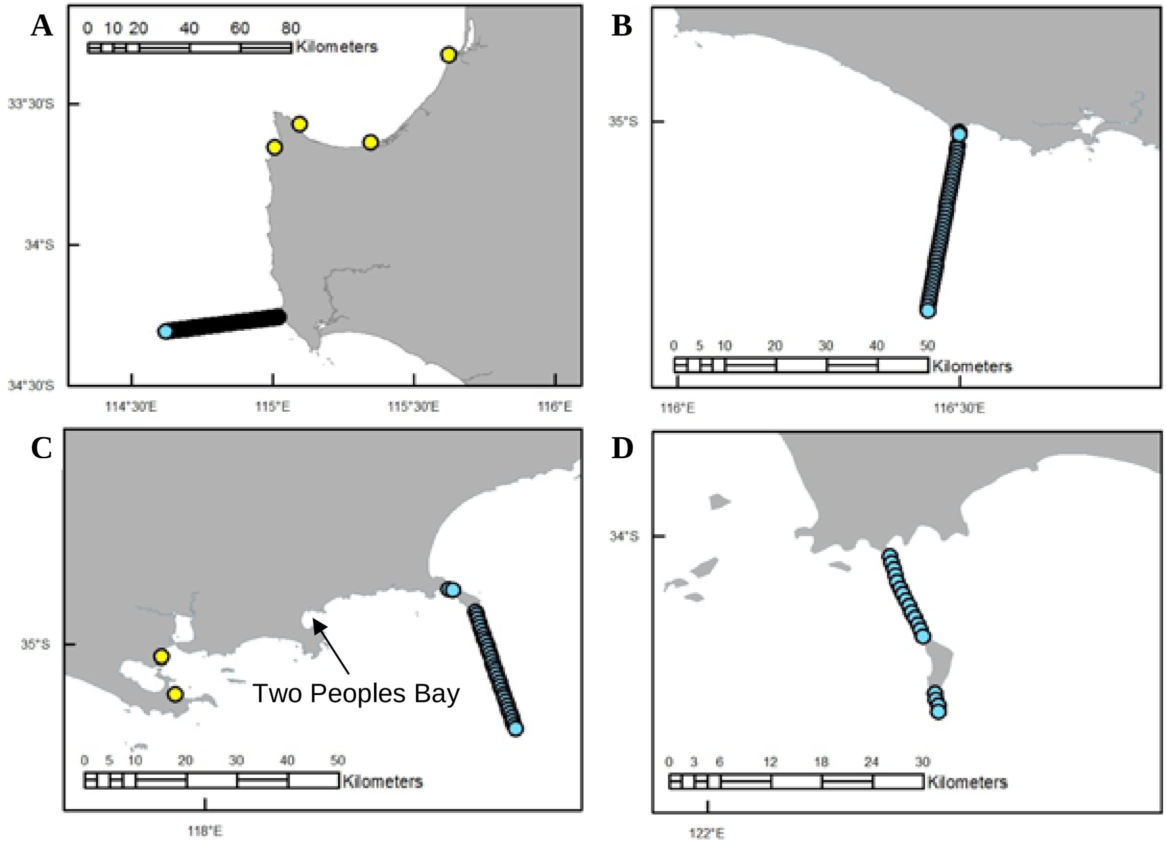

Figure 7. Locations and types of receivers deployed during the SMN operational phase (2012-2015) in (A) the Geographe Bay/Cape Naturaliste array, (B) Chatham Island array, (C) Albany and Bald Island arrays and (D) Recherche Archipelago array. Yellow circles indicate VR4G stations, blue circles indicate VR2W stations.

Additional detections of tagged sharks have been obtained from The Australian Animal Tracking and Monitoring System's (AATAMS) Ningaloo Reef Ecosystem Tracking Array (NRETA), the CSIRO VR4G that was installed at North Neptune Islands Bay between May 2008 and June 2013 (Bradford et al., 2011), AATAMS' Gulf St. Vincent (GSV) array (Figure 8) and a temporary 6 receiver VR2W array in Two Peoples Bay between July and September 2010 (25km East of Albany, Figure 7C).

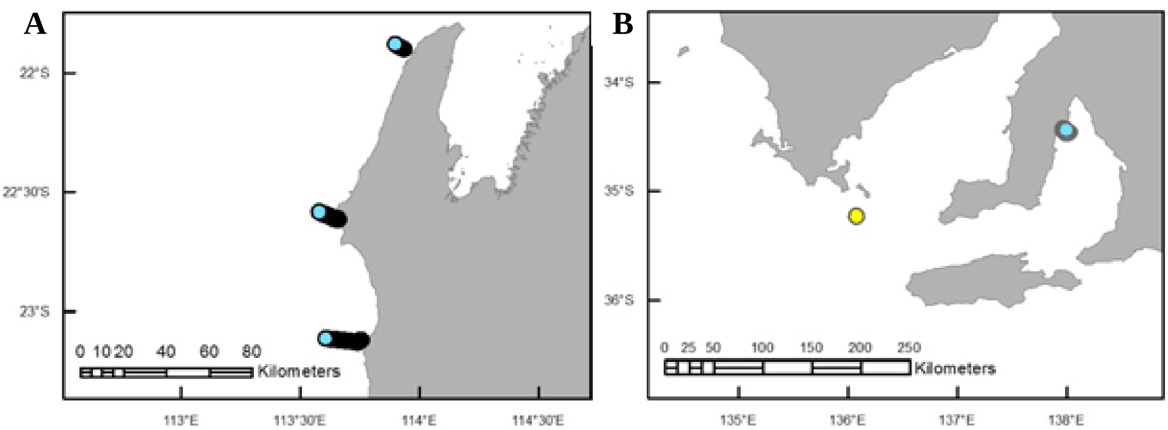

Figure 8. Locations and types of receivers from which ancillary data were obtained (A) at Ningaloo Reef (AATAMS) and (B) in South Australia (VR2Ws = AATAMS and VR4G = CSIRO). N.B. the location of the temporary Two Peoples Bay array is shown in Figure 7C.

2.3 Data acquisition and management

Detection data from both VR2W and VR4G receivers are maintained with associated receiver deployment and recovery times, dates and locations ('metadata') in a purpose-designed SQL database. Detection logs from VR2W receivers are uploaded to the database approximately annually once receivers have been physically recovered and downloaded. Detection logs from VR4Gs are delivered via email and uploaded to the SMN database weekly. In addition to sending log files containing records of every detection, VR4G receivers are programmed to immediately report detections of specified tag ID numbers. For the public safety purposes of the Shark Monitoring Network, specified tag ID codes include all white, tiger and WA-tagged bronze whaler shark tag IDs. However, because effective public safety response actions do not depend on notification of every detection of the same shark by a receiver (i.e. every 50-150 seconds), VR4Gs are programmed to report only the first (and last) detections of 5 minute reporting periods[7]. Thus, when a shark is initially detected by a VR4G, an immediate notification is sent via the protocols outlined below. If that same shark is re-detected by that receiver during the following 5 minutes, those detections are stored in the receiver's memory but will not be reported (they are, however, recorded in the weekly log file). After the initial 5 minute reporting period has expired, the next detection will be reported and the 5 minute reporting schedule is re-started. Alternatively, if the same shark is not re-detected within 7.5 minutes of the previous notification (i.e. the 5 minute reporting window plus maximum 150 second transmission interval time), its last detection will be reported to the Shark Monitoring system. For further information about VR4G messaging protocols, see Bradford et al. (2011).

As originally designed, VR4G receiver notifications were sent to the SMN database by email. However, delivery of these time-critical notifications was occasionally delayed by 3rd party service provider issues that were beyond the Department of Fisheries' and Vemco's direct control. Thus since 2012, tagged shark notifications have also been received from Vemco via

[7] The 5 minute reporting schedule was arbitrarily determined before SMN data were routinely used for public safety responses. As this reporting frequency is inconsistent with safety authorities' subsequently developed shark hazard response protocols (eg. Surf Life Saving WA specify that shark hazard responses remain in place for 1 hour from detection/sighting), this reporting schedule could be reviewed.

a secure, direct-communication link. This data delivery system has not only improved notification delivery time (1-2 minutes after detection) but has also provided significant improvements in the reliability of data-transfer. However, email notifications are still received and used as a backup system.

When VR4G notification messages are received, the tag and receiver serial numbers are referenced to the associated data in the SMN database. The species of shark, receiver location and the local time and date (notifications are given in Universal Time Coordinate, UTC) are then automatically sent by SMS and email to registered contacts within multiple stakeholder organisations. Contacts are assigned to regions (e.g. metropolitan, Albany, Geographe Bay), so that they only receive notifications from receivers within their jurisdictional responsibility area. The same information (species, location and time) are also ‘Tweeted’ through the Surf Life Saving Western Australia (SLSWA) Twitter service, thereby any member of the public can receive SMN alerts directly to their mobile phone or computer, free-of-charge. Because this function involves sending a single message (for each notification) to the SLSWA Twitter feed (i.e. not to thousands of individuals), Tweeting shark detection notifications to the public does not compromise the SMN system’s intended primary function of promptly alerting public safety agencies. Members of the public can also view up-to-date information about tagged shark detections, reported shark sightings and the latest tagged shark detections by VR2W arrays (including the OTN) through interactive maps on the Shark Smart website (http://sharksmart.com.au). The intention of providing public access to up-to-the-minute and accurate scientific information about tagged shark detections, is to facilitate and encourage more informed decision-making about the risks posed by sharks to water users. This additional functionality also addresses long-standing community interest in being kept informed of the latest research into shark distribution and movements in local waters.

2.4 Data analyses and presentation

For ease of reference to when and where sharks were tagged and in accordance with the terms of data sharing agreements with collaborating research organisations[8], tagged sharks have been assigned aliases based on their State of release (white sharks) or species (bronze whaler and tiger sharks) and their chronological order of release. White sharks have been designated with “SA” prefixes for South Australian-tagged sharks and “WA” for Western Australian tagged sharks; bronze whalers are designated by “BW” prefixes and tiger sharks by “TG” prefixes, followed by the same release State codes used for white sharks. In addition to the release State and species designations, the chronological tagging order is designated by 3 digit numbers from 001 upwards for white sharks and 2-digit numbers for bronze whaler and tiger sharks. Therefore tag WA024, is the 24th white shark tagged in Western Australian waters, BWWA31, is the 31st bronze whaler tagged in WA, etc.

Detection data from VR2W receivers were most recently collected between November 2014 and 19 June 2015, while VR4G detections were collected weekly (each Monday morning via email attachments). As all data reported below were extracted from the Shark Monitoring

[8] Namely: the Commonwealth Scientific and Industrial Research Organisation (CSIRO); South Australian Research and Development Institute (SARDI), Fox Shark Research Foundation (FSRF) and Flinders University.

Network database on 30 June 2015, VR2W data are current as of those receivers' retrieval dates and VR4G data are current as of Monday 29 June 2015 (Australian WST), inclusive.

Various measures are used below to describe the frequency of tagged shark detections by acoustic receivers. These measures are defined as follows. A **detection** is an acoustic tag ID recorded by either a VR2W or VR4G receiver; a **notification** is a message generated by a VR4G receiver to report the first and last detections within the 5 minute reporting period (see 2.3 above); a **detected shark** refers to an individual shark detected by a receiver (regardless of how many times that shark's tags are detected, i.e. detection of both of a dual-tagged shark's tags is a single detected shark); a **shark (detection) day** is a calendar day on which a shark is detected, regardless of how many times that shark is detected (e.g. 1 individual shark detected on 2 separate days = 2 shark days; 2 individual sharks detected on the same day = 2 shark days, etc.) and a **shark hazard event** is adapted from Surf Life Saving WA's (SLSWA) shark safety protocol[9], defined as the first detection of a shark by a receiver or the first detection of a shark that is more than 1h after its previous detection by the same receiver.

Distances of tagged sharks' movements between acoustic receiver arrays ($\Delta\sigma$), were calculated as displacement vectors between two receivers, according to the great-circle (or orthodromic) equation:

$$distance = arcos(sin\emptyset_1 . sin\emptyset_2 + cos\emptyset_1 . cos\emptyset_2 . \cos(\lambda_1 - \lambda_2)).r$$

Where $\emptyset_1$, λ_1 and $\emptyset_2$, λ_2 are the latitude and longitude of receivers 1 and 2 and *r* is the radius of the earth (in radians).

Wherever possible, tagged sharks' movements (displacement vectors) between arrays and sharks' release and terminal locations, were calculated as the least-possible (great-circle) distance between locations. To avoid estimating unrealistic movements across land, where necessary, displacement vectors were forced around arbitrary turning points. Turning point locations were the same for all sharks and defined as points off:

> Dirk Hartog Island (25.5^{o}S 118.0^{o}E); Cape Naturaliste (33.5^{o}S 115.0^{o}E); Cape Leeuwin (34.4^{o}S 114.9^{o}E); Black Point (35.0^{o}S 116.0^{o}E); Albany (35.2^{o}S 118.0^{o}E) and Cape Arid (34.1^{o}S 123.3^{o}E)

As displacement vectors assume constant straight-line travel, these should be considered as minimum displacement distances and their associated speeds, as minimum average speeds.

[9] "If the shark is 2 - 3 metres in length … (beaches are closed) … 1km either side of the shark location for one hour" (http://surflifesavingwa.com.au/safety-rescue-services/shark-safety).

3 Results

Shark Monitoring Network and associated WA receivers have detected 64 individual acoustically-tagged white sharks, a total of 22,291 times since 2009 (Table 1). The majority of sharks and detections were recorded in the Perth metropolitan region, followed by the Chatham Island, Bald Island and Hamelin Bay SMN arrays (Hamelin Bay receivers recorded the most detections but fewest sharks of the 3 south-western arrays).

Table 1. Annual detection frequency and abundance of tagged white sharks by region. NB South Australian detections are not included in this table.

		White		Bronze whaler		Tiger	
Region	**Year**	**Detections**	**Sharks**	**Detections**	**Sharks**	**Detections**	**Sharks**
Albany (Including Two Peoples Bay)	2010	1,914	5				
	2013			2	2		
	2014	151	3	16	5		
	2015	2	1	1	1	10	3
Albany Total		**2,067**	**9**	**19**	**8**	**10**	**3**
Bald	2012	81	6	9	2		
	2013	210	7	19	6		
	2014	266	15	93	12	22	3
	2015	132	7	9	4	52	5
Bald Total		**689**	**28**	**130**	**21**	**74**	**6**
Chatham	2012	70	5				
	2013	221	11	129	15	21	1
	2014	296	15	60	21	48	2
	2015	221	9	61	17	197	5
Chatham Total		**808**	**31**	**250**	**32**	**266**	**6**
Geographe	2013	16	2	9	5		
	2014	39	4	132	13	12	2
	2015	4	1	72	6	15	3
Geographe Total		**59**	**7**	**213**	**19**	**27**	**4**
Hamelin	2012	19	3	4	3	48	1
	2013	392	10	66	6	16	1
	2014	587	11	35	6	131	4
	2015	182	7	24	2	133	6
Hamelin Total		**1,180**	**24**	**129**	**15**	**328**	**7**
Metro	2009	1143	5				
	2010	2	1				
	2011	79	6				
	2012	4,524	7	15,316	21	615	2
	2013	9,172	10	53,201	26	1807	4
	2014	1,588	15	72,341	33	2,438	11
	2015	15	2	8,399	13	87	5
Metro Total		**16,523**	**36**	**149,257**	**42**	**4947**	**12**
Ningaloo	2008	3	1				
	2010	7	2				
	2011	41	3				
	2012	22	3				
	2013	21	2			1,039	9
	2014	6	1	9	2	313	6
	2015					13	1
Ningaloo Total		**100**	**11**	**9**	**2**	**1,365**	**12**
Recherche	2013	865	2	9	3	0	0
	2014			1	1	0	0
Recherche Total		**865**	**2**	**10**	**4**	**0**	**0**
Grand Total		**22,291**	**64**	**150,017**	**46**	**7,017**	**21**

As some of the objectives from the project's two distinct phases are complementary, in some cases, the following results are reported under combined objective headings.

3.1 Objective (i) collect information on the occurrence, movements and behaviour of white sharks off metropolitan beaches and the associated risks of human encounters

In total, 36 acoustically-tagged white sharks have been detected in metropolitan waters since May 2009. Eighteen of these were tagged in South Australia, one off Albany, one off Cheynes Beach and the rest were tagged off the metropolitan coast. Sharks tagged in WA were detected significantly more frequently (n=16,277 detections, χ^2=15,460, d.f.=1, p=0.000) and on significantly more days (n=396, χ^2=15,710, d.f.=1, p=0.000) than South Australian-tagged sharks (n=278 detections and n=35 shark detection days).

Three sharks tagged off Perth (WA018, WA020 and WA027), were responsible for more than 70% of metropolitan detections. One of these (WA020) was detected during five calendar months between October 2012 and November 2013; WA018 was detected over two discrete periods from October 2012 to January 2013 and again between June and August 2013, while WA027 was detected during four consecutive months between September and December 2013 (Figure 9). Only five sharks were detected off Perth for more than seven consecutive calendar days (median consecutive detection period=3.3d). The longest consecutive detection period by an individual shark (referred to as WA018) in the metropolitan Perth region was 17d between 21 November and 7 December 2012. This shark was also detected by metropolitan receivers for consecutive periods of a week or more, on 5 other occasions between October and December 2012 and July and August 2013. The four other sharks detected off Perth for consecutive periods of a week or more (WA013, WA020, WA027 and WA041), are known to have visited Perth waters for shorter periods of between 1 and 6 weeks.

Data collected so far, suggest that inter-annual returns to the metropolitan region are relatively uncommon. Only three WA-tagged sharks (WA003, WA020 and WA028) have been re-detected more than one year after their release[10] and only one of those (WA003) was re-detected after more than 2 years (865d), although there was a 787d hiatus between two discrete detection periods in May-August 2009 and October 2011. Two other sharks were re-detected 326d (WA018) and 349d (WA029) after their releases.

Although external tag shedding is likely to have limited long-term re-detection rates prior to 2013, there was little evidence that SA-tagged sharks regularly return to waters off the Perth coast. Although three SA-tagged sharks (SA093, SA125 and SA126) were re-detected by receivers in South-West WA over periods exceeding a year (see section 3.4 below), none of the SA-tagged sharks were detected over such long periods in the metropolitan region (Figure 9). Nine (50%) of the SA-tagged sharks detected off Perth were detected for periods of less

[10] Since data were extracted (30 June 2015), another shark (WA029) has been re-detected by metropolitan receivers in three consecutive (calendar) years.

than 24h (median of those 9 sharks' detection periods=19.6h) and only 3 were re-detected over periods of more than 100d (SA042, SA088 and SA132; max.=182d).

The number of sharks detected by the combined metropolitan receiver arrays has been highly variable over the six years that data have been collected and there have been complete absences of tag detections in many months (Figures 9 and 10). However, monthly detection rates have steadily increased since 2012, when internal tagging commenced in the region (Figure 10A). By pooling data from all years, tagged white sharks appear to be most abundant off the metropolitan coast between September and December, although they have been detected in all months (Figure 10B). On average, individual sharks spent relatively longer in the region during winter (6.5 dm^{-1} in June) and spring (8 dm^{-1} in October) than in summer and autumn (1-1.5 dm^{-1}, between February and May). The pooled monthly abundance of detected white sharks was also noticeably lower (n=2-6) during late summer-autumn than in winter and spring (n=9-14).

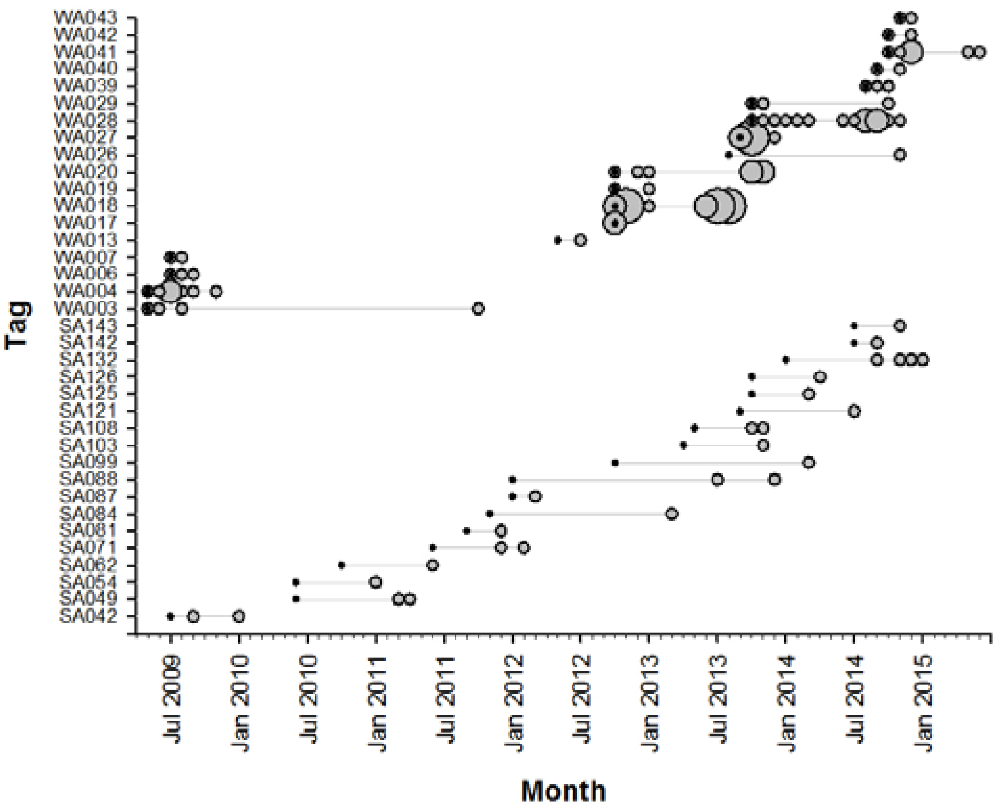

Figure 9. Summary of individual white sharks' monthly detections by combined (SMN, OTN and DoF) metropolitan Perth receiver arrays. Circle diameter indicates number of detection days per month (dm^{-1}): ○= less than $10dm^{-1}$; ○= 10-19 dm^{-1}; ○ = 20-30 dm^{-1}; • = initial tag release date.

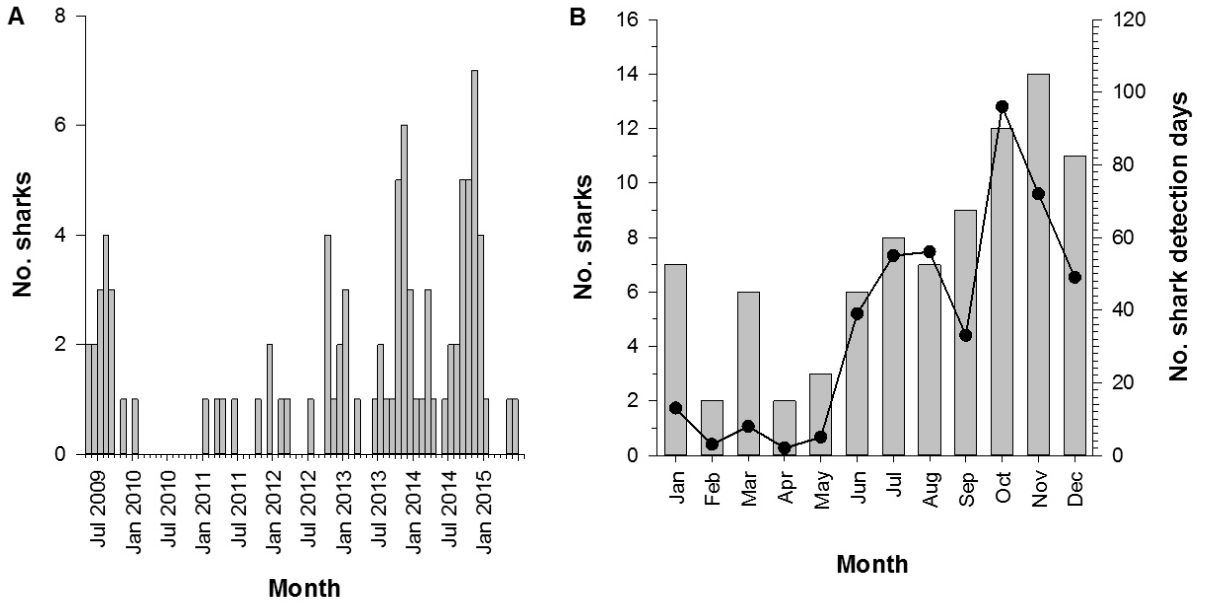

Figure 10. Monthly abundance (no.) of tagged white sharks detected by metropolitan acoustic receiver arrays: (A) by month (May 2009-Jun 2015, inclusive) and (B) pooled across all years (indicated as bars against the left axis). Pooled monthly detection frequency of tagged white sharks (shark detection days) is indicated as the solid black line in (B).

The highest tagged white shark detection (day) frequencies were recorded by receivers in the southern metropolitan area, specifically: around the northern end of Garden Island, within Cockburn Sound and across Gage Roads (Figure 11A). Maximum frequencies of 68-74 white shark detection days, recorded by receivers off Garden Island, were almost twice those of OTN receivers across Gage Roads (24-40d) and nearly 10 times the mean rate of beachside (VR2W and VR4G) receivers (7.7d). A similar pattern was observed in the abundance (number) of tagged white sharks detected by receivers at those locations (Figure 11B). As many as nine different white sharks were detected by receivers around the northern end of Garden Island (mean of 7.2), slightly more than the maximum of eight across Gage Roads (mean of 6.8). Although the mean frequency of white shark detections by receivers located West of Rottnest Island (4.8) was less than one third of receivers closer to shore, the number of sharks detected by offshore OTN receivers was generally higher (mean=4.8) than detected by receivers within 3km of the mainland (mean=2.7). Additionally, more than half (n=13) of the 24 white sharks detected by OTN receivers west of Rottnest (Figure 4B) were not detected by any receivers closer to shore, indicating that many white sharks travel rapidly past Perth and generally too far offshore to pose a threat to the majority of water users in the region.

While these results might suggest that white sharks occur in southern metropolitan waters more than those in the northern part of the region, it should be noted that the most frequently-visited receivers are located further offshore than receivers in the northern metropolitan waters. A slightly higher detection frequency by offshore VR2W receivers was also observed along the outside of Three Mile Reef off Scarborough-Hillarys, suggesting that distance from shore may be important in determining white sharks' fine-scale regional preferences. Nevertheless, differences in the habitat-structure and/or seasonal prey availability in areas around the northern end of Garden Island and Gage Roads may play a role in attracting white sharks to this particular part of the metropolitan coastline. The channels through the southern part of the near-continuous reef between Garden and Rottnest Islands are known to be the exclusive passageways and staging posts for snapper entering Cockburn Sound to spawn during spring and early summer. As several white sharks (and many more bronze whalers) have been caught and tagged in close proximity to spawning aggregations of snapper in the Sound, it seems likely that sharks are using the same channels to enter (and exit) the area.

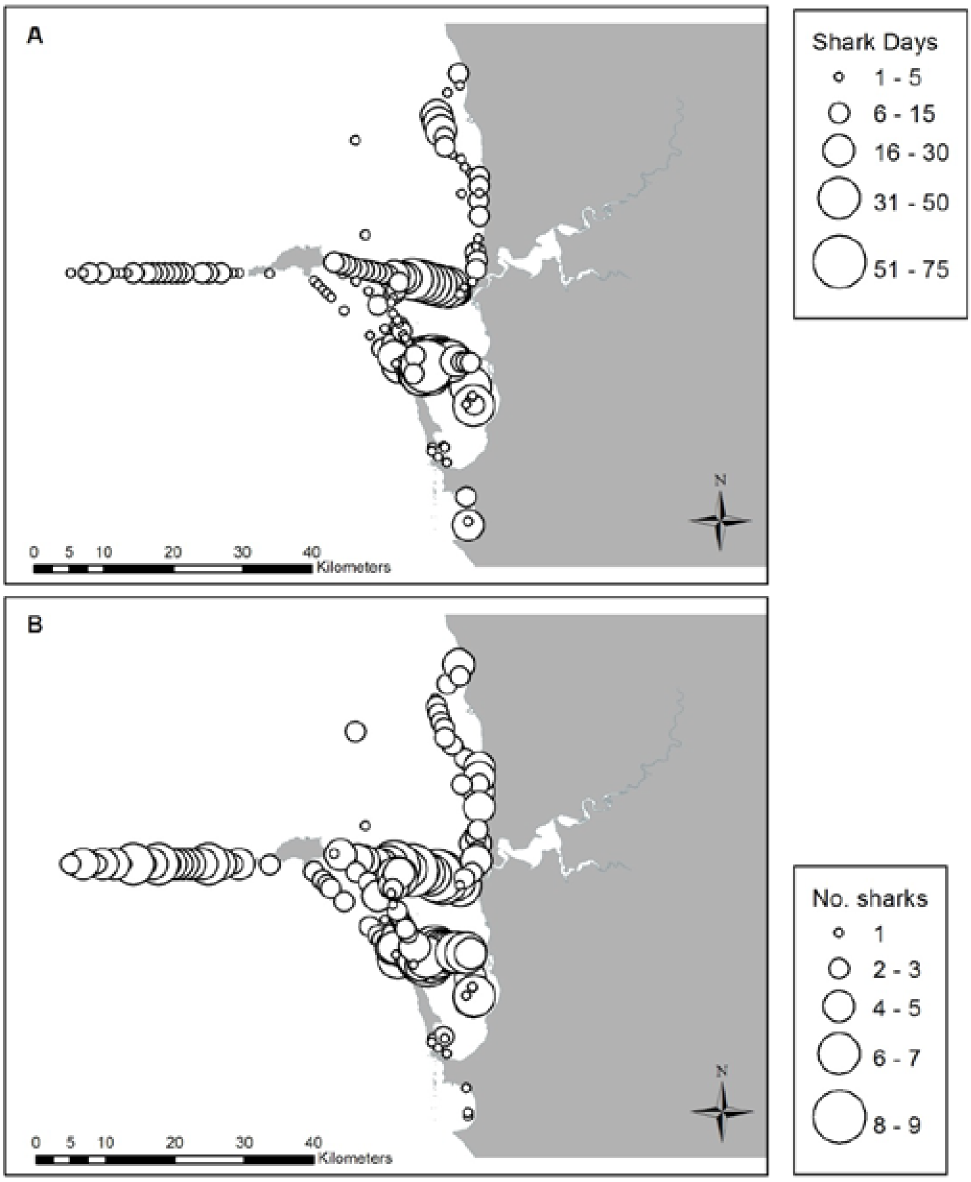

Figure 11. White sharks' (A) detection frequency (shark days) and (B) abundance (number of detected sharks) at Metropolitan (SMN, OTN and DoF demersal scalefish research) receivers.

In addition to recording the presence and movements of tagged white sharks, metropolitan receiver arrays have also detected 42 bronze whaler sharks a total of 149,257 times, over 3,616 shark detection days and 12 tiger sharks a total of 4,947 times, over 263 shark detection days. Because the data collected for these species are outside the scope of this project's original objectives but, nevertheless inform a more general understanding of potential and perceived shark hazards off the metropolitan coast, data collected for these species by metropolitan receivers are summarised in Appendix 1. More detailed examinations of these data are planned for future publications.

3.2 Objectives (ii) evaluate the feasibility and public safety benefits (relative to aerial surveillance) of using communicating acoustic receivers as an 'early-warning' system for notifying public safety authorities of the presence of acoustically-tagged sharks close to populated beaches and (vii) provide a system for alerting public safety officials and the public, about risks of encountering tagged sharks (and sharks more generally) close to populated areas, beaches and surf breaks in the Capes and Albany regions.

Because satellite-linked VR4G receivers' coverage (i.e. the number and geographic extent of VR4G installations) and the number of acoustically-tagged sharks in the study have continually changed since the first receivers were deployed in January 2009, caution should be exercised in comparing the following results between years. Similarly, as the type, number and geographic scales of aerial surveillance data sources have changed since the first metropolitan fixed-wing shark surveillance program began in the summer of 2001/02, aerial surveillance data are also not directly comparable between years.

3.2.1 VR4G acoustic receiver detections

A total of 73 different acoustically-tagged sharks have been detected by VR4G receivers, a total of 3,139 times since the first three receivers were installed off the metropolitan coast in January 2009 (Table 2). These detections resulted in 2,748 near-real-time notifications of 920 specific white, bronze whaler and tiger shark hazard events (i.e. involving confirmed species of mostly measured lengths). Pooled VR4G notification frequencies of white, bronze whaler and tiger sharks' (combined) detections throughout the expanded SMN are shown by location, in Figure 12. Notification frequencies and numbers of sharks detected by VR4G receivers are shown separately for each individual receiver station in Appendix 2.

Table 2. Annualised summary of numbers of sharks detected by VR4G receivers and numbers of detections, notifications, detection days and identified shark hazard events.

Name	Species	Year	No. Sharks	VR4G Detections	VR4G Notifications	Shark Hazard Events	Shark days
White	*Carcharodon carcharias*	2009	1	15	7	4	4
White	*Carcharodon carcharias*	2010	0				
White	*Carcharodon carcharias*	2011	2	5	5	2	2
White	*Carcharodon carcharias*	2012	4	469	381	72	26
White	*Carcharodon carcharias*	2013	6	123	100	38	21
White	*Carcharodon carcharias*	2014	11	558	425	109	48
White	*Carcharodon carcharias*	2015	3	15	13	10	9
Total			***23***	***1185***	***931***	***235***	***110***
Bronze whaler	*Carcharhinus brachyurus*	2012	6	24	23	12	8
Bronze whaler	*Carcharhinus brachyurus*	2013	16	141	131	58	51
Bronze whaler	*Carcharhinus brachyurus*	2014	28	740	695	301	180
Bronze whaler	*Carcharhinus brachyurus*	2015	14	258	233	86	58
Total			***39***	***1163***	***1082***	***457***	***297***
Tiger	*Galeocerdo cuvier*	2012	2	17	16	4	***2***
Tiger	*Galeocerdo cuvier*	2013	4	263	244	70	***28***
Tiger	*Galeocerdo cuvier*	2014	7	436	411	133	48
Tiger	*Galeocerdo cuvier*	2015	6	75	64	21	15
Total			***11***	***791***	***735***	***228***	***93***
Grand total (3 species)			**73**	**3139**	**2748**	**920**	**500**

Because acoustic tags transmit every 50-150 seconds, continuous sequences of detections or notifications by VR4G receivers cannot be considered as representing separate shark hazard events. Therefore, a variation on Surf Life Saving WA's shark safety protocol[6] was adopted to define the number of discrete potential shark 'hazards' identified by the VR4G network. White sharks were generally detected for brief periods by VR4G receivers, with a mean continuous detection period of 6 minutes and 36 seconds (n=201, SD=8.6 minutes). Bronze whaler and tiger sharks' mean continuous detection periods were similarly brief at 5.7 and 7.2 minutes (S.D. of 5.0 and 7.6 minutes), respectively. The VR4G network identified 920 separate, confirmed 'shark hazard events' (see definition in 2.4) between 2 July 2009 (5 months after the first receivers were installed) and 19 June 2015, some of which (e.g. during daylight hours, near a beach etc.) resulted in pre-emptive safety responses (e.g. evacuating bathers from the water). Bronze whalers accounted for nearly half of these (n=457), while similar numbers of white (n=235) and tiger (n=228) shark hazard events were identified.

Six VR4G receivers were responsible for more than 75% of tagged shark notifications and each of these has provided more than 100 notification alerts to public safety authorities (Table 3). However, as receivers have been active for different periods (due to staggered deployments[11] and maintenance issues), comparison of notification and detection rates (e.g. rates per 100 days of operation: $100d^{-1}$) is a more appropriate basis for comparing relative levels of tagged shark activity between different receiver locations (Table 3). In these terms, the Warnbro Sound, Garden Island, Middleton Beach (Albany) and Meelup receivers have

[11] Ocean Reef, 2km off Scarborough and Garden Island receivers were installed in December 2009, Warnbro Sound in May 2010,Bunbury, Busselton, Meelup, Middleton Beach, Frenchman's Bay, Mullaloo North and South receivers in late 2013 and the receiver at Smith's Beach in December 2014.

been the most active in the network, with notification rates an order of magnitude greater than the median rate of 7.3 notifications per 100 days across all VR4G receivers. In contrast, several of the popular metropolitan beach-side receivers have been relatively inactive, with notification rates lower than the median rate. Unlike Meelup and Garden Island receivers which have detected the highest number of different sharks, the detection records of VR4G receivers at Ocean Reef, Warnbro Sound and Middleton Beach (and to a lesser extent 2km off Scarborough) were dominated by protracted detection sequences of individual sharks. For example a single white shark (WA032) was responsible for all of the 108 notifications from Middleton Beach; 74% of Warnbro Sound notifications were caused by single white (WA041; n=189), tiger (TGWA11; n=246) and bronze whaler (BWWA45; n=214) sharks and 251 of the Ocean Reef notifications were caused by concurrent detections of 2 white sharks (WA018 and WA020) over a continuous five day period in October 2012.

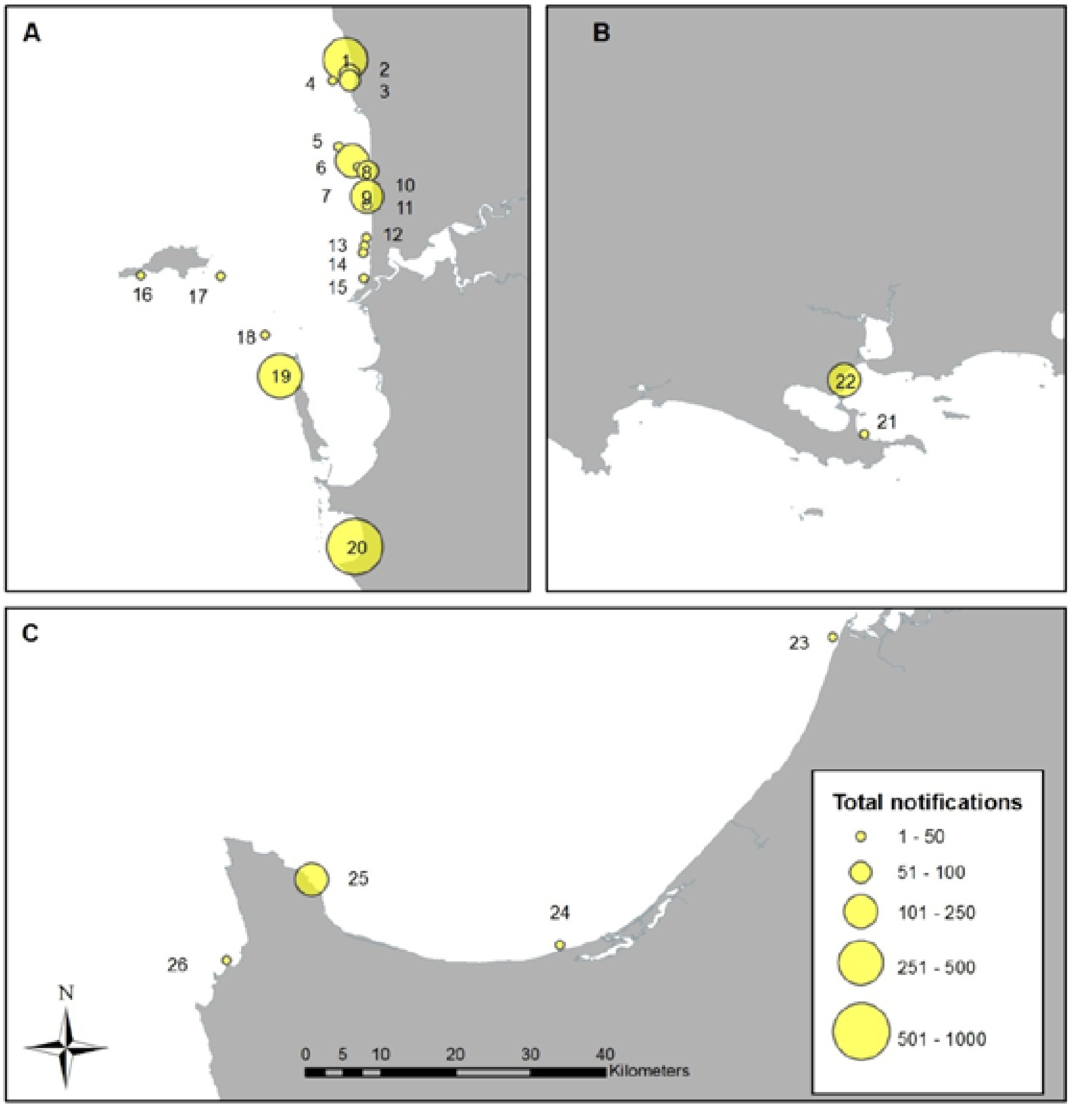

Figure 12. Relative frequencies of (combined white, bronze whaler and tiger) shark notifications by VR4G receivers in (A) the metropolitan, (B) Albany and (C) Geographe Bay-Capes regions. Individual species notification rates are given in Appendix 2. N.B. numeric labels in or beside receiver locations indicate receiver number (not notification frequency) for reference to Table 3.

The majority of receivers (n=21) have detected fewer than 10 sharks in total, at rates of generally less than one per hundred days of operation (Table 3). The Meelup and Garden Island receivers are the obvious exceptions with detections of 29 and 41 different sharks, at rates of 4.6 and 2.1 sharks per 100 days, respectively. Those two receivers were also responsible for detecting the most white (6 and 7, respectively) and bronze whaler (19 and 30, respectively) sharks. Smaller numbers of tiger sharks (1-4) were more evenly detected across the metropolitan VR4G receiver array but only five have so far been detected by a single regional VR4GS.

Table 3. VR4G receiver stations' notification frequencies, numbers of sharks detected and associated rates (per 100 days). NB Station number refers to numerical labels in Figure 11 and Appendix 2.

Station		**Notifications**					**Number of sharks detected**				
No*	**Location name**	***white sharks***	***bronze whalers***	***tiger sharks***	***Total***	***Rate (100d^{-1})***	***white sharks***	***bronze whalers***	***tiger sharks***	***Total***	***Rate (100d^{-1})***
1	Ocean Reef	258	4	35	**297**	**14.7**	4	1	3	**8**	**0.4**
2	Mullaloo North		18	63	**81**	**14.0**		2	4	**6**	**1.0**
3	Mullaloo South		28	42	**70**	**12.1**		2	3	**5**	**0.9**
4	2.5 km off Mullaloo	12	5	9	**26**	**1.3**	3	2	3	**8**	**0.4**
5	3.5 km off Trigg	3	1	2	**6**	**0.3**	3	1	1	**5**	**0.3**
6	2.5 km off Trigg	4	11	5	**20**	**1.2**	1	2	2	**5**	**0.3**
7	2km off Scarborough	74	17	98	**189**	**10.1**	3	3	4	**10**	**0.5**
8	1.5km off Scarborough	5	8	18	**31**	**1.9**	2	2	3	**7**	**0.4**
9	Scarborough	42	2	29	**73**	**3.1**	5	1	3	**9**	**0.4**
10	Floreat	58	10	36	**104**	**5.1**	5	3	3	**11**	**0.5**
11	City Beach	3	3	15	**21**	**1.2**	2	2	3	**7**	**0.4**
12	Swanbourne	8	0	14	**22**	**1.3**	2		3	**5**	**0.3**
13	North Cottesloe	10	1	17	**28**	**1.9**	2	1	3	**6**	**0.4**
14	Cottesloe	23	0	19	**42**	**1.8**	4		2	**6**	**0.3**
15	Leighton	17	2	2	**21**	**1.1**	2	2	2	**6**	**0.3**
16	Strickland Bay, Rottnest	9	2	13	**24**	**1.6**	2	1	2	**5**	**0.3**
17	Bickley Point, Rottnest	4	16	11	**31**	**1.6**	1	3	3	**7**	**0.4**
18	Stragglers Reef	6			**6**	**0.4**	1			**1**	**0.1**
19	Garden Island (north)	43	324	25	**392**	**19.7**	7	30	4	**41**	**2.1**
20	Warnbro Sound	189	430	253	**872**	**55.3**	1	8	4	**13**	**0.8**
21	Frenchman Bay, Albany	7	5	6	**18**	**3.2**	4	2	2	**8**	**1.4**
22	Middleton Bch, Albany	108	5	3	**116**	**20.4**	1	1	1	**3**	**0.5**
23	Bunbury	11	8	2	**21**	**3.3**	1	4	1	**6**	**0.9**
24	Busselton	4	14		**18**	**3.4**	2	1		**3**	**0.6**
25	Meelup	33	163	18	**214**	**33.9**	6	19	4	**29**	**4.6**
26	Smiths Beach		5		**5**	**2.5**		4		**4**	**2.0**

* Station numbers refer to numeric labels in Figure 12

3.2.2 Aerial surveillance data

There have been three distinct periods of aerial shark surveillance in Western Australia since the first flights commenced in November 2001. Summer patrols over metropolitan beaches were conducted in fixed-wing Cessna aircrafts by pilots and observers from Edith Cowan

University's aviation school between 2001/02 and 2007/08 (Nardi and McAuley, 2008; Table 4). For the first three seasons, fixed wing patrols flew on most days between November and January and after 2003/04 they flew on most days between November and February and also on weekends and public holidays in October and March. Since 2008/09 Surf Life Saving WA (SLSWA) have conducted aerial shark surveillance using the Westpac "Lifesaver" Rescue Helicopter along the metropolitan coast and with a second Westpac "Lifesaver" Rescue Helicopter (Busselton) patrolling the State's south west coast since the end of 2011 (http://surflifesavingwa.com.au/safety-rescue-services/helicopters).

Table 4. Shark sightings reported by Western Australian aerial shark surveillance programs. Surveillance hours and timing of programs are also given.

Season	Aircraft	Hours (duration)	Sharks	Species
2001/02	Cessna 172 RG 'Cutlass'	n/a (Nov-Jan)	5	5 unidentified
2002/03	Cessna 172 RG 'Cutlass'	316 (Nov-Jan)	7	7 unidentified
2003/04	Cessna 172 RG 'Cutlass'	448 (Nov-Jan)	19	19 whalers
2004/05	Cessna 172 RG 'Cutlass'	604 (Oct-Feb)	6	6 unidentified
2005/06	Cessna 172 RG 'Cutlass'	584 (Oct-Mar)	57	**1 white**, 1 hammerhead, 4 whalers, 51 unidentified
2006/07	Cessna 172 RG 'Cutlass'	553 (Oct-Mar)	197[a]	**1 white**, 1 hammerhead
2007/08	Cessna 172 RG 'Cutlass'	539 (Oct-Mar)	698[b]	698 unidentified
2008/09	Agusta Westland 119ke (Koala)	265 (Dec-Mar)	23	**2 white**, 1 hammerhead, 2 tiger, 2 whaler, 16 unidentified
2009/10	Agusta Westland 119ke (Koala)	301 (Oct-Apr)	13	5 hammerheads, 4 tiger, 4 whaler
2010/11	Agusta Westland 119ke (Koala)	331 (Oct-Mar)	169	23 hammerheads, 8 tiger, 1 whale, 137 unidentified
2011/12	Agusta Westland 119ke (Koala) & Eurocopter AS350SD	620[c]	247	**3 white**, 3 whale, 3 whaler, 25 hammerheads, 11 tiger, 202 unidentified
2012/13	Agusta Westland 119ke (Koala) & Eurocopter AS350SD	751[c]	285	**24 white**, 1 whale, 6 whaler, 93 hammerheads, 64 tiger, 97 unidentified
2013/14	Agusta Westland 119ke (Koala) & Eurocopter AS350SD	703[c]	247	**19 white**, 1 whale, 23 whaler, 25 hammerheads, 71 tiger, 108 unidentified

[a] 192 sharks were sighted in aggregations in Cockburn Sound and include multiple re-sightings on the same day

[b] 695 sharks were sighted in aggregations in Cockburn Sound and include multiple re-sightings on the same day

[c] Year round metropolitan service; peak summer period and other key holiday periods service in the south west

Aerial surveillance programs have reported a total of 1,973 shark sightings since 2001 (Table 4). The initial fixed-wing program was characterised by very low sighting rates during its first four years, followed by a rapid upward trend in sightings during its last three years, when nearly all sightings were repeat observations of shark aggregations in Cockburn Sound. When sightings of these aggregations were excluded and declining surveillance effort (patrol hours) between 2005/06 and 2007/08 was considered, the sighting rates of non-aggregated sharks declined from 1.4 sharks per 100h to 0.6 sharks per 100h during the last 3 years of fixed-wing patrols. Sighting rates of 8.7 and 4.3 sharks per hundred hours were reported during the first two years of helicopter surveillance in the metropolitan region, an order of magnitude higher than the rates reported by fixed-wing aerial surveillance. Metropolitan helicopter sighting rates then jumped to 51.1 sharks per 100h in 2010/2011 before dropping to 29.6, 25.2 and 40.3 per 100h in the subsequent 3 years. Sighting rates by the south-western helicopter have been similar at 43.5, 61.6 and 38.8 sharks per hundred hours in the 2011/12, 2012/13 and 2013/14 seasons, respectively. Data were not available for 2014/15 at the time of writing.

The species and sizes of sharks sighted by fixed-wing patrols were reported to Department of Fisheries through electronic reporting logs between 2002/03 and 2007/08 (Nardi and McAuley, 2008). Most of the sharks sighted during these patrols were unidentified species (92%) and described as small to medium -sized (Table 4). Only two white sharks were identified during the 7 years of fixed-wing surveillance, one of which was confirmation of a sighting reported by a member of the public. The species and sizes of sharks sighted during the helicopter surveillance program were reported by SLSWA in a series of annual reports to the Shark Hazard Committee between 2008/09 and 2010/11, inclusive (Peck and du Plessis, 2011). Since then, the composition of helicopter sighting records has been obtained directly from SLSWA.

During the initial 3 years of metropolitan-only helicopter surveillance (2008/09-2010/11, inclusive), 205 shark sightings were reported by the helicopter. Of those: 75% were reported as unidentified species (n=153), 14% as hammerhead sharks (*Sphyrna* spp.[12], n=29), 7% as tiger sharks (n=14), 3% as whaler species (*Carcharhinus* spp., n=6) and 1% as white sharks (n=2; Peck and du Plessis, 2011). Between 2011/12 and 2013/14 (inclusive), combined metropolitan and South-West helicopter patrols reported 779 shark sightings: 52% of which were unidentified species (n=407), 18% were identified as hammerhead sharks (n=143), 19% as tiger sharks (n=146), 4% as whaler species (n=32) and 6% as white sharks (n=46). Verification of shark sightings varies according to the particular circumstances of each sighting.

3.2.3 Other sightings records

Since 2009, Western Australians have been encouraged to report shark sightings to the WA Water Police call centre. Sighting information is then relayed via SMS to safety officials and since 2014, sighting reports have also been published via SLSWA's Twitter service and the Government's live web-mapping http://sharksmart.com.au/shark-activity/. While all reasonable efforts were made to preserve the complete history of these SMS records over six years between 2009 and 2015, these data have been reconstructed from multiple mobile phones. As a consequence, SMS records (particularly from November 2012 to August 2013) may be incomplete. Furthermore, as the original source of shark sighting reports was usually unspecified in messages, it is impossible to accurately determine the source of all sightings. In those cases, the current authors' judgement was used to attribute the sources of these reports. It is, however, likely that these 'other' sightings records include some unattributed aerial surveillance records that are previously-reported in 3.2.2 and are therefore duplicated here. Excluding reports that were clearly attributed to SMN project activities and official aerial surveillance programs (previously reported in 3.2.1 and 3.2.2, respectively), at least 1,046 shark sightings were reported by 'other' sources between October 2009 and 30 June 2015 (Table 5).

[12] The smooth hammerhead shark (*Sphyrna zygaena*) is by far the most commonly encountered hammerhead species in metropolitan and south-western waters.

The majority (n=704) of other shark sightings were reported by members of the public, whilst engaged in various aquatic activities, including commercial and recreational fishing, boating, beach-going, diving and surfing. Most of the remaining other sighting records were reported by unknown sources (n=160) and organisational representatives (n=157), the latter including Department of Fisheries and contractor drum-line vessels, Volunteer Marine Rescue crews, beach-based Surf Life Savers, Department of Parks and Wildlife officers and Water Police. The remainder of the other shark sightings were reported by commercial, private and media aircraft.

Relative to aerial surveillance data, a much higher portion of white sharks was identified by these other sources (19%). The percentages of tiger sharks (13%) and unidentified species (64%) were similar to those recorded in the combined metropolitan and south-western Lifesaver helicopters. However, as the sources and descriptions of these other reports are extremely diverse and usually unverified, their reliability is highly uncertain. Furthermore, accurate identification of shark species can be a difficult task even under ideal conditions and particularly for similar-looking whaler species. Thus, some of the reported species (e.g. bull, reef and school sharks), which are very unlikely to occur in the regions they were reported, are thought to be descriptive names rather than attempted species identifications and some reports have later been found not to be sharks [e.g. dolphins, pinnipeds (seals and sea lions), rays, sunfish (Molidae) and other teleosts].

Table 5. Other reported shark sightings (from reconstructed SMS records).

Name	Species	Year	Other aerial[a]	Land and sea Organisations[b]	MOP[c]	Unknown Sources	Total all Sources
Tiger	*Galeocerdo cuvier*	2010		1	2		3
Tiger	*Galeocerdo cuvier*	2011			6	2	8
Tiger	*Galeocerdo cuvier*	2012		1	7	4	12
Tiger	*Galeocerdo cuvier*	2013	4	2	6	7	19
Tiger	*Galeocerdo cuvier*	2014		65	13	1	79
Tiger	*Galeocerdo cuvier*	2015		1	13	3	17
Total tiger			**4**	**70**	**47**	**17**	**138**
Whaler	*Carcharhinus* spp.	2011			2		2
Whaler	*Carcharhinus* spp.	2012			2	2	4
Whaler	*Carcharhinus* spp.	2013			5	4	9
Whaler	*Carcharhinus* spp.	2014	2	2	4		8
Whaler	*Carcharhinus* spp.	2015			11		11
Total whaler			**2**	**2**	**24**	**6**	**34**
White	*Carcharodon carcharias*	2009			2		2
White	*Carcharodon carcharias*	2010		3	4	1	8
White	*Carcharodon carcharias*	2011			27	2	29
White	*Carcharodon carcharias*	2012		1	20	21	42
White	*Carcharodon carcharias*	2013		2	16	2	20
White	*Carcharodon carcharias*	2014	3	10	42	4	59
White	*Carcharodon carcharias*	2015			36		36
Total white			**3**	**16**	**147**	**30**	**196**
Unidentified		2009			4	1	5
Unidentified		2010	2	6	24	3	35
Unidentified		2011	2	12	92	25	131
Unidentified		2012	2	5	53	41	101
Unidentified		2013	5	5	95	13	118
Unidentified		2014	4	17	112	18	151
Unidentified		2015		22	101	3	126
Total unidentified			**15**	**67**	**481**	**104**	**667**
Hammerhead	*Sphyrna* spp.	2010	1	1	2		4
Hammerhead	*Sphyrna* spp.	2011		1	2	2	5
Hammerhead	*Sphyrna* spp.	2012			1	1	2
Total hammerhead			**1**	**2**	**5**	**3**	**11**
Grand Total			**25**	**157**	**704**	**160**	**1,046**

[a] Includes commercial, police and media aircraft (mainly helicopters); [b] Department of Fisheries (mostly releases from the trial drum line program in 2014; DoF., 2014), WA Water Police, Volunteer Marine Rescue, SLSWA (non-helicopters) and Local Government Authority beach inspectors/rangers; [c] MOP = Members of Public.

3.3 Objectives (iii) monitor movements and behaviour of tagged white sharks in the South West of the State and (iv) obtain a more accurate understanding of white sharks' large-scale movements from South Australia into the South West and lower west coast regions of WA

The number of tagged white sharks detected in the combined South-West receiver arrays has steadily increased in-line with the number of sharks that were cumulatively tagged over the three years that data were recorded. Nonetheless, there were complete absences of tag detections in four calendar months after receivers were deployed in April 2012 (April, July and October 2012 and June 2014; Figure 13A). Pooled detection data indicate that tagged white sharks are more consistently abundant throughout the year off the south and south-western coasts than in the metropolitan region. Although sharks were detected in all months, they were less frequently detected during June and July than in other months. Also, individual sharks' mean detection periods (no. shark detection days) were more consistent in the south-western arrays than in the metropolitan region (Figure 13B).

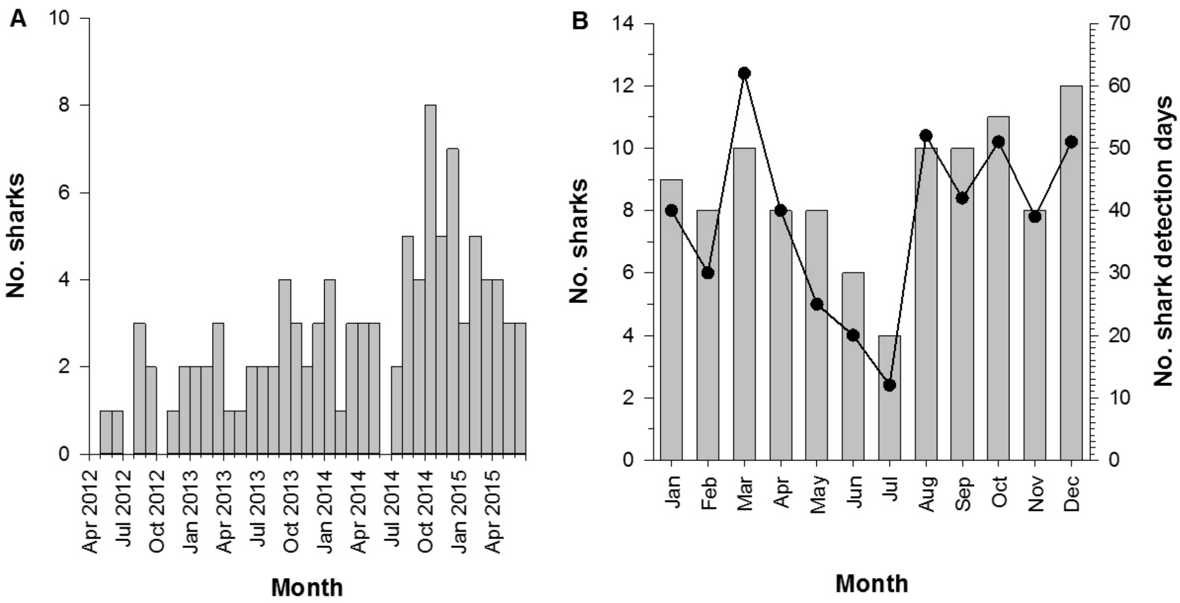

Figure 13. Monthly abundance of tagged white sharks detected by combined south-western acoustic receiver arrays (Geographe Bay/Cape Naturaliste, Hamelin Bay, Chatham Island, Bald Island and Recherche Archipelago): (A) by month and (B) pooled across all years (2009-Jun 2015, inclusive; left axis). Pooled monthly shark detection frequency (shark days) is also shown on the right-hand axis of (B).

Tagged white sharks were detected throughout all three South-West receiver arrays, although the majority of detections were in waters deeper than 50m (94%) and further than 10km from the mainland coast (88%; Figures 14 and 15). On average, receivers located in depths greater than 50m off the South and South West coasts detected more than twice the number of white sharks (2.12 $receiver^{-1}$) than those in shallower waters (0.80 $receiver^{-1}$). This apparent preference for deeper offshore waters in the south-west of the State is in contrast to data from the comparable cross-shelf metropolitan OTN array, which contain a relatively larger proportion of detections from shallow water receivers (67% of OTN detections were by receivers in less than 20m depth), located within 10km of shore (74% of OTN detections; Figure 11). However, the majority of inshore OTN receiver detections (77%) were derived from four sharks (WA004, WA018, WA027 and WA029) that remained in the region for relatively extended periods (Figure 9) and, in two cases (WA018 and WA029), were detected over multiple separate periods. Bronze whaler and tiger sharks' south-western detection frequencies are shown separately in Appendix 3.

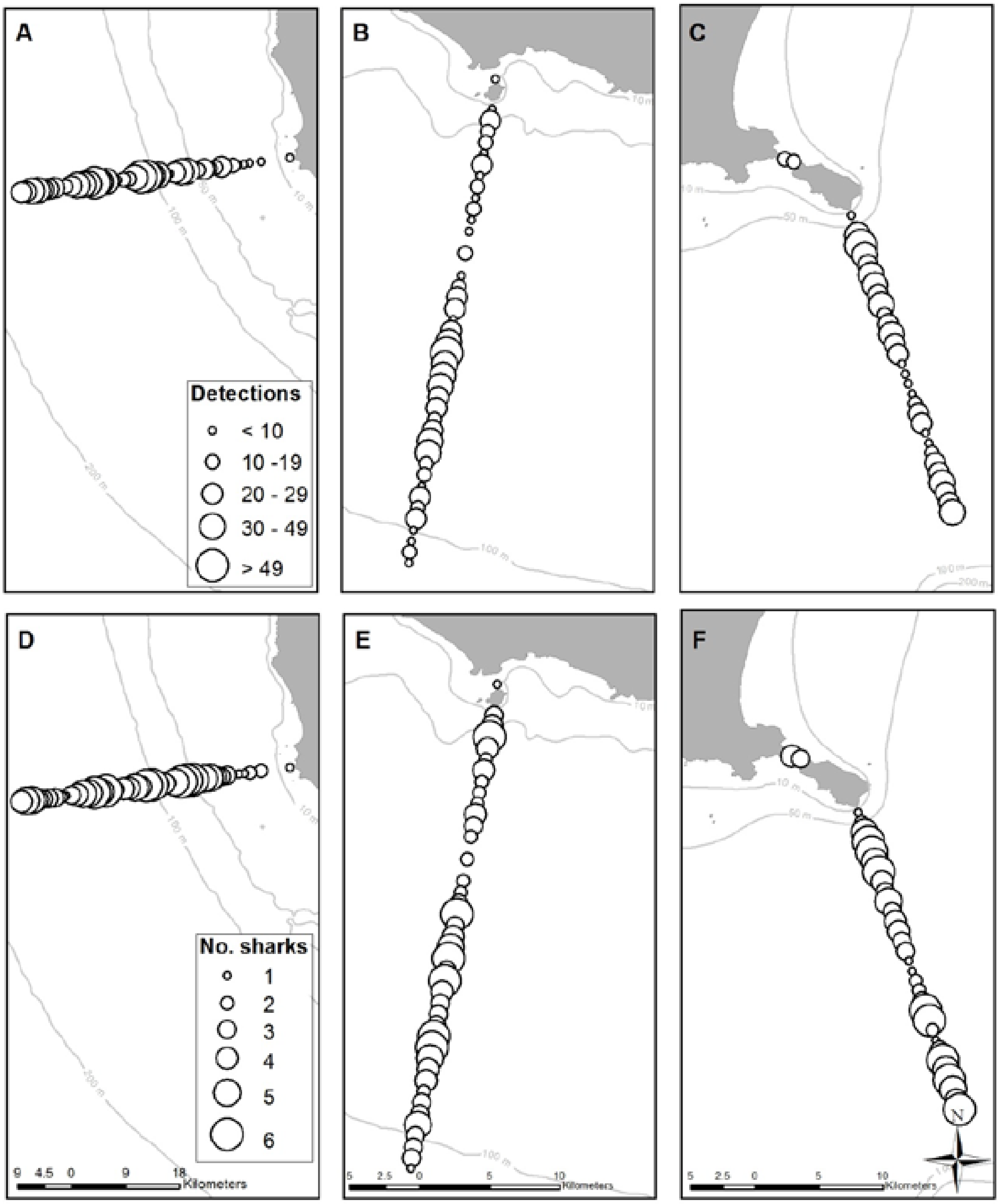

Figure 14. White sharks' detection frequency (no. detections) at the (A) Hamelin Bay; (B) Chatham Island and (C) Bald Island arrays and abundance (number of sharks) at the (D) Hamelin Bay; (E) Chatham Island and (F) Bald Island arrays. Detection frequency symbol values for (A) – (C) are given in upper left hand panel and number of sharks detected symbol values are given for (D) – (F) in the lower left hand panel.

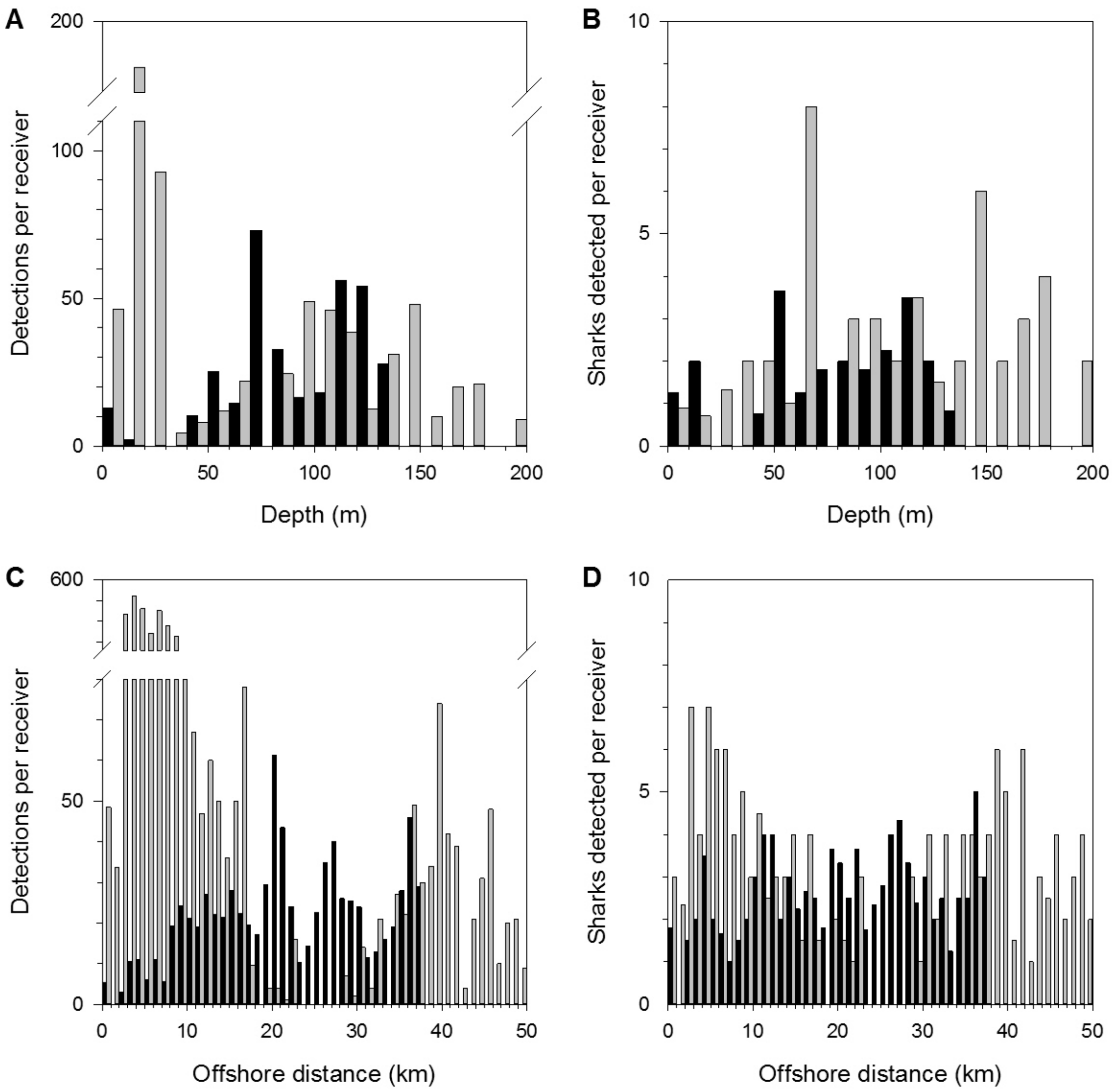

Figure 15. Frequency distributions of white shark detections and number of sharks detected relative to water depth (A & B, respectively) and distance off the mainland coast (C & D, respectively). Black bars show South-West receiver array data (Hamelin Bay, Chatham Island and Bald Island) and grey bars show metropolitan data (OTN only). N.B. detections by South Australian receivers are not included.

Including data from South Australian, South-West, metropolitan and Ningaloo receiver arrays; as well as the known locations of tagged sharks' release, re-captures and deaths, 211 inter-regional movement vectors, totalling 134,592km were recorded for 51 tagged white sharks. The majority of individual movements (n=145, 69%) were between adjacent receiver arrays (or release/mortality locations) and over distances of less than 300km (Figure 16A). However, more than 25% (n=54) of individual movement vectors were over distances exceeding 1,000km, up to a maximum distance of 3,375km. That maximum movement distance was one of 6 between the Neptune Islands in South Australia and Ningaloo Reef in the North-West of WA. Multiple inter-regional movements were recorded for most tagged white sharks (n=35) and individual sharks were recorded travelling cumulative distances of up to 6,542km (mean individual cumulative movement distance=638km; Figure 16B). Individual white sharks' cumulative movement vectors are shown in Appendix 4.

The maximum Rate of Movement (ROM) of 5.6kmh^{-1} was estimated for a shark that travelled between VR2W receivers off Bald and Chatham Islands (a straight-line distance of 193km) in less than 35h. Thirteen other sharks were estimated to have maintained ROMs in excess of 4kmh^{-1} over similar distances (Figure 16C), two of which exceeded average speeds in excess of 3kmh^{-1} over much larger distances. Those sharks were detected by the CSIRO Neptune Islands VR4G receiver, only 24 and 43 days prior to their respective detections by OTN Perth and NRETA receivers, indicating that they maintained ROMs of at least 3.8kmh^{-1} and 3.2 kmh^{-1} over minimum distances of 2,213km and 3,288 km, respectively. A weak positive linear relationship was found between minimum displacement distance and the time between detections (time interval) although this relationship was highly variable (Figure 16D; r^2=0.32).

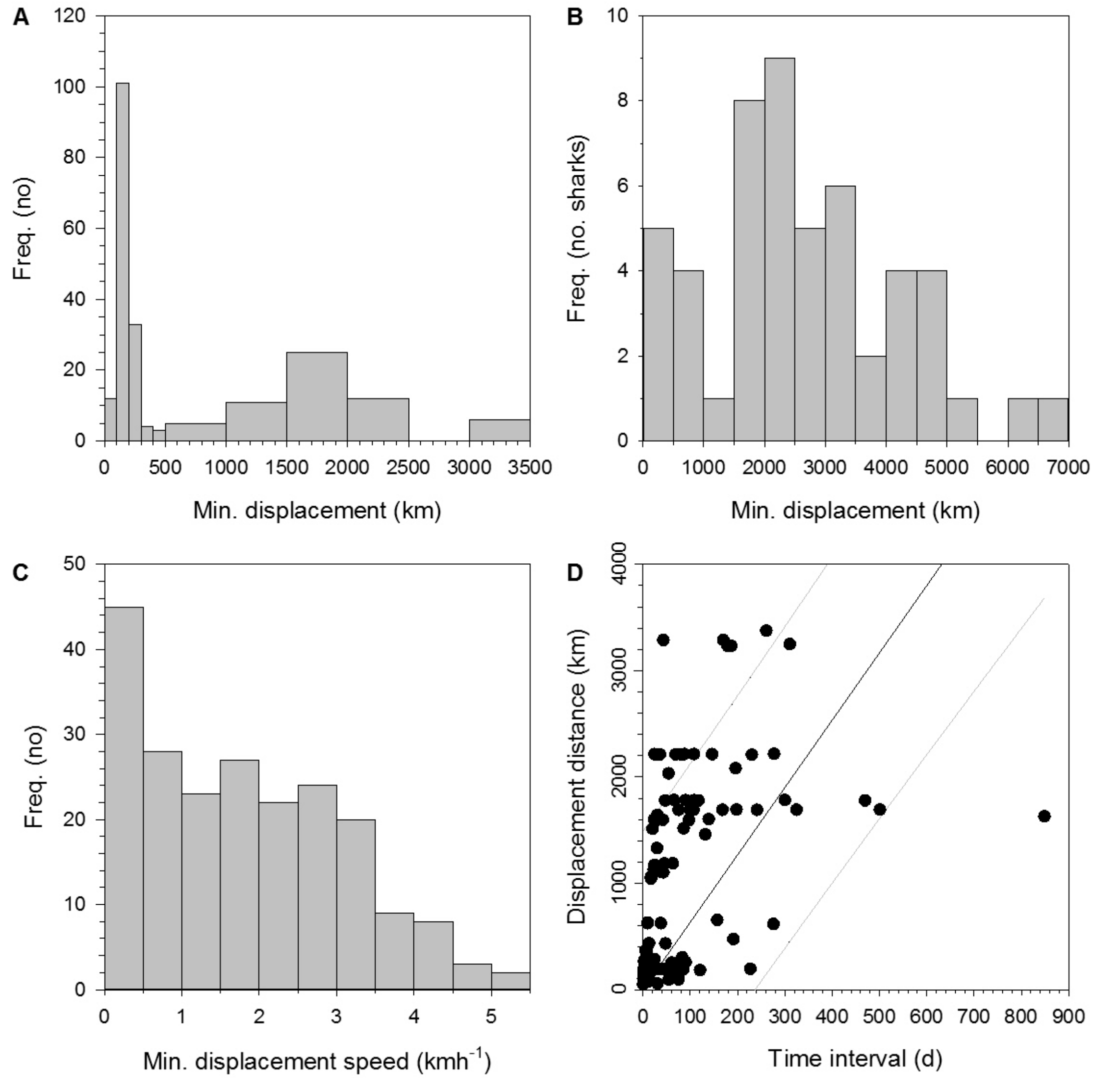

Figure 16. Frequency of estimated minimum displacement distances (A) for inter-regional movements, (B) cumulatively for individual sharks, (C) average speeds and (D) as a function of detection time interval (with 95% confidence bounds).

The pooled monthly frequency and directions of tagged white sharks' movements between acoustic receiver arrays are shown in Figure 17. Although the majority (68%) of inter-regional displacements occurred within single calendar months, movements over 2 or 3 calendar months (15%) were included in the following results by assuming sharks moved unidirectionally in each of the months during which those movements took place. Inter-regional displacements taking more than 3 months (17% of all data) were not considered due to greater uncertainty that movements were unidirectional (i.e. greater potential for sharks to have circumvented arrays and been detected travelling in the opposite direction). In order to explicitly include detections by the relatively small number of VR4G receivers around Geographe Bay and Cape Naturaliste, direct displacements between the Hamelin Bay and Metropolitan arrays and *vice-versa*, were considered to have passed through those intermediary receivers, thereby exaggerating the actual number of Geographe Bay detections.

Although all arrays recorded shark movements in both directions during most months, there was a net westward movement of tagged white sharks from SA and the Recherche Archipelago to the Bald Island array between May and January (Figure 17A). However, the relatively small and disparate receiver coverage in south-eastern WA and South Australia severely limited the availability of data and interpretation of movement patterns to and from the East of Bald Island and should be treated with caution. Similarly, receiver coverage north of Perth was limited and, except for one shark that beached itself and died near Geraldton (SA128), no data were collected from the mid-west and Gascoyne coasts. Nevertheless, a subtle net northward movement of sharks along the mid and upper West coasts was inferred from metropolitan and NRETA detections during October, November and December, followed by a net southward movement between January and March (Figure 17F). This pattern is consistent with the more general northerly movement patterns between Hamelin Bay, Geographe Bay and metropolitan arrays during spring/summer and to the south in late summer and autumn (Figure 17 D, E, F). While there was a general increase in the frequency of movements between south coast arrays (Bald and Chatham Island) during winter and summer months, the directions of those movements remained approximately equal throughout the year.

When displacement data were seasonally aggregated and viewed across all receiver arrays, it was apparent that white sharks may be active in southern and south-western WA waters at any time of the year (Figure 18). These data also confirm the conclusions drawn from more limited previous satellite telemetry data. Bruce and Stevens (2004) observed that white sharks' northerly movements along the west coast, particularly those that travel as far as Ningaloo Reef, are most likely to occur during spring and summer, before they return southwards during late summer and autumn. Nine of the eleven sharks (six females and 3 males) detected by AATAMS receivers at Ningaloo Reef were first detected in the region between late November and early January, possibly indicating that movements to the North-West of the population's range may be both more common and more synchronised than was previously understood. Co-ordination of movements to the north-west may also be indicated by two separate examples of the detection of 'groups' of sharks, tagged within a month of each other at the Neptune Islands (SA054, SA055 and SA057) and off Perth (WA018, WA019 and WA020), being then detected within days to weeks of each other at Ningaloo Reef. While these concurrent movements to Ningaloo could have been coincidental, the three WA-tagged sharks were also subsequently re-detected in Perth and off the south-west within a few weeks of each other. The three female South Australian-tagged sharks' movements subsequently differed, with SA054 being re-detected at the Neptune Islands three months later and SA055 being re-detected at Ningaloo 6 months after first detection there. Shark SA057 was not re-detected. Despite these specific examples of co-ordinated or, at least co-incidental, movement behaviour, data from the current study indicate that movements along WA's temperate coastline are more generally asynchronous and bi-directional.

Of the 151 sharks tagged in South Australia between 20 December 2007 and 18 April June 2015, 34 have been detected by Western Australian-located receivers, including one that was recaptured and re-tagged in King George Sound, Albany in June 2013 and another which stranded on a beach near Geraldton in July 2014. This represents a detection rate of South Australian-tagged white sharks in WA of 23%. However, due to unknown and possibly variable rates of external tag-shedding and changes in the extent of acoustic receiver coverage in WA, the true number of South Australian-tagged sharks that travelled into Western Australian waters is likely to be higher than indicated by these figures. A higher proportion (32%) of sharks tagged in South Australia since 2012 has been detected in WA during the period that SMN receiver arrays have been installed in waters South of Perth. Nevertheless, this is also likely to be an underestimate of the true interstate movement rates due to tag shedding. After excluding four sharks that were externally-tagged off WA between 2007 and 2010 (2-5 years before south coast receivers were installed) and eight sharks that were internally-tagged off Cape Arid in November 2014 and April 2015 (after Recherche Archipelago receivers were last downloaded), 30 of the 39 WA-tagged sharks have been detected by WA receivers. Only one WA-tagged shark (WA017) has so far been detected by South Australian receivers, although a second (yet to be identified individual) was photographed at the Neptune Islands after data were compiled for this report. The apparently low detection rate of WA-tagged sharks in South Australia is likely to be a direct consequence of the low and geographically-limited acoustic receiver coverage in SA. A recent expansion of receiver deployments in SA waters and specifically in areas of the eastern GAB may improve data on interstate movements across southern Australia.

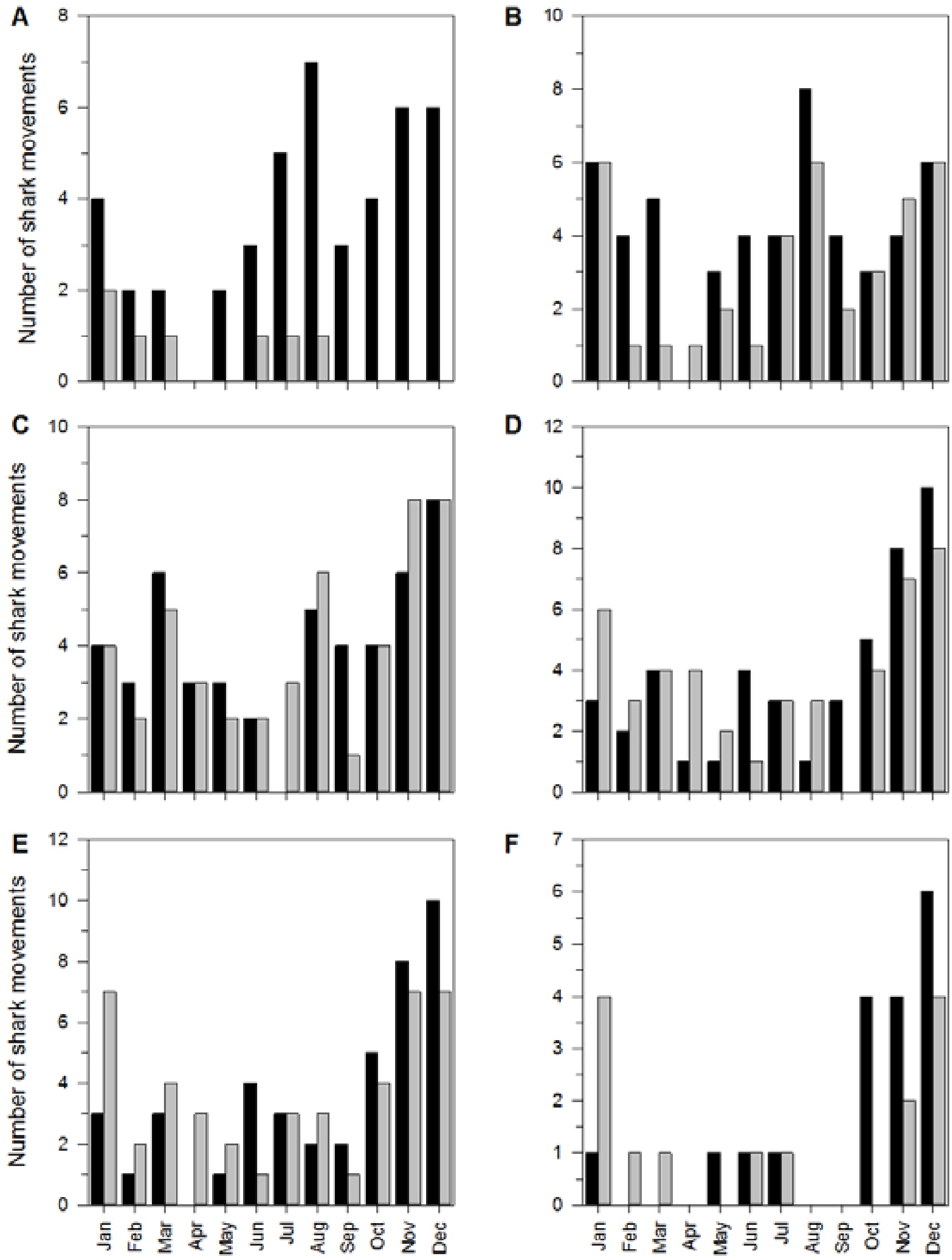

Figure 17. Pooled monthly movements of tagged white sharks: (A) East of the Bald Island array (i.e. to and from Recherche and South Australian receivers); (B) between Bald and Chatham Islands arrays; (C) between Chatham Island and Hamelin Bay arrays; (D) between Hamelin and Geographe Bays arrays; (E) between Geographe Bay and Metropolitan arrays and (F) north of the metropolitan arrays (i.e. to and from NRETA receivers). Black bars indicate westward/northward movements and grey bars indicate eastward/southward movements.

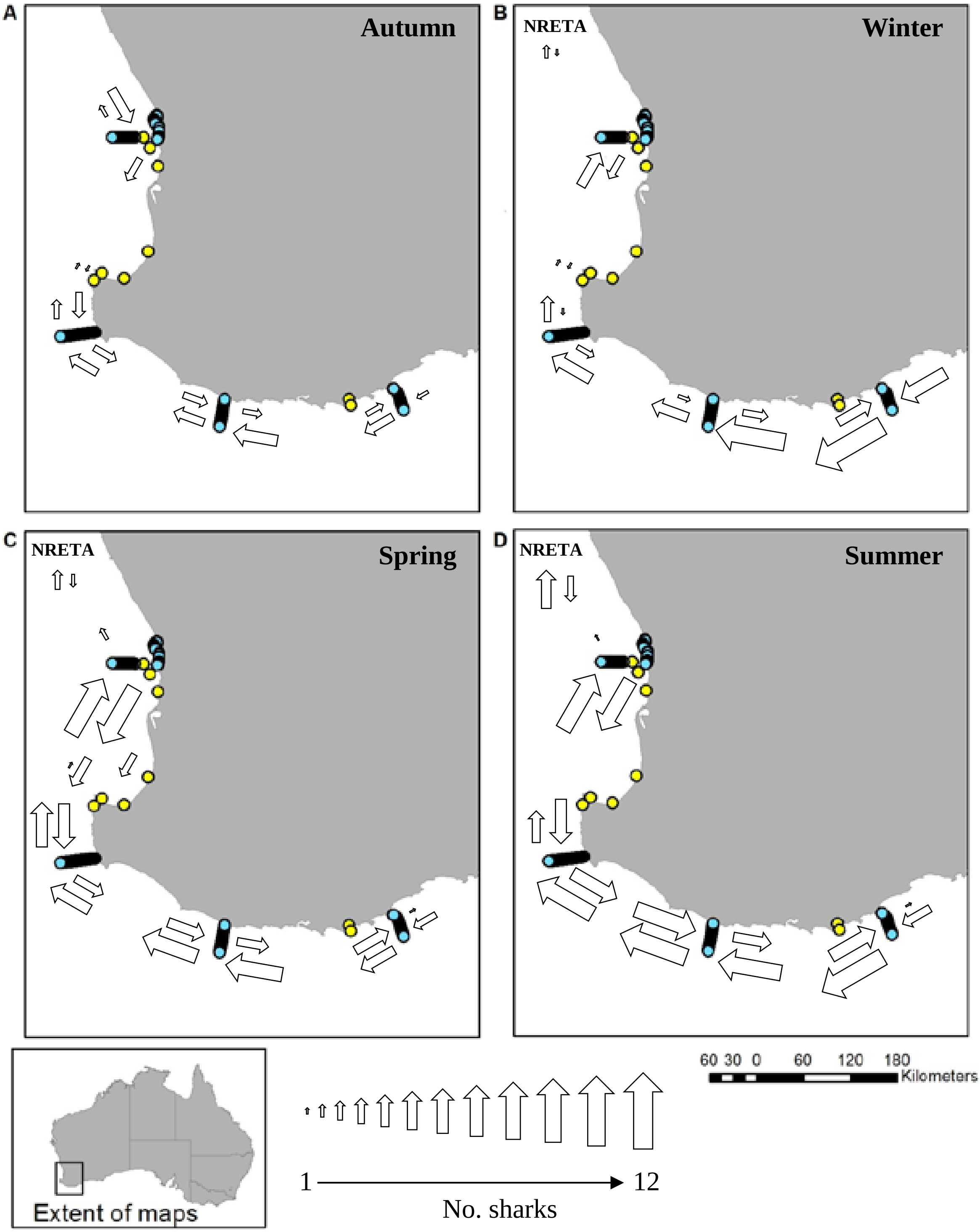

Figure 18. Seasonal movements of tagged white sharks between receiver arrays during (A) autumn (March-May), (B) winter (June-August), (c) spring (September-November) and (D) summer (December-January). Arrow sizes indicate the number of sharks and direction to next and from previous arrays. N.B. arrows' distance from shore does not indicate distance from shore of actual movements (i.e. northerly and westerly movements are not necessarily further offshore than southerly and easterly movements).

3.4 Objective (vi) collect data for investigating whether individual sharks repeatedly visit particular locations in the SW of the State and whether sharks tagged in the area are residential or non-residential in those area

All but eight of the 39 individual white sharks detected by the South-West SMN arrays[13] were tagged and/or detected in South Australia, metropolitan Perth or Ningaloo regions, indicating that the majority of sharks occurring in the South-West of WA make extensive movements through and outside the region (Appendix 4). Seven of the eight sharks that were not detected outside of the SW travelled rapidly and extensively (minimum cumulative movement distances of between 94 and 1872km) between widely-separated locations within the region over periods of 2 to 128d. The eighth shark (a 5.04m FL female, WA032), spent 36d moving between VR4G receivers off Frenchman's Bay (Table 3, Station No. 21) and Middleton Beach (Table 3, Station No. 22) in Albany, during March-April 2014 and has not been detected since. As all of these sharks' detection patterns indicate that they were healthy while they were being monitored, their fate(s) after last detection is unclear. Although tag shedding may have reduced the potential to detect the two externally-tagged sharks outside of the region, it is unlikely to explain the fate of the other six sharks. More likely explanations for their fate are therefore that they either died, emigrated from the region, tags failed or their movements were outside the ranges of receiver arrays.

Despite very limited receiver coverage in SA, two of the SA-tagged sharks detected in south-western WA were subsequently redetected by receivers at the Neptune Islands (SA054 and SA093). One of these (SA093), travelled from the Neptune islands to south-western WA twice between August 2012 and January 2013 and again between July and August 2013. However, only one WA-tagged shark (WA017) was detected in SA prior to July 2015. Although being detected by AATAMS receivers in Gulf St. Vincent, this shark was not detected by any receivers at the Neptune Islands[14]. Following those South Australian detections in February and March 2014, WA017 was redetected by receivers in the Recherche Archipelago in October 2014 before being caught and killed off Esperance on 5 October 2014. It is likely that external tag shedding and the limited receiver coverage reduced the potential to detect WA-tagged sharks in SA and, therefore, that inter-State movements were actually more common than the data in this report show.

Temporal patterns of south-western detections, were characterised by short detection periods, punctuated by relatively rapid movements between adjacent arrays (Figure 19), further suggesting that sharks did not "reside" within or between monitored areas for more than brief periods. Only two sharks (WA022 and WA032) were detected within individual South-West receiver arrays for periods exceeding 10 days in a single month (Recherche Archipelago and Albany VR4G arrays, respectively). However, neither of these sharks was subsequently

[13] An additional five white sharks that were only detected by the temporary array deployed in Two People's Bay in 2010, are not included

[14] A second, as yet unidentified, shark has been sighted by a cage-diving operator at the Neptune Islands since VR2W receivers were last downloaded.

detected by the same arrays, suggesting that these types of extended visits to particular locations may not be regular or predictable behaviours. Shark WA032 has not been re-detected since April 2014 After a 36 day period of nearly daily detections by the Middleton Beach and Frenchman's Bay receivers, WA022 was detected by Chatham Island and Hamelin Bay receivers (approximately 700km to the west) five months after being in the Recherche Archipelago but has not been re-detected since.

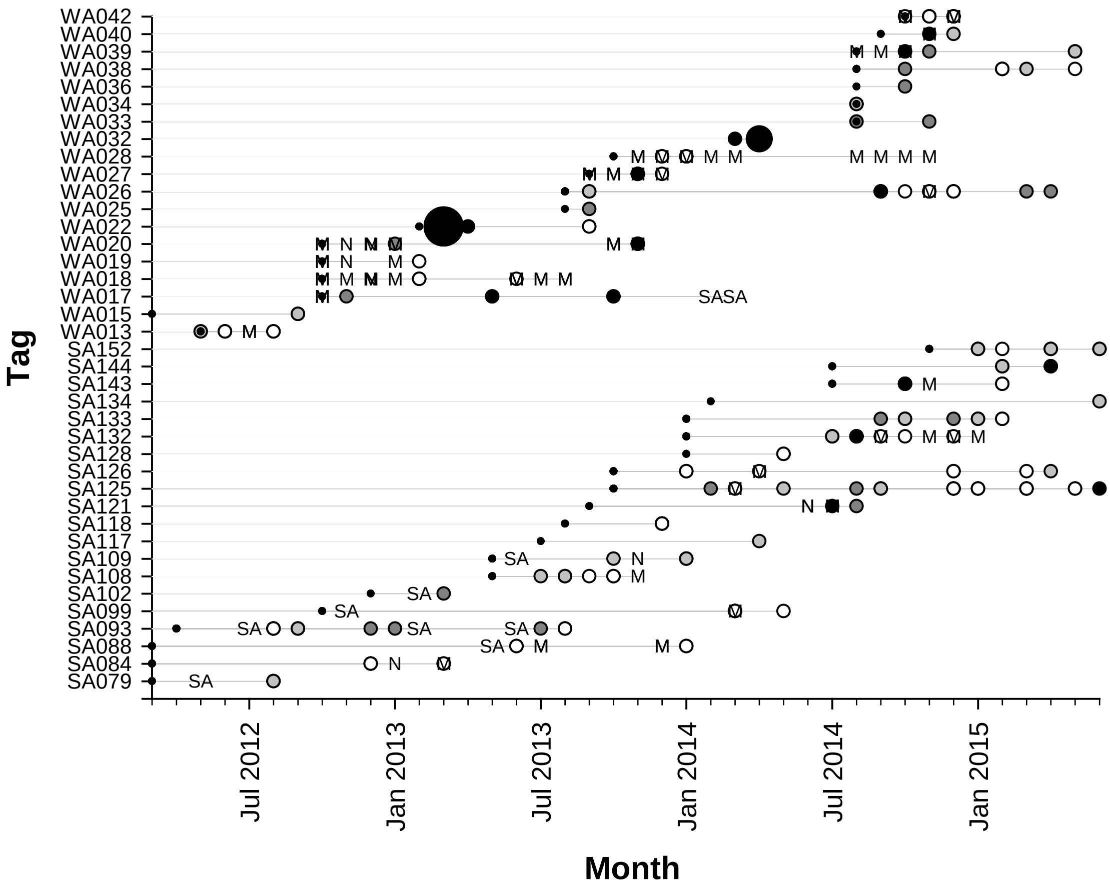

Figure 19. Individual sharks' south-western detection histories. Circle diameter indicates the number of detection days per month (dm^{-1}): ○= less than $10dm^{-1}$; ○ = 10-19 dm^{-1}; ○ = 20-30 dm^{-1}; • = initial tag release date. Symbol shading indicates detection array: white = Hamelin Bay; light grey = Chatham Island; dark grey = Bald Island; black and white = Recherche Archipelago and black = SW VR4Gs (King George Sound, Smith's Beach and Geographe Bay). Letters indicate detections arrays outside the South-West region: M=metropolitan; N= NRETA; SA= South Australia. NB detections by multiple receiver arrays are indicated by the most recent detection array symbol and detections by multiple receiver arrays in any month should not be discounted.

An assessment of the inter-annual returns of white sharks to the south-western region was limited by only four tagged sharks being detected for periods of 12 months or more (Figure 19). Three of these were externally-tagged in SA (SA093, SA125 and SA126) and one (WA026) was dual-tagged with internal and external tags off Cheynes Beach in WA in August 2013. Each of these sharks appeared to use south-western waters very differently. One male SA-tagged shark (SA093), travelled from the Neptune Islands to Hamelin Bay twice, where this individual was detected in August 2012 and August 2013. This shark's previous arrivals at Bald Island on 3 August 2012 and 29 July 2013 were also almost exactly one year apart. The second male SA-tagged shark (SA125) apparently moved continuously between Hamelin Bay and Bald Island arrays (and unknown distances either side) for 16 months without showing particular preference for any specific locations within that 400km stretch of coastline. The third male SA-tagged shark (SA126) was detected between Hamelin Bay and Chatham Island arrays in January and April 2014 and in the same area in December 2014, March and April 2015. The male WA-tagged shark (WA026) was detected by Bald and Chatham Island receivers in September 2013 and then not again until September 2014, when this individual was repeatedly detected between Hamelin Bay and Bald Island until April 2015 (when receiver data were last collected). The only data consistent with regular movements between South and Western Australia was the similarity in arrivals and departures of SA093 in both 2012 and 2013 and the detection of WA026 after a 12 month hiatus in September 2014.

In summary, the data collected from the expanded network of receivers around the South-West of the WA coast, strongly suggest that white sharks rarely spend extended periods in particular locations of the region. Furthermore, the scale and frequency of detected movements within and outside SMN receiver arrays are consistent with white sharks being mostly transient and not resident at particular locations around the SW coast of Western Australia (Appendix 4).

4 Discussion

4.1 White shark distribution and movement ecology

Understanding the ecological factors influencing the frequency of white shark encounters and attacks in Western Australia has historically been hampered by an almost complete lack of reliable data to describe the species' apparently sporadic occurrence around the State's extensive coastline (Anon. 2004). When the Shark Monitoring Network (SMN) project was proposed, few reliable records of white sharks' occurrence in Western Australian waters existed. These included four catch records from State-managed commercial fisheries, 31 voluntary capture reports by commercial fishers, 11 observed captures during Department of Fisheries' research programs (e.g. McAuley and Simpfendorfer, 2003), 27 confirmed or suspected bite incidents since 1803 (ASAF, 2015), two sightings from aerial surveillance programs and data from four electronically-tagged sharks (e.g. Bruce and Stevens, 2004; Bruce et al., 2006). Apart from the limited tag telemetry data, none of these records provided detailed information about sharks' movements and few provided even basic biological information about sharks' lengths and sexes. Thus, existing data were of little value in explaining how the relative probability of human encounters with this species changes with time and location around the Western Australian coast. In lieu of reliable scientific evidence to explain these rare and unpredictable interactions, there has been considerable speculation about the possible causes of white shark encounters and attacks around the State and many theories and opinions have instead gained popular acceptance (DoF, 2012).

The SMN project was developed to collect reliable empirical data about when, where and potentially why white sharks may occur off different parts of the State's lower West and South-West coastlines. This included potentially answering frequently asked questions, such as: whether the same sharks repeatedly visit particular metropolitan beaches, how long they remain in areas following sightings or incidents, how widespread pre-emptive safety measures need to be and how long these should remain in place after sightings.

Since their implementation, the SMN and associated projects (OTN, DoF and AATAMS) have collected information on the movements of 64 individual white sharks over 588 separate days. Cumulatively, over 134,592km of movements have been recorded. More than one quarter of the 211 individual displacements between arrays (and other known locations, i.e. releases, recaptures and deaths) were over distances exceeding 1,000 km and many of those movements were completed within a few weeks or months. These results further support previous evidence that white sharks are generally highly mobile off the WA coast (Bruce and Stevens, 2004; Bruce et al., 2006) and, consistent with telemetry studies completed in other parts of the world, have shown that this species undertakes rapid long-distance movements, interspersed by periods of temporary 'residence' (e.g. Bonfil et al., 2005; Domier and Nasby-Lucas, 2008; Bruce and Bradford, 2012; Duffy et al., 2012). This study is, however, one of the few to have tagged a significant number of sharks away from predictable aggregation sites, which might therefore provide new insights into the movement ecology and population structure of this species in southern and western Australian waters.

Pooled tag detections have revealed that while white sharks may be encountered off metropolitan Perth and the South-West coasts of WA at any time of the year. Tagged white sharks were most abundant in metropolitan waters between late winter and early summer and least abundant during late summer and autumn. The mean duration of white sharks' metropolitan detection periods followed the same seasonal pattern, suggesting that individual water users' encounter risk off the metropolitan coast is highest between September and December and lowest (but never zero) between February and May. Off the South and South-West coasts, based on available detection data, the encounter risk appears to be more consistent throughout the year. This is in keeping with previous analyses that found a significant decline in the rate of attacks with increasing water temperature and a relatively higher incidence of white shark attacks off the metropolitan coast during winter and to late spring (DoF, 2012). For the south and south west regions, the detection patterns indicate that sharks were present during most of the year, which is consistent with previous analyses which found no seasonal pattern in attacks for these regions (DoF, 2012). In addition to these differences in seasonal occurrence patterns, human encounter risks will also be affected by participation rates in aquatic activities, which for some (e.g. swimming) may increase during warmer water months.

Despite these seasonal occurrence patterns, the direction and timing of individual white sharks' movements were highly variable. Apart from the specific examples of concurrent movements to Ningaloo Reef and in some of those cases, back to Perth and the Neptune Islands, white sharks were observed travelling along the WA coast in both directions at most times of the year. The ecological reasons for the unusually coordinated or coincidental movements to North-western WA are uncertain but presumably relate to reproduction, foraging, intra-specific competition or predation-avoidance. When reporting a tagged 380cm TL female's return migration between South Africa and North West Cape, Bonfil et al. (2005) suggested that this region might be an area of inter-breeding between widely separated African and Australian populations. However, like the South African-tagged shark, all of the white sharks detected at Ningaloo during the current study, were juveniles and sub-adults (2.0-3.5m estimated TL), thus reproductive migration seems an unlikely reason for these sharks to visit the region. As there are multiple relatively abundant sources of prey between Ningaloo Reef and the Neptune Islands, where most (n=8) of these sharks were tagged, foraging behaviour may provide the best explanation for these movements.

While the data do not support the theory that white sharks follow the humpback whale (*Megaptera novaeangliae*) migration northwards along the WA coast during winter (June-August) and southwards in spring (August-November; Jenner et al., 2001; Kent et al., 2012), they do provide evidence that white shark movements up the west coast will result in them encountering whales along much of their migration route. Another theory is that sharks are attracted to the increasing number and densities of long-nosed fur seal (*Arctocephalus forsteri*, also known as New Zealand fur seal) colonies off the South and lower West coasts of the State (Campbell et al., 2014). However, data from receivers in close proximity to the seal colony at Chatham Island and permanent haul-out site at the western end of Rottnest Island were noticeably lower than those of receivers further offshore from those locations. Detection rates of white sharks by receivers within 2km of Chatham Island were 49% lower (10.2 detections receiver^{-1}) than the average detection rate of receivers further off Chatham Island (19.9 detections receiver^{-1}). Detection rates by OTN receivers within 2km of the West End of Rottnest Island, where an expanding long-nosed fur seal colony has been blamed for perceived increases in shark activity in the metropolitan area and a fatal bite near the colony in October 2011, were 71% lower (4.7 detections receiver^{-1}) than the average detection rate of OTN receivers located further offshore (24.6 detections receiver^{-1}). Also, as the Neptune Islands (and South Australian waters, more generally), host some of the largest seal colonies in Australia (Shaughnessy et al., 1994) and Western Australian colonies are typically an order of magnitude smaller (Campbell et al., 2014), it seems unlikely that seal predation is a major driver of white sharks' movements between South and Western Australia.

Recorded movements of SA-tagged sharks into WA waters were relatively common and their visits were sometimes prolonged. By contrast, only two WA-tagged sharks have been detected in SA to date: a 2.7m (FL) female shark (WA017) was detected by AATAMS receivers in Gulf St. Vincent in February-March 2014 and an as yet unidentified WA-tagged shark was sighted at the Neptune Islands[11] in June 2015. Despite the small number of acoustic receivers at the Neptune Islands, receivers have been in nearly-continuous operation around the Islands since 2008 (Bradford et al., 2011; Rogers et al., 2014). Given that identical tagging methods were employed in South and Western Australia and that and increasing number of sharks have been permanently-tagged with internal transmitters in WA over the last 3 years, it seems unlikely that the WA-tagged sharks frequently visit this specific aggregation site. Although there are several possible explanations for the paucity of WA-tagged shark detections in SA (e.g. low levels of SA receiver coverage, tag shedding, mortality, etc.), previous studies have noted fine-scale segregation of sharks of different sexes and sizes in relatively small geographic areas (Anderson and Pyle, 2003; Robbins and Booth, 2012; Kock et al., 2013). It is possible that more WA-tagged sharks did migrate to SA but not sufficiently near to the Neptune Island receivers. Expansion of acoustic receiver coverage in South Australia would be required to determine this more definitively.

Noting the initial reliance on external tags and the duration of the project, there was only limited evidence that white sharks regularly returned to the same locations in WA. For metropolitan Perth, which had the highest level of monitoring, five white sharks (all tagged in the region during spring) were re-detected in different years. Two of these sharks (both female, WA020 and WA029) returned the following spring; another female (WA018) returned the following June and the fourth (male, WA028), returned in January after a very brief departure to the South coast. All but one of these sharks (WA029) remained in the metropolitan area for periods of over a month following their return. Only one shark had been re-detected after more than 2 years (WA003 was detected off Rottnest, 29 months after being tagged off the metropolitan coast) and none had been detected in more than 2 consecutive years[15] by July 2015. Thus, while multi-year returns have been observed, further data are required to determine whether these individual sharks' metropolitan-return behaviour might

[15] Since compiling these data, one shark has been detected for the third consecutive year by metropolitan receivers.

be persistent. Off the south coast, two sharks (SA093 and WA017) were redetected in consecutive years by the Recherche Archipelago and Hamelin Bay receivers, respectively.

Apart from three of the sharks mentioned above (WA018, WA020 and WA028) and three others that were detected by the metropolitan arrays over periods of 4 to 5 consecutive months (WA004, SA132 and WA027), tagged white sharks were generally only detected in the metropolitan region for few days at a time. Even those sharks that were present for longer periods, were absent from the array for multiple periods of days to weeks and it cannot be determined how extensively they may have travelled during these absences. Relatively high numbers (i.e. abundance) of different sharks were detected by receivers around the northern end of Garden Island, Cockburn Sound and Gage Roads, with those receivers having higher detection frequencies compared to the receivers located off the northern metropolitan coast. However, conclusions about any white shark preference for southern metropolitan waters must be qualified by the higher number of receivers that are located further off the southern metropolitan coast than in the northern part of the array(s). Nearly twice as many sharks (9) were detected by receivers off the northern end of Garden Island than the maximum number detected at beachside locations (5 at Floreat and Scarborough, mean of 3.2 receiver^{-1}). The detection rates of 68-74 white shark days recorded by some Garden Island receivers were nearly 10 times the mean rate of beachside (VR2W and VR4G) receivers (7.7d). Given that detections by the South-western receiver 'curtains' suggest that white sharks prefer deeper offshore shelf waters, at least while travelling, the uneven spatial distribution of metropolitan receivers might have biased the relative rate of detections observed between these two regions.

Nevertheless, the high abundance of tagged-sharks detected by Cockburn Sound/Garden Island receivers (particularly those tagged in the metropolitan region during spring) did coincide with the seasonal formation of spawning aggregations of snapper (*Chrysophrys auratus*) close to these particular locations. Additionally, more than half (n=9) of the 16 metropolitan-tagged white sharks were also caught and tagged (n=11) in this area during spring. The regular occurrence of these and other schools of large demersal teleosts ('scalefish') off the metropolitan coast provides at least a circumstantial explanation for the increase in tagged sharks' abundance, prolonged detection periods and inter-annual metropolitan returns at this time of year. As seasonally-abundant spawning aggregations of demersal scalefish might therefore also attract sharks to other locations along the WA coastline (e.g. snapper in Warnbro Sound), these events may similarly be expected to result in increased encounter risks if people happen to be using those areas at the same time(s). However, data collected for two of the sharks most closely associated with the Cockburn Sound snapper schools (WA018 and WA020) also show that even when these predictable local prey sources are available, sharks do not feed on them exclusively. During their extended periods of detection in Cockburn Sound in October and November 2012, both of these sharks were concurrently detected for separate 3-5 day periods by VR4G receivers between Floreat and Scarborough and off Ocean Reef at the northern extent of the metropolitan arrays. Not only did the near real-time VR4G notifications alert safety agencies and beachgoers about the prolonged presence of these sharks at these locations, they also enabled investigations of local ecological conditions at the time the sharks were there. In both cases large schools of unidentified baitfish were observed and at the second (Ocean Reef) event, larger predators including skipjack tuna (*Katsuwonis pelamis*); Australian sea lions (*Neophoca cinerea*); bottlenose dolphins (*Tursiops aduncus*) and various seabirds were also present. Once these transient prey events passed, WA018 returned to Cockburn Sound where this shark was detected for a month before departing to Ningaloo Reef where WA020 was also next detected.

White sharks may also opportunistically take advantage of less predictable prey sources and may occur in relatively high numbers at different locations and times of year. Shortly after data were compiled for this report, six white sharks (2.1–3.9m FL) were caught around a highly unseasonal school of Australian salmon (*Arrips truttaceus*) at Mewstone Reef, 8km North of Garden Island during 3 (non-consecutive) days in August 2015. White sharks were also captured (for tagging) in relatively large numbers whilst scavenging humpback (*M. novaeangliae*) and sperm whale (*Physeter macrocephalus*) carcasses off the metropolitan (n=6), Albany (n=5) and Esperance (n=1) coasts. Observations of multiple sharks at most of these carcasses indicate that they may result in elevated shark encounter risks (depending on their proximity to water users). Monitoring of five sharks tagged at the site of a beached humpback carcass in Two Peoples Bay (25km East of Albany) between June and September 2010, revealed that tagged sharks continued to visit this location for up to 17 days (mean=6.6d) after the carcass had come ashore. However, these visits were typically brief (mean of 7h per day) and declined in frequency and duration over time. Presumably, these visitation patterns reflect sharks' diminishing interest in the scent from this carcass after repeated unsuccessful scavenging attempts. In recognition of the demonstrated association of white sharks with whale carcasses, the WA Government has implemented new policies regarding the management of dead whales and advising the public of potential associated shark hazards.

Although the data collected through the Shark Monitoring Network and associated OTN, AATAMS and DoF demersal scalefish research projects have rapidly and substantially improved understanding of white sharks' movement ecology in south-western Australian waters, it is not yet possible to explain or predict the specific patterns of individual shark movements. Based on the numbers of sharks detected, their detection frequencies, locations and times of year, these data suggest that the abundance, distribution and movements of white sharks in WA waters varies from one year to another. These results have, nonetheless, identified periods and locations where white sharks are more or less likely to occur and have begun to identify the range of ecological factors that may influence the probability of encountering this species off the WA coast. More detailed analyses of these data in relation to specific environmental parameters (e.g. ocean temperatures, circulation patterns, etc.), may help to further explain the patterns observed in this study.

4.2 Evaluation of safety benefits of near real-time tagged shark notifications

A wide range of strategies are currently and have previously been employed around the world to mitigate the risks posed by sharks to human safety. These strategies can broadly be categorised as: control (generally large-mesh gillnet and drum-line fishing); deterrence (e.g. electric, visual, chemical); exclusion (barriers, shark re-location) and monitoring. Because, the objectives, target species, geographic location, scale and duration of these programs are entirely different, it is difficult to directly compare the effectiveness of specific programs. However, the concurrent collection of acoustic telemetry and visual surveillance data in Western Australia since 2009, allows for direct comparison of these strategies.

Twenty satellite-linked Vemco VR4 Global (VR4G) receivers were gradually installed along the metropolitan coast (including offshore islands) between January 2009 and May 2010 and at key South-western locations between October 2013 and December 2014. Between the initial installation of three metropolitan receivers in 2009 and 1 July 2015, the SMN VR4G array has detected 3,139 tag transmissions from 73 different sharks on 372 different calendar days (500 shark days). These detections resulted in 2,748 notifications of identified and confirmed shark hazard events to public safety authorities (931 white, 1082 bronze whaler and 735 tiger shark notifications; Table 2). These detections and notifications were estimated to have represented 920 individual shark hazard events (see 2.4 for definition) identified by VR4G receivers. This number is very similar to the number of shark sightings by helicopter surveillance over the same period (n=961). While this is slightly less than the 1,046 sighting reports compiled from WA Police SMS records, the latter may contain duplicates and a large proportion of unconfirmed and/or of unidentified species and sizes.

Detections of known species and sizes of sharks provide a more certain basis for responding to potential hazards; plus, VR4G receivers operate 24 hours a day and 365 days a year. Thus, at monitored locations, VR4Gs provide the only means of detecting the presence of sharks during periods when aerial and shore-based surveillance programs are not operating. Similarly, VR4Gs operate during pre-dawn hours, when early morning swimmers and surfers may be in the water and when environmental conditions otherwise restrict sub-surface visibility, e.g. when the sea-breeze, storms and turbidity occur. A clear example of these benefits was during October 2012 when two tagged white sharks (WA018 and WA020) were detected 273 times over 5 days by the VR4G receiver at Ocean Reef. As these persistent detection sequences occurred in the days before the first spring weekend over which temperatures were forecasted to exceed 30^0C, they resulted in considerable media attention. However, despite nearly continual observation of this location by up to three separate news media helicopters, no sightings of either shark were reported, even while sharks were within range of the receiver, which was clearly visible from the air.

The standardised electronic data (tag and receiver serial numbers and time) transmitted by the VR4G system also provide beneficial options for rapidly notifying over one hundred safety officials and the public of verified shark hazard events in near to real-time. Because these data allow detections from less-hazardous species and sizes of sharks to be automatically filtered-out by SMN data-management systems, unnecessary reporting of those sharks can be avoided. Due to morphological similarities and difficulties in accurately identifying individual shark species and sizes (even for experienced fishers and observers), it is unsurprising that the majority of sighting reports (aerial and other) are of unidentified species. Even though aerial surveillance and public reporting programs are able to detect untagged sharks in areas that are not monitored by VR4G receivers, their ability to do so is affected by numerous environmental, observer and shark behavioural factors (Nardi and McAuley, 2008; Robbins et al., 2011). For example, in New South Wales, fixed-wing and helicopter observers respectively detected 12.5% and 17.1% of experimental plywood shark analogues located within 250m of flight paths, approximately half those rates at 300m and these shark-shaped targets could not be seen at all when they were positioned more than 2.7m below the surface (Robbins et al., 2011). Furthermore, there are multiple examples of reported shark sightings that were subsequently confirmed to be dolphins, pinnipeds (seals and sea lions), fish, innocuous shark species (particularly hammerheads) and rocks.

Despite the benefits of acoustic telemetry monitoring it is impossible to tag every shark or even the majority of potentially dangerous sharks that may be present off the Western Australian coast at any given time. Second, due to receivers' limited detection range; and the logistical constraints of maintaining this equipment in harsh nearshore environments, the geographic scale of near real-time acoustic monitoring is limited to individual beach locations. Therefore, individually, none of the surveillance methods currently employed in WA can reliably identify all shark hazards off the WA coast. Instead, as each method has particular strengths and weaknesses, the current mix of monitoring strategies that currently contribute to the identification of shark hazards off the Western Australian coast should be considered as complementary.

5 Conclusions

The Shark Monitoring Network project has successfully achieved its dual research and public safety goals. It has significantly improved the level of understanding of the movements of white sharks bronze whalers and tiger sharks in Western Australian waters and developed a new standard for deep-water acoustic receiver management. It has also provided hundreds of near real-time notifications of verified shark hazard events to enable pre-emptive public safety responses. Additionally, social media and interactive web-mapping have provided members of the public with a more reliable basis for understanding the likelihood of white sharks' presence off some of the State's most popular beaches. These originally-unanticipated functions have also addressed long-standing community requests for access to the latest scientific information about sharks' local behaviour and movements.

The acoustic telemetry approaches evaluated in this study have clear limitations in identifying shark hazards, as do all other currently-available monitoring methods. The SMN VR4G receiver network has, however, realised detection rates that are at least equivalent to other surveillance methods employed in WA with the added benefits of 24h year-round operation and immediate verification of sharks' species and sizes. Positive identification of shark hazards allows greater certainty in determining appropriate public safety responses and eliminates the risk of responding to false alarms.

Data collected during this study have revealed patterns in the occurrence and movements of white sharks that can inform public safety authorities and Government decision-makers about how encounter risks vary over time and by location. Given the results show that white sharks exhibit rapid, extensive and generally uncoordinated movements around the Western Australian coast, sharks' movement ecology remains a significant impediment to accurately predicting when, where and why people might encounter this species. Although white sharks tend to be highly mobile and transient through waters that are usually too far offshore to pose a significant risk to most water users, at times, some may come close to shore for periods of a few hours to a few weeks and, in some cases, even for a few months. As these patterns are not consistent among years it is unlikely that a greater period of data collection will generate an overall predictive model. The continued use of tagged sharks as 'proxies' for determining wider risk levels may prove to be a valuable component of the WA Government's overall shark hazard mitigation program.

6 Acknowledgements

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The implementation and continued development of this project would not have been possible without the hard work and considerable support of many colleagues and friends. In particular the authors very gratefully acknowledge the contribution of the WA Department of Fisheries' shark monitoring research team (Chris Dowling, Dani Waltrick de Souza, Lisa West, Rick Allison and Rod O'Halloran) plus a large number of staff from all sections of the agency both past and present who were instrumental for its success.

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The finalisation of the text for this report was aided by comments from many staff. Finally we thank all others that have been instrumental in bringing this project to completion.

7 Appendices

APPENDIX 1. Tagged bronze whaler and tiger shark detection statistics from combined (SMN, OTN and DoF demersal scalefish research) acoustic receiver arrays.

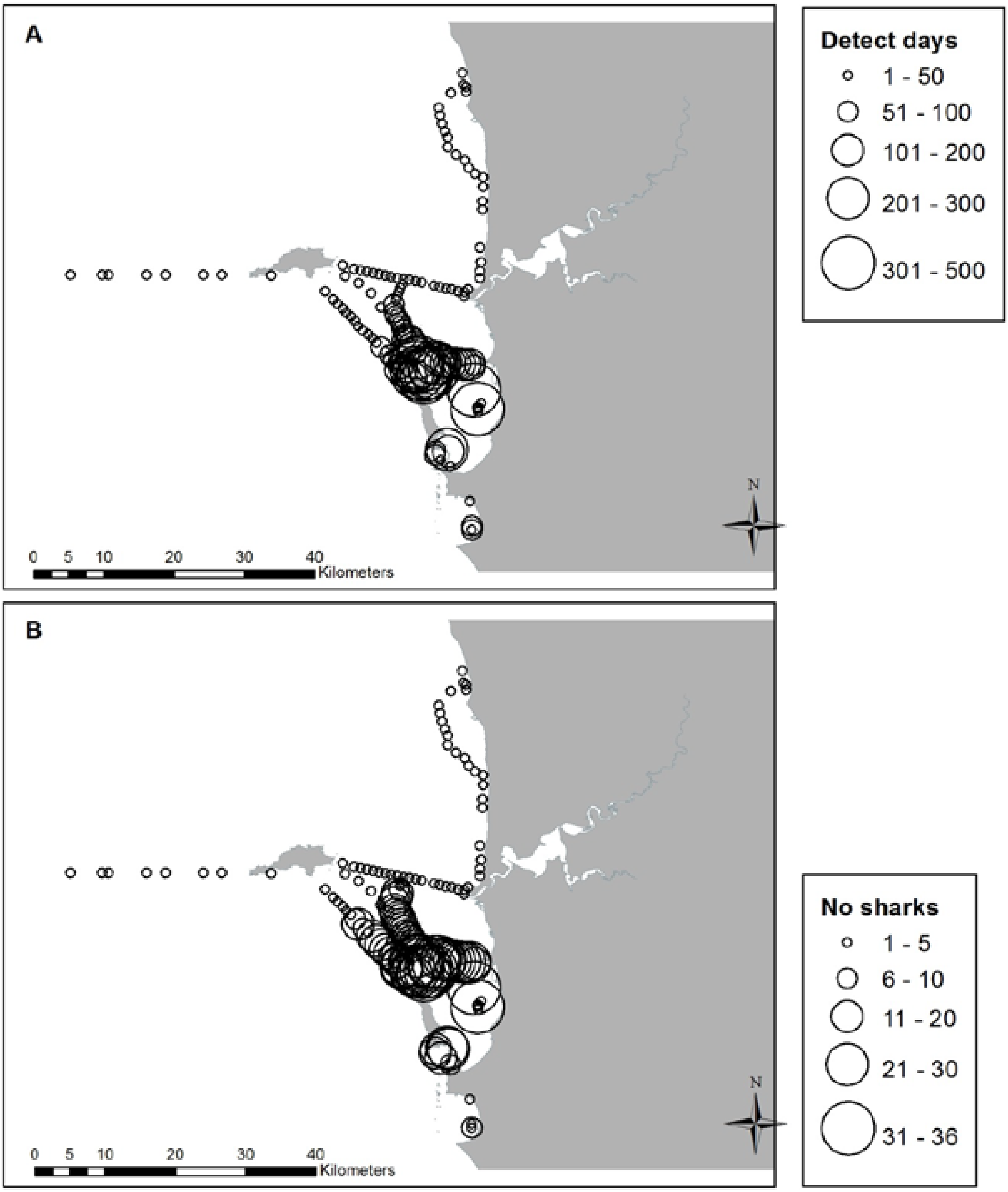


Figure A1.1. Bronze whaler sharks' (A) detection frequency (shark days) and (B) abundance (number of sharks) at Metropolitan (SMN and OTN) receivers.

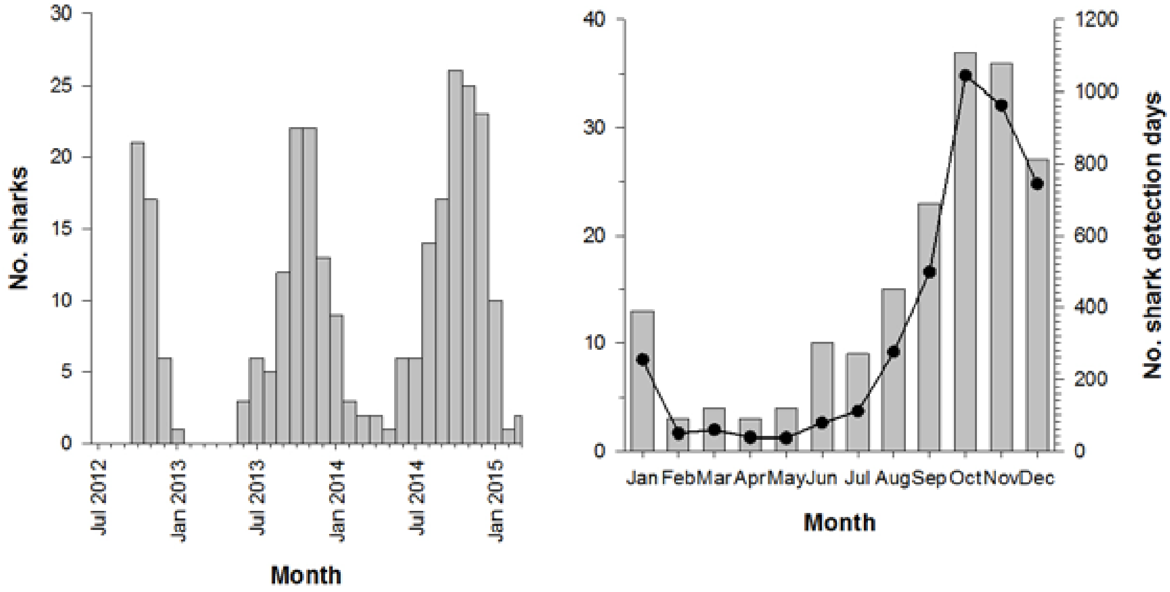


Figure A1.2. Abundance of tagged bronze whaler sharks detected by metropolitan acoustic receiver arrays (A) by month, July 2012 – June 2015 (inclusive) and (B) pooled all years (left axis) and detection frequency (shark days, right axis).

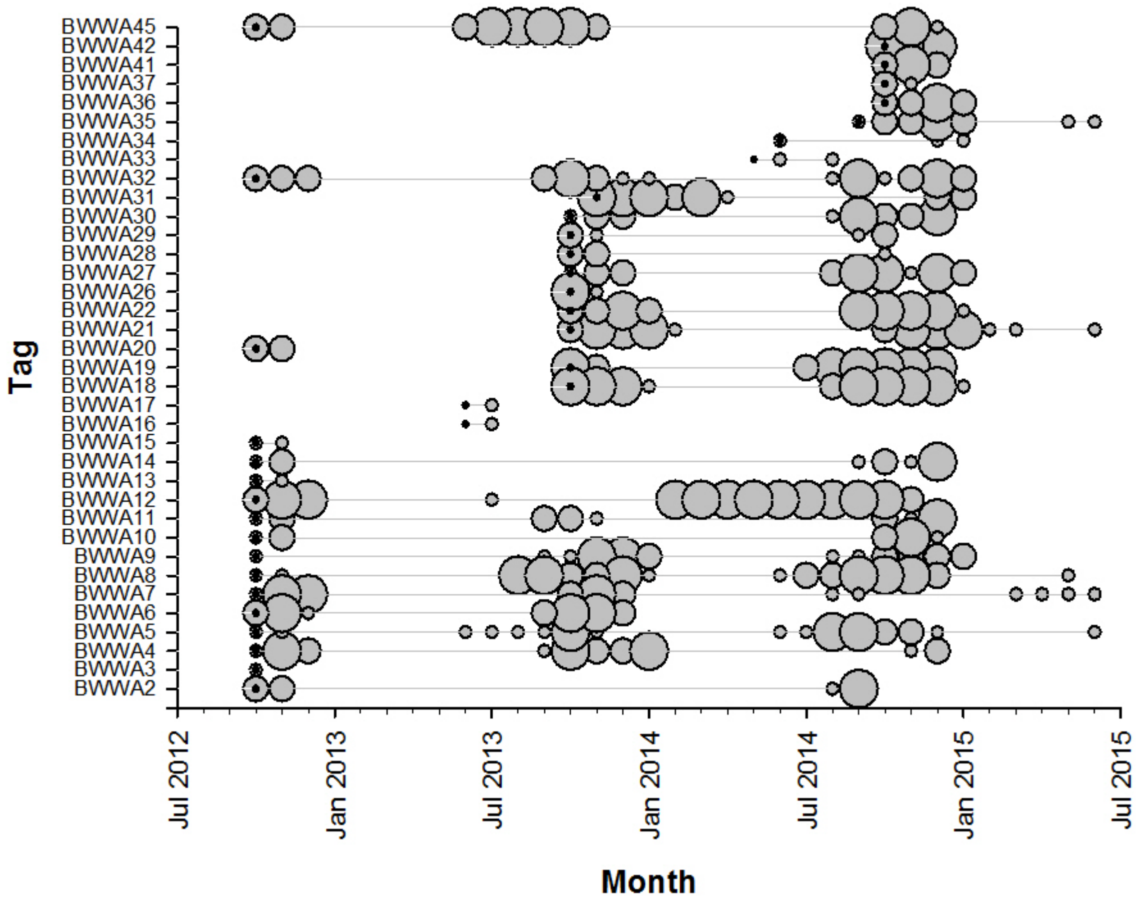


Figure A1.3. Individual bronze whaler sharks' metropolitan detection histories. Circle diameter indicates the number of detection days per month (dm^{-1}): ○= less than $10dm^{-1}$; ○= 10-19 dm^{-1}; ○: 20-30 dm^{-1}; •: initial tag release date.

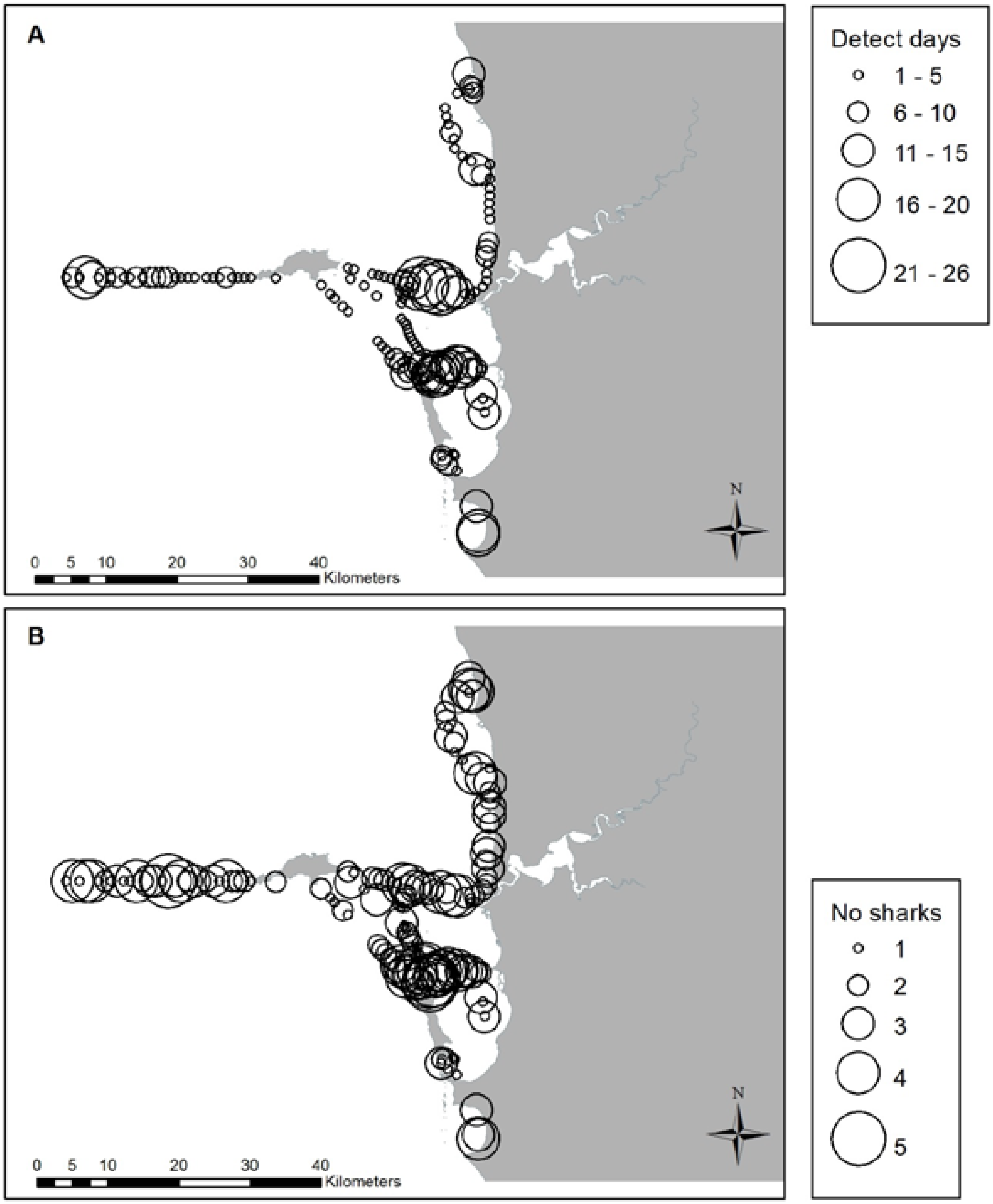


Figure A1.4. Tiger sharks' (A) detection frequency (shark days) and (B) abundance (number of sharks) at Metropolitan (SMN and OTN) receivers.

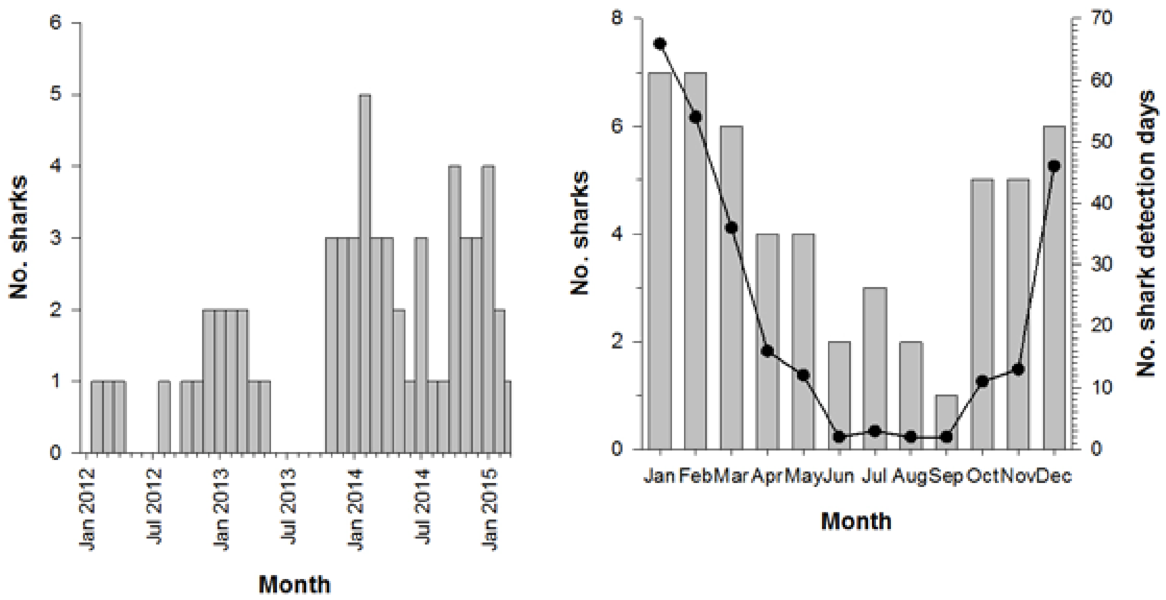


Figure A1.5. Abundance of tagged tiger sharks detected by metropolitan acoustic receiver arrays (A) by month, July 2012 – June 2015 (inclusive) and (B) pooled all years (left axis) and detection frequency (shark days, right axis).

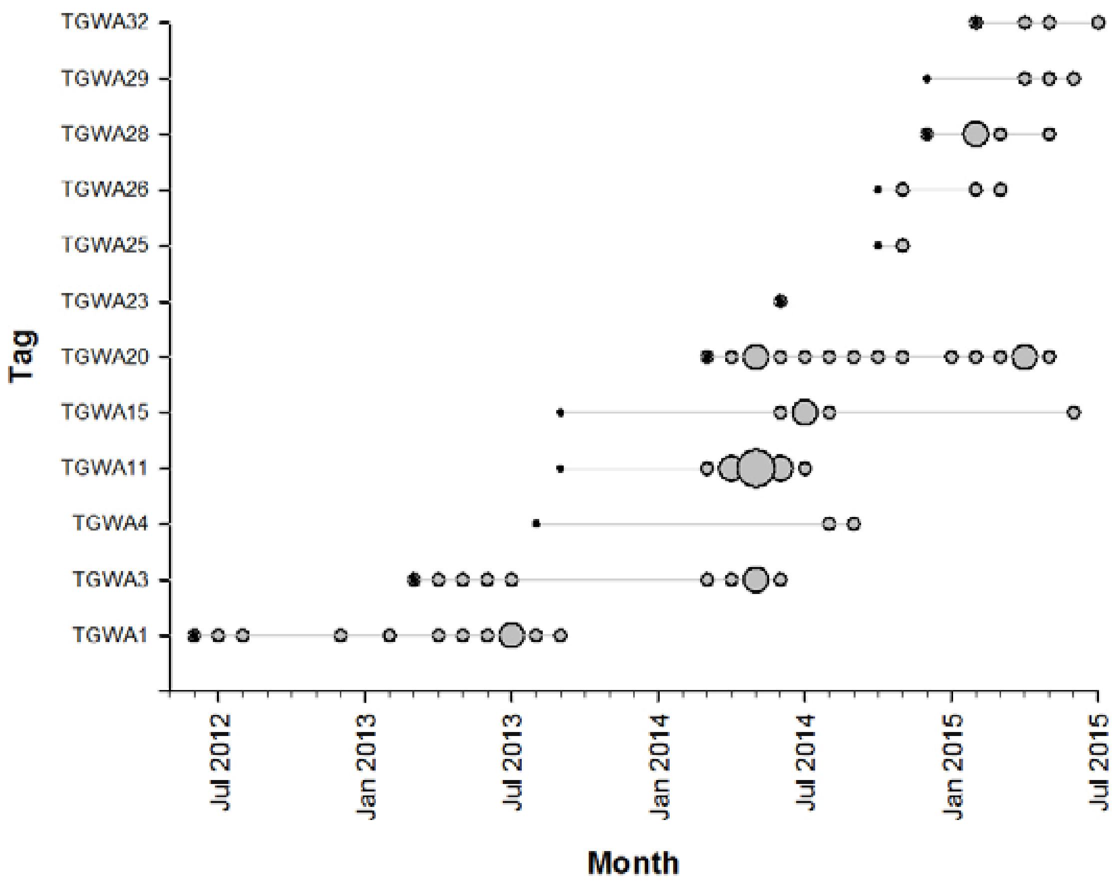


Figure A1.6. Individual metropolitan detection histories of tagged tiger sharks. Circle diameter indicates the number of detection days per month (dm^{-1}): ○ = less than $10dm^{-1}$; ○ = 10-19 dm^{-1}; ◯ = 20-30 dm^{-1}; •: initial tag release date.

APPENDIX 2. Notification frequencies and numbers of sharks detected by VR4G receivers

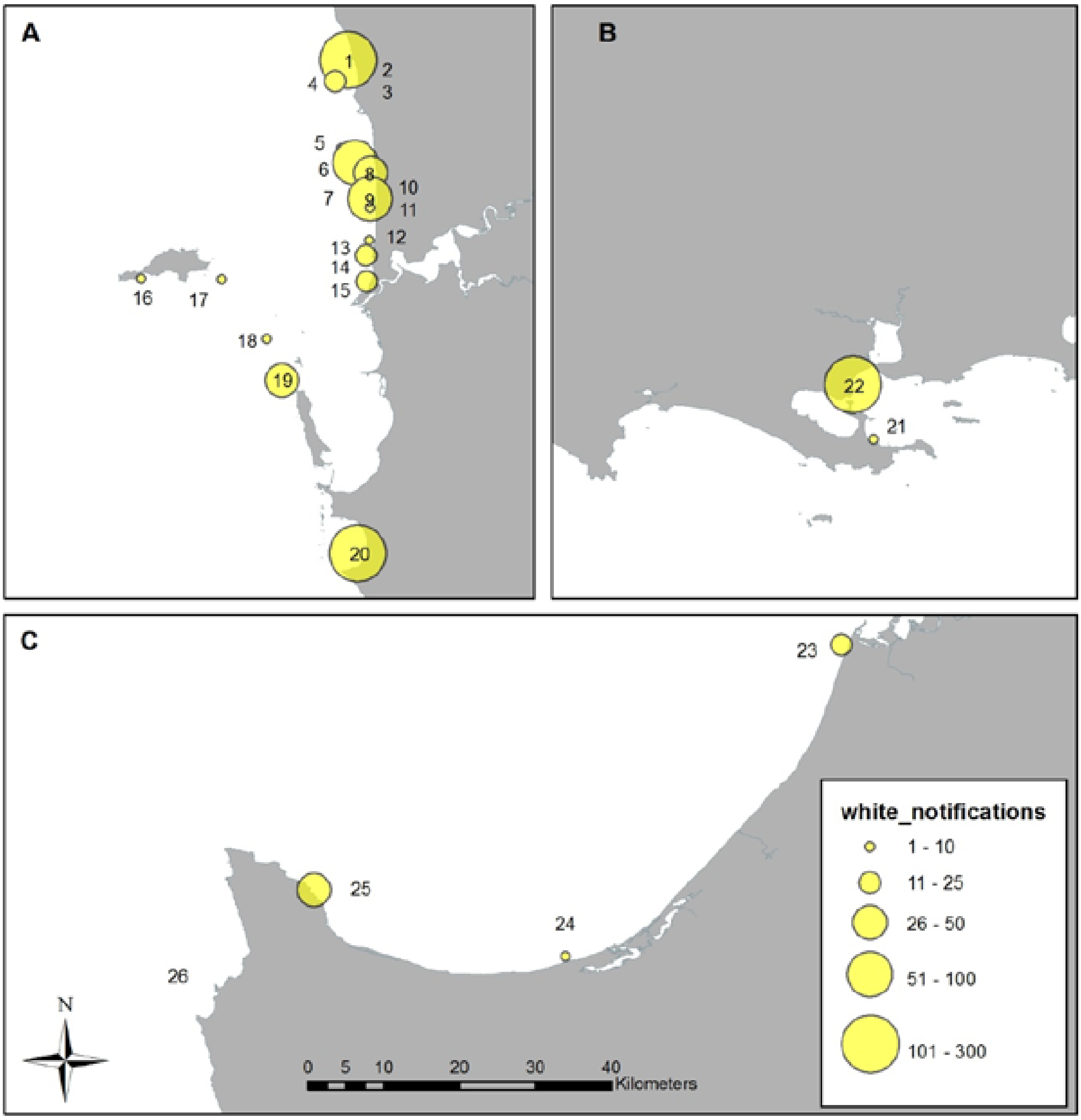


Figure A2.1. Relative frequencies of white shark notifications by VR4G receivers in (A) the metropolitan, (B) Albany and (C) Geographe Bay-Capes regions. Numerical labels in or beside receiver locations indicate receiver number for reference to Table 3.

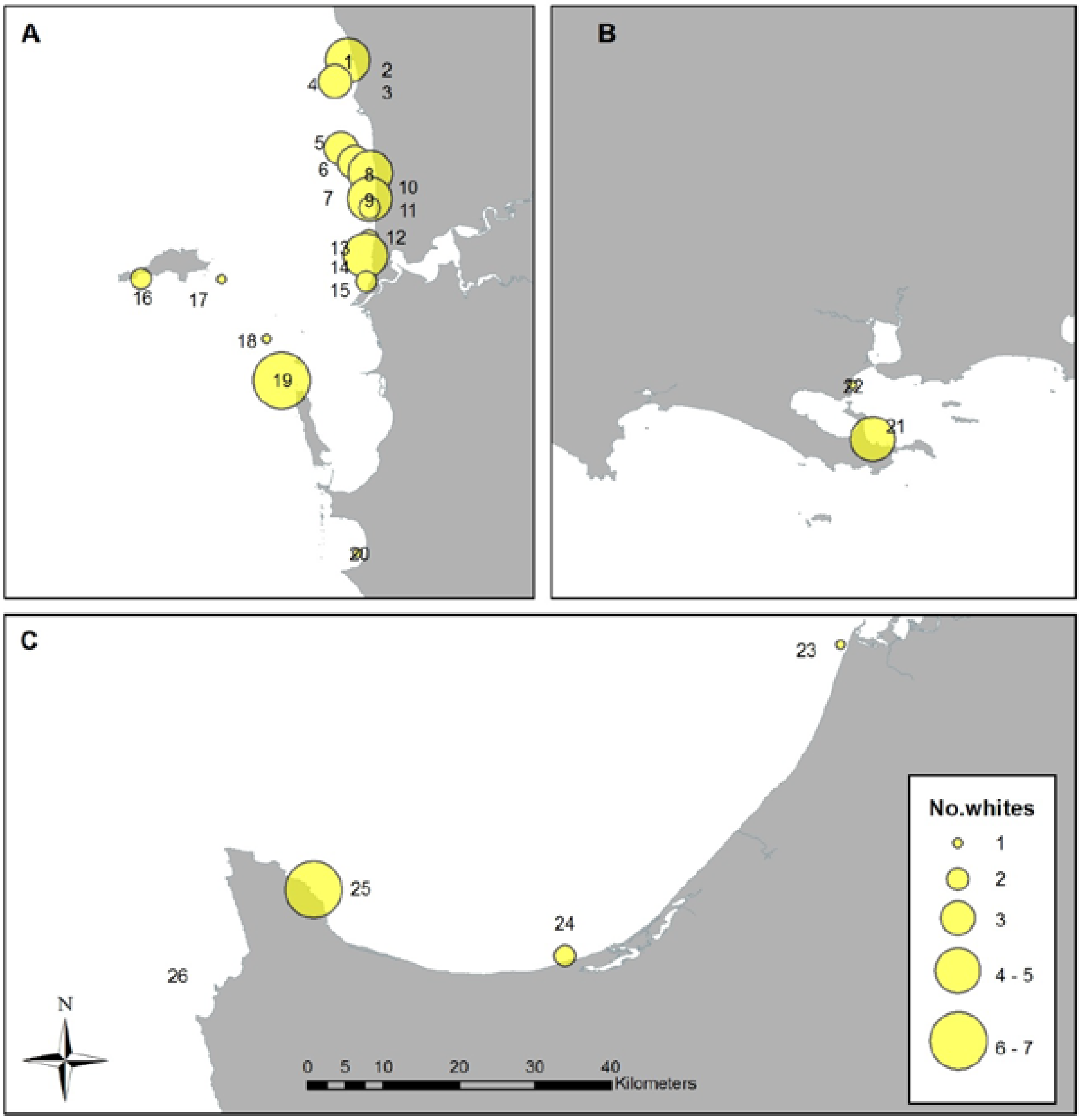


Figure A2.2. Number of white sharks detected by VR4G receivers in (A) the metropolitan, (B) Albany and (C) Geographe Bay-Capes regions. Numerical labels in or beside receiver locations indicate receiver number for reference to Table 3.

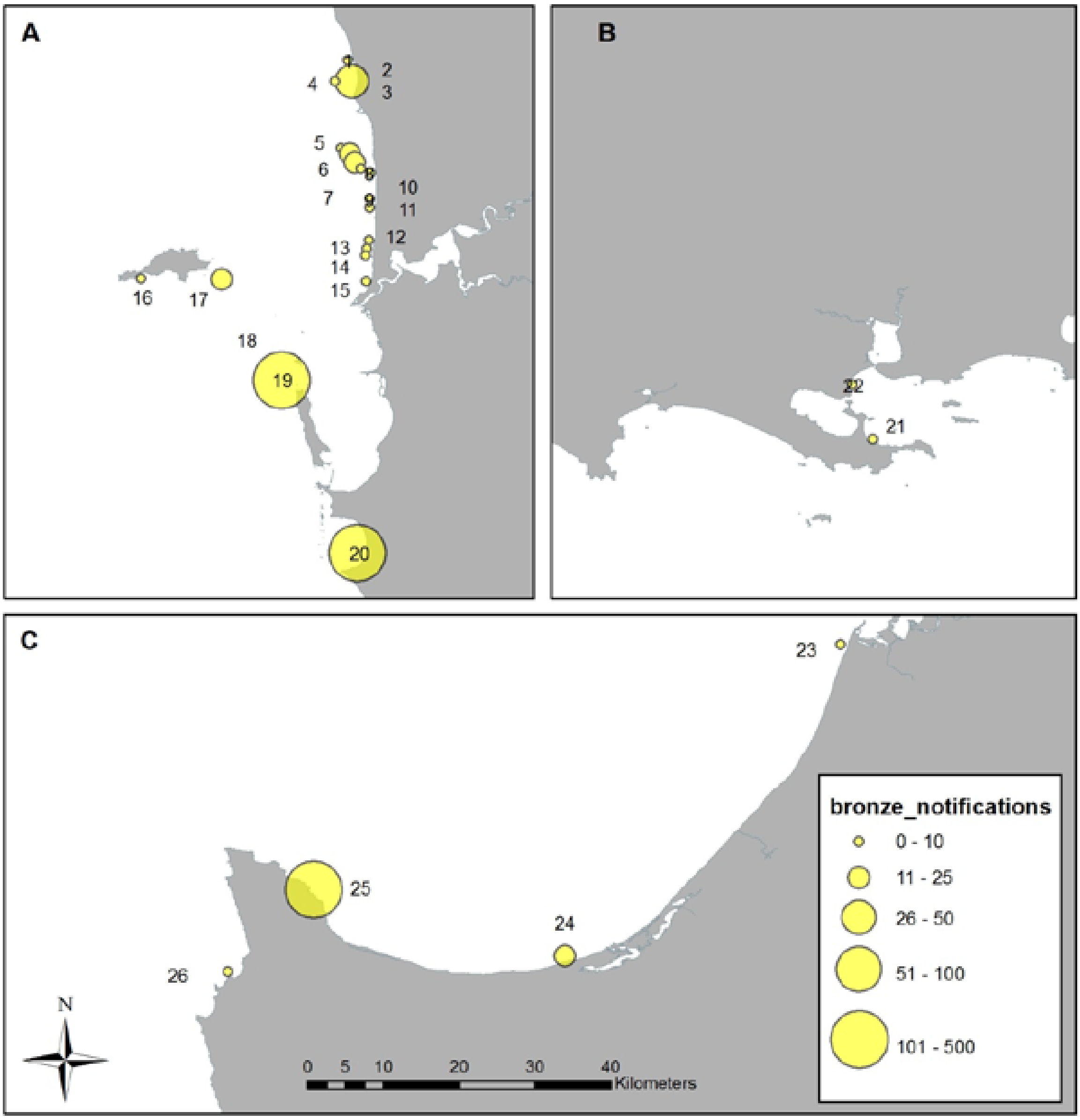


Figure A2.3. Relative frequencies of bronze whaler shark notifications by VR4G receivers in (A) the metropolitan, (B) Albany and (C) Geographe Bay-Capes regions. Numerical labels in or beside receiver locations indicate receiver number for reference to Table 3.

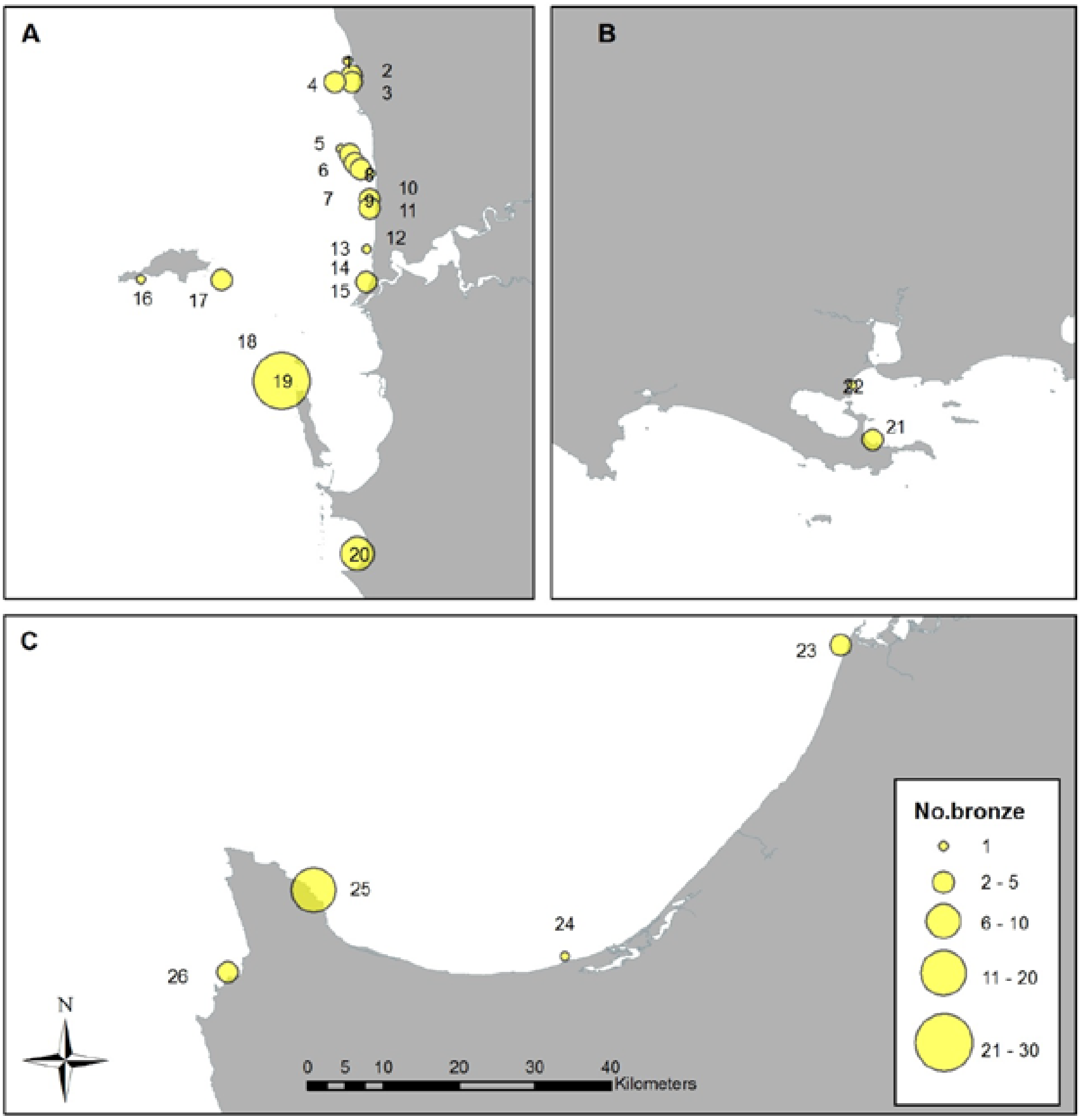


Figure A2.4. Number of bronze whaler sharks detected by VR4G receivers in (A) the metropolitan, (B) Albany and (C) Geographe Bay-Capes regions, since acoustic tagging of bronze whaler sharks commenced in 2012. Numerical labels in or beside receiver locations indicate receiver number for reference to Table 3.

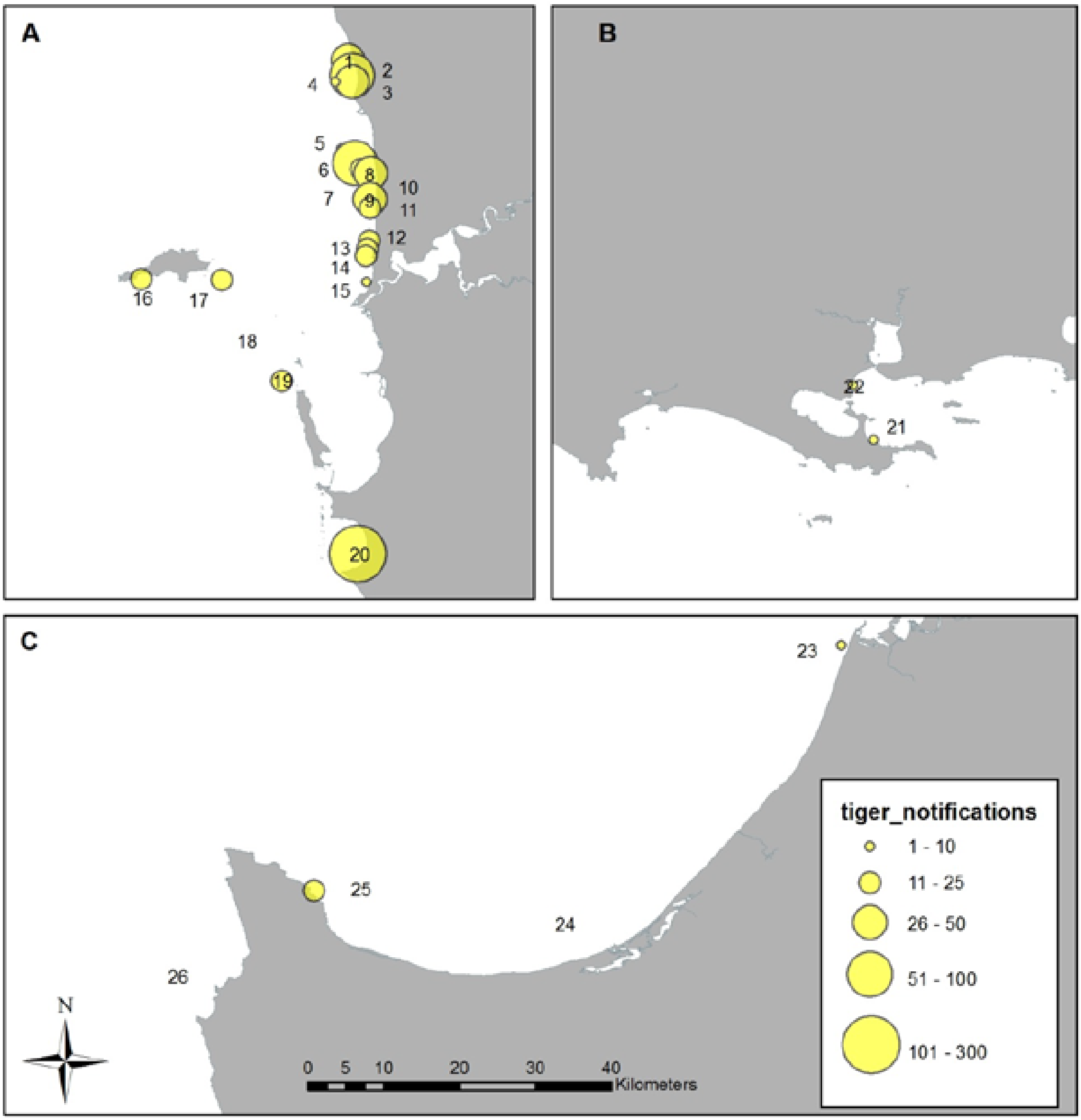


Figure A2.5. Relative frequencies of tiger shark notifications by VR4G receivers in (A) the metropolitan, (B) Albany and (C) Geographe Bay-Capes regions. Numerical labels in or beside receiver locations indicate receiver number for reference to Table 3.

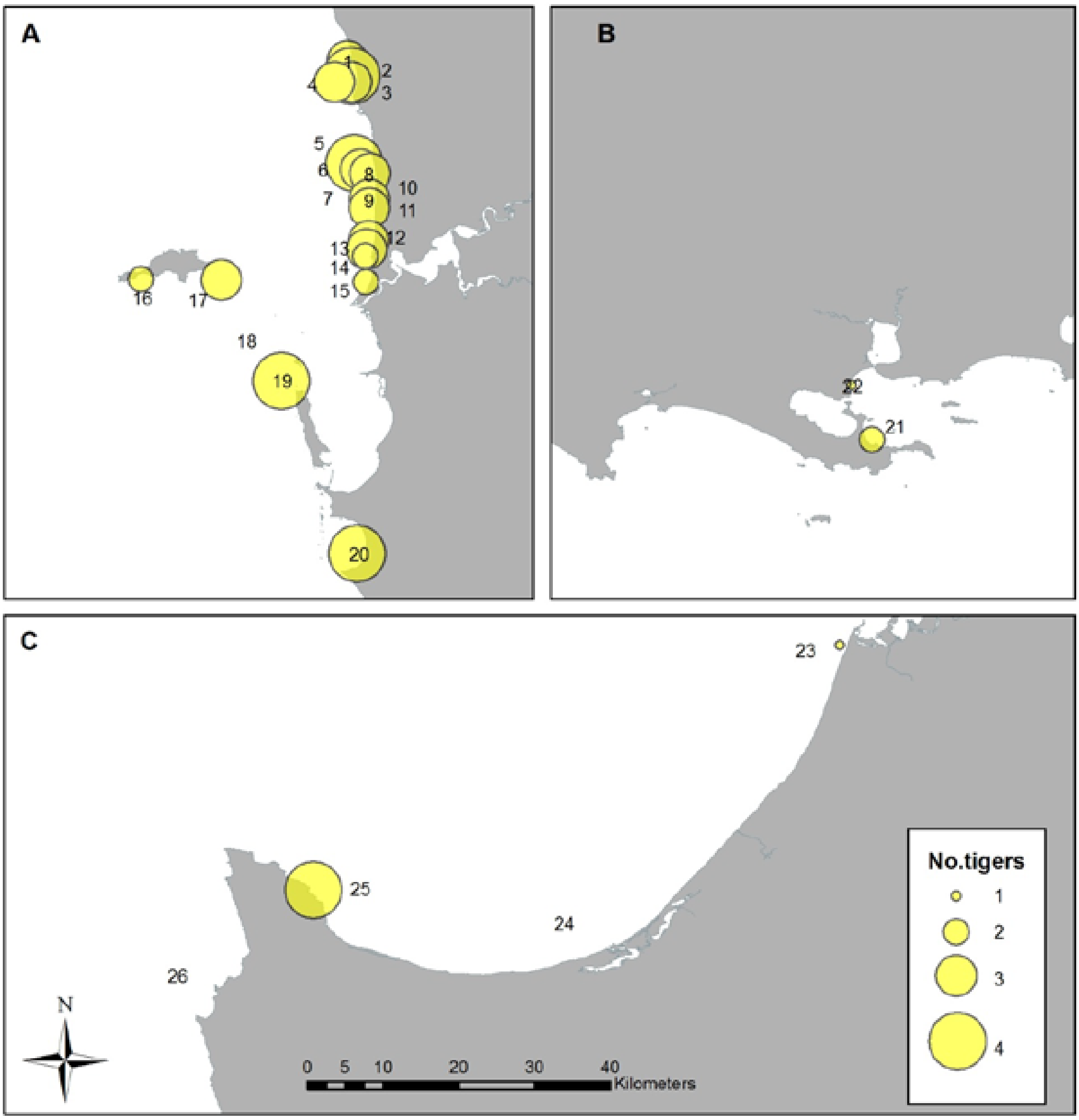


Figure A2.6. Number of tiger sharks detected by VR4G receivers in (A) the metropolitan, (B) Albany and (C) Geographe Bay-Capes regions, since acoustic tagging of tiger sharks commenced in 2012. Numerical labels in or beside receiver locations indicate receiver number for reference to Table 3.

APPENDIX 3. Bronze whaler and tiger shark detections in south-western regional arrays

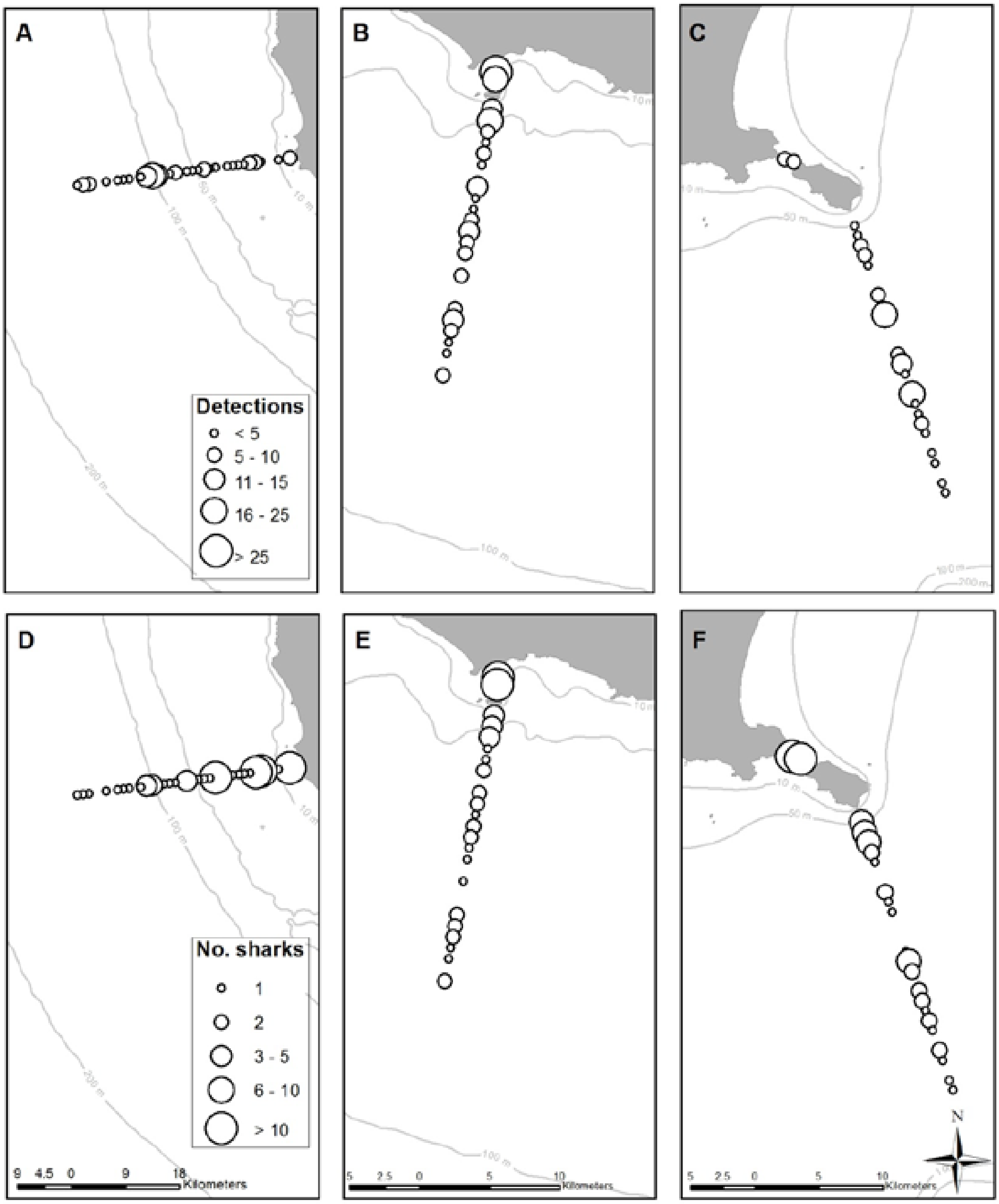


Figure A3.1. Bronze whaler sharks' detection frequency (no. detections) at the (A) Hamelin Bay; (B) Chatham Island and (C) Bald Island arrays and abundance (number of sharks) at (D) Hamelin Bay; (E) Chatham Island and (F) Bald Island arrays. Detection symbol values given in upper left hand panel are for (A) – (C) and No. sharks symbol values given in lower left hand panel are for (D) – (F). NB tagged shark deployments, deaths and SA detections are not included in this table.

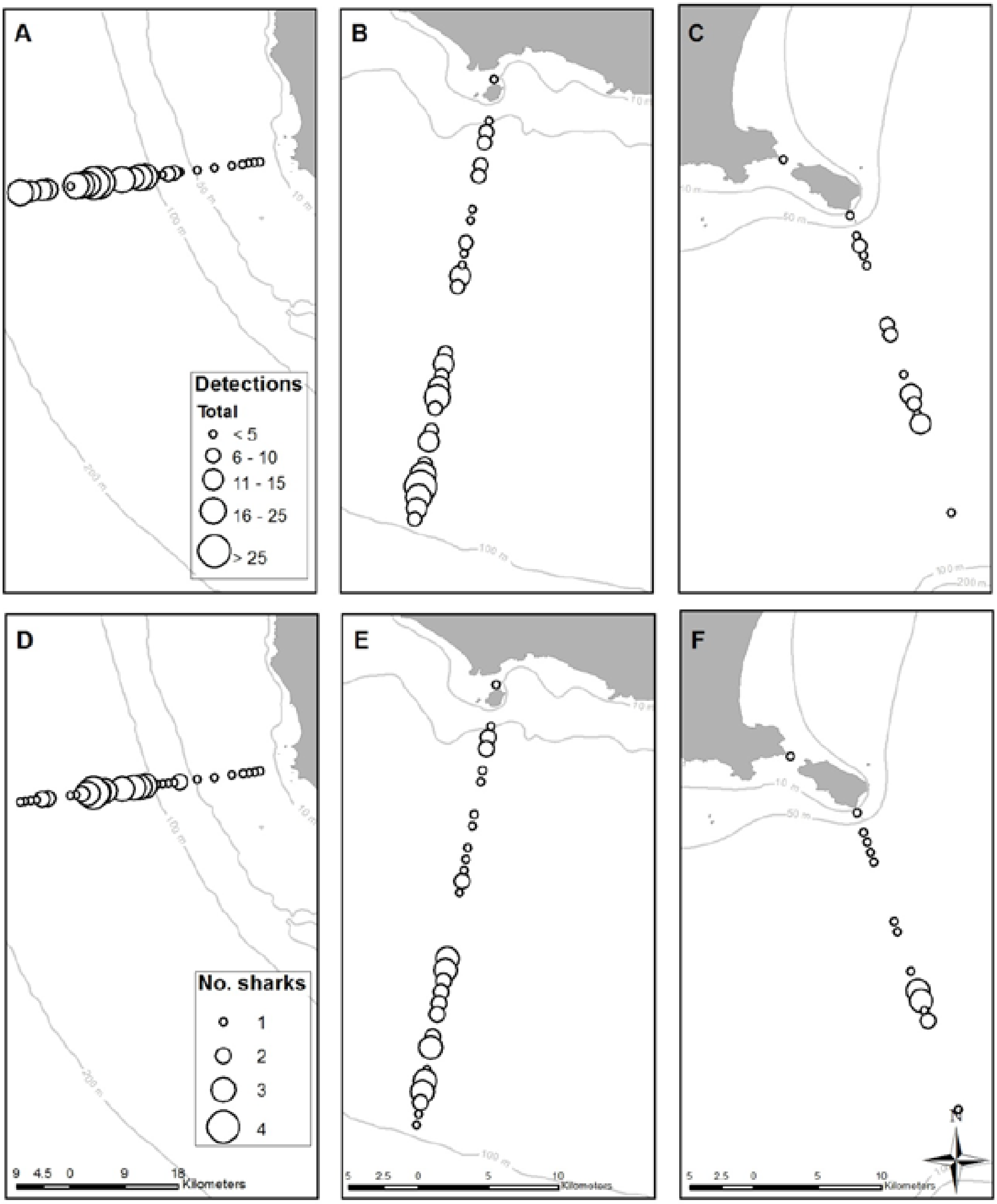
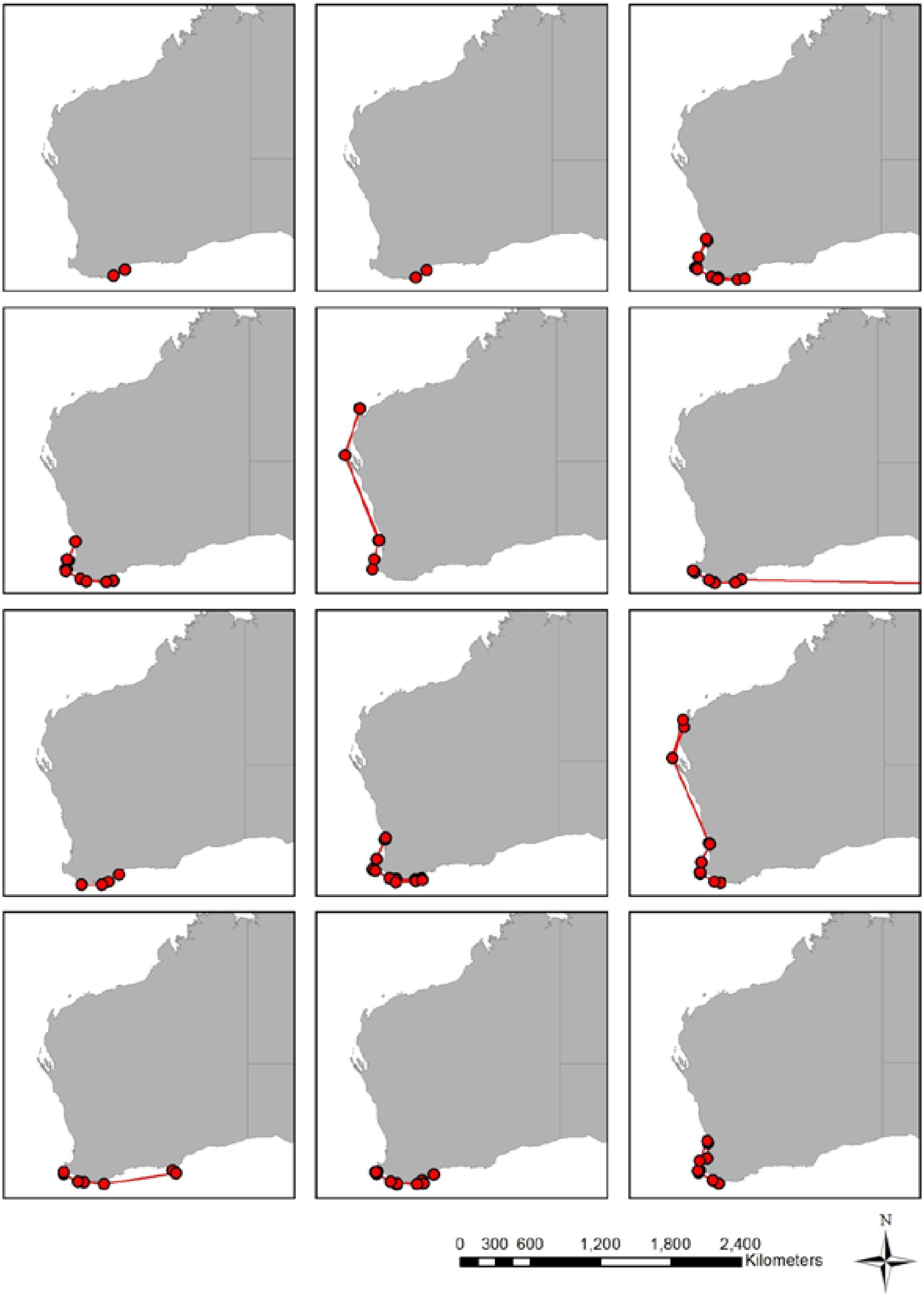
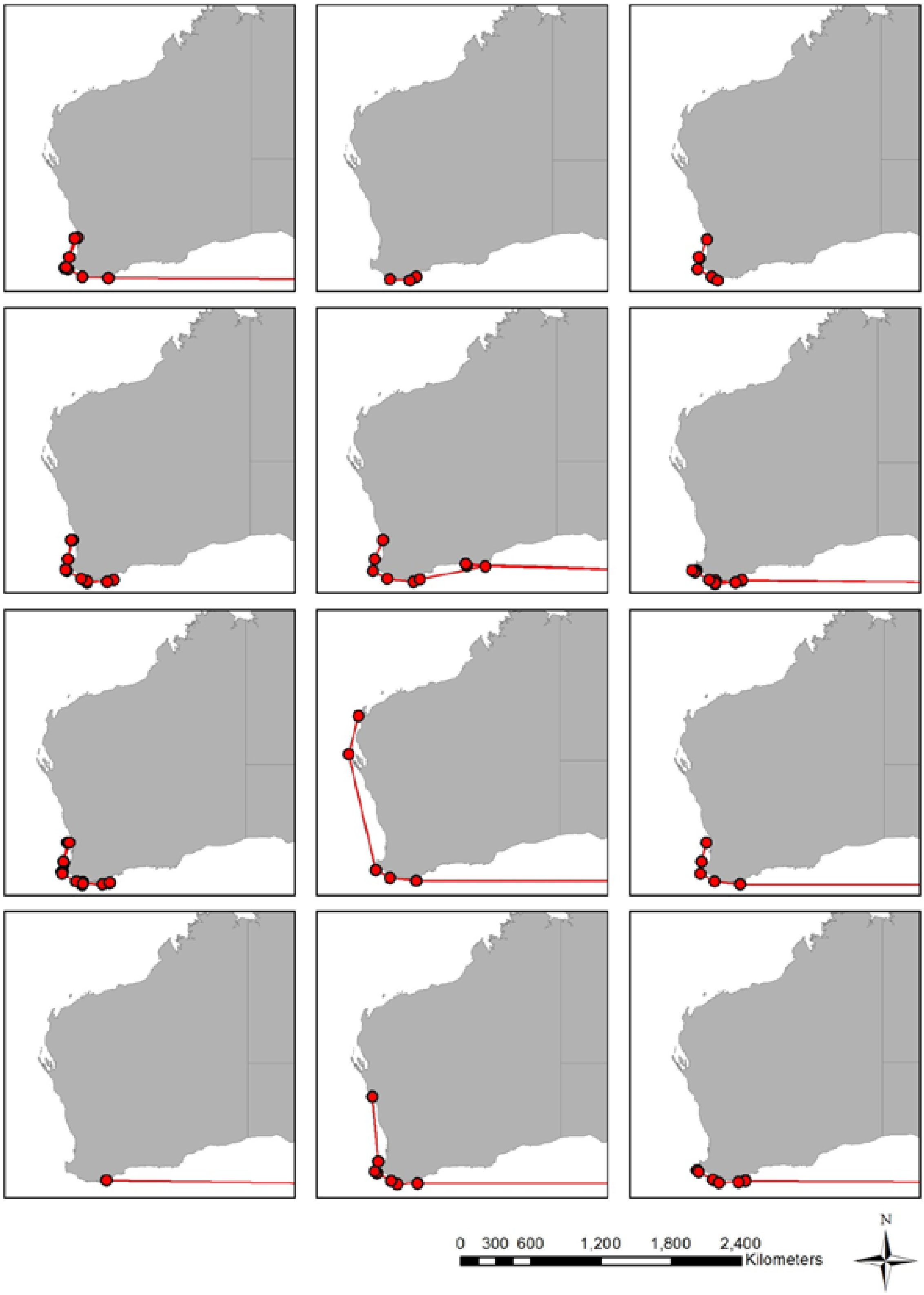


Figure A3.2. Tiger sharks' detection frequency (no. detections) at the (A) Hamelin Bay; (B) Chatham Island and (C) Bald Island arrays and abundance (number of sharks) at (D) Hamelin Bay; (E) Chatham Island and (F) Bald Island arrays. Detection symbol values given in upper left hand panel are for (A) – (C) and No. sharks symbol values given in lower left hand panel are for (D) – (F). NB tagged shark deployments, deaths and SA detections are not included in this table.

APPENDIX 4. Displacement vectors (n=211) of 51 white sharks.



Movements shown are for shark IDs (from top left to bottom right panels): WA033, WA036, WA042, WA039, WA019, SA118, WA034, WA013, WA018, WA022, WA038, WA027



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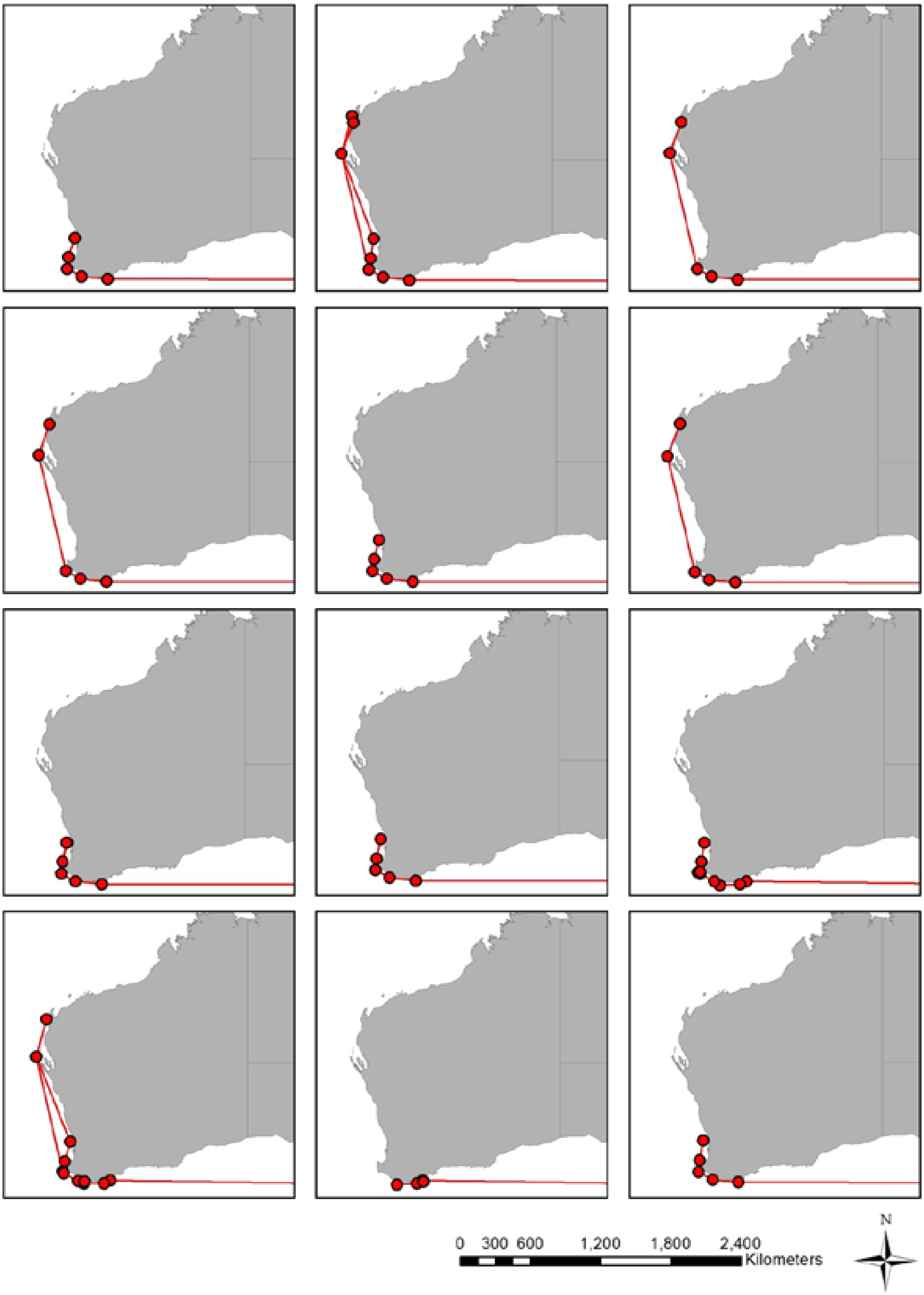
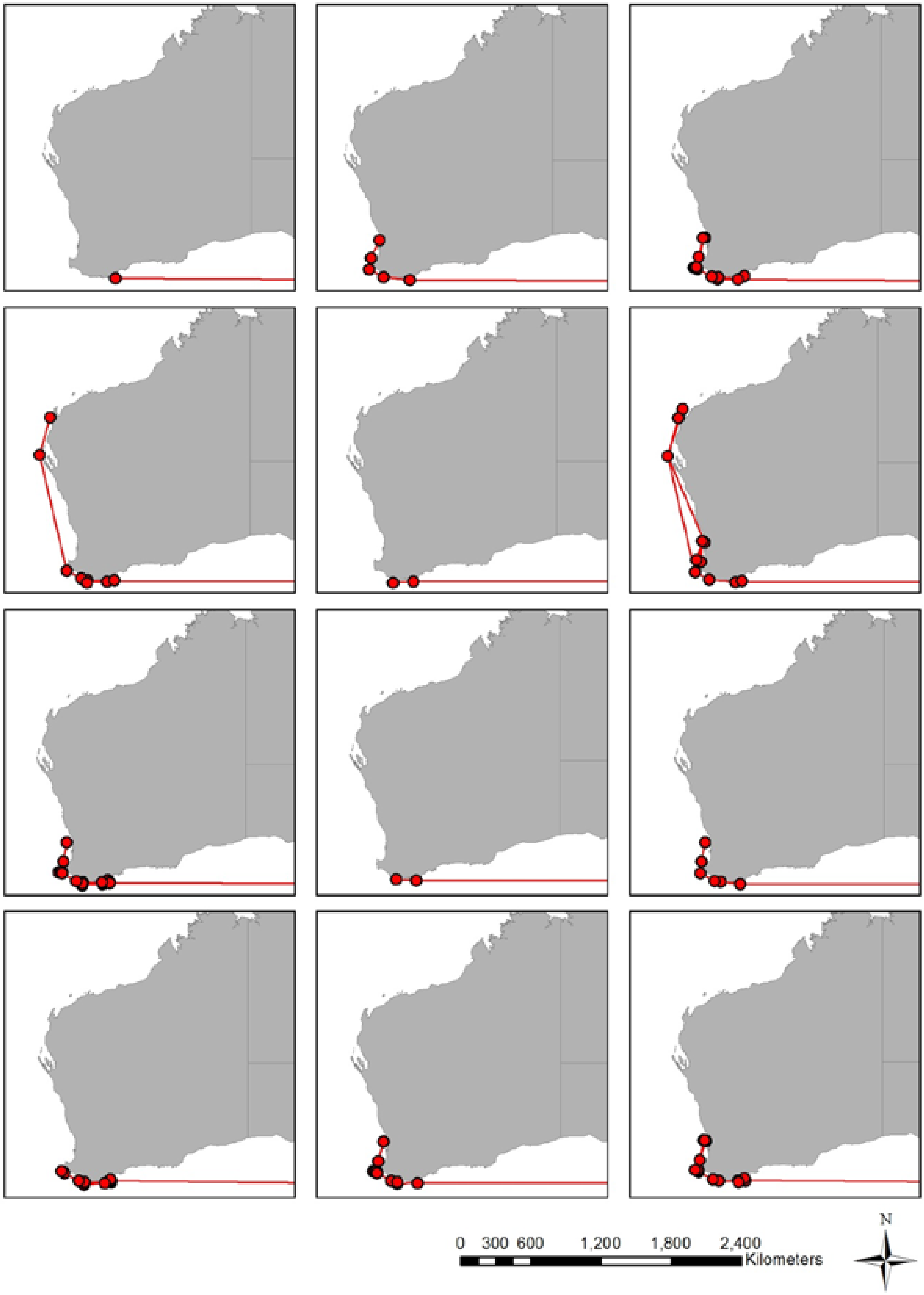
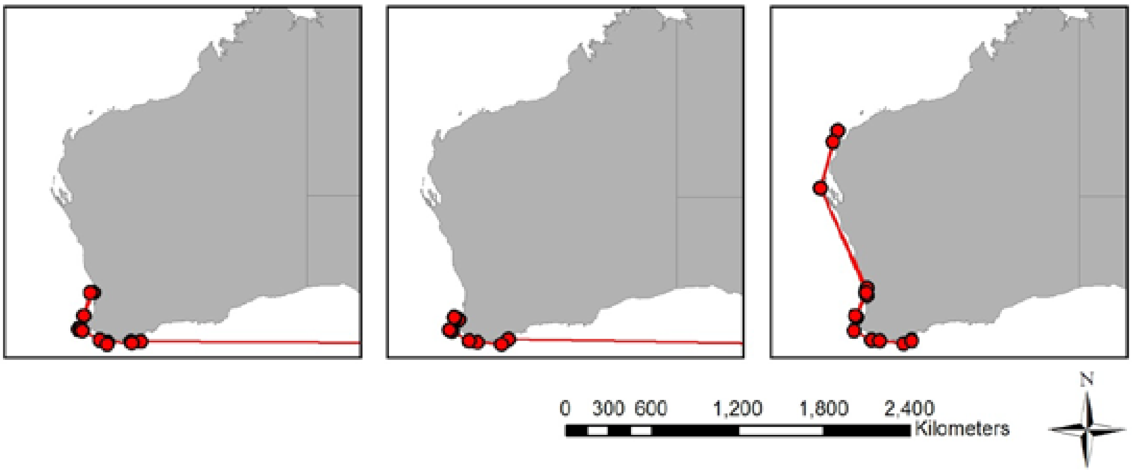


Movements shown are for shark IDs (from top left to bottom right panels): SA049, SA054, SA055, SA057, SA062, SA064, SA071, SA087, SA099, SA084, SA078, SA081



Movements shown are for shark IDs (from top left to bottom right panels): SA102, SA103, SA108, SA109, SA117, SA121, SA125, SA134, SA141, SA133, SA126, SA132



Movements shown are for shark IDs (from left to right panels): SA142, SA145, WA020

8 References

Abecassis, M, Dewar, H., Hawn, D. and Polovina, J. 2012. Modeling swordfish daytime vertical habitat in the North Pacific Ocean from pop-up archival tags. Marine Ecology Progress Series **452:** 219–236

Anderson, S. D., and P. Pyle. 2003. A temporal, sex specific occurrence pattern among white sharks at the South Farallon Islands, California. California Fish and Game **89**: 96–101

ASAF. 2015. Australian Shark Attack File (ASAF). Taronga Conservation Society Australia. Mosman, Australia.

Blower, D. C., J. M. Pandolfi, B. D. Bruce, M. D. Gomez-Cabrera, and J. R. Ovenden. 2012. Population genetics of Australian white sharks reveals fine-scale spatial structure, transoceanic dispersal events and low effective population sizes. Marine Ecology Progress Series **455**: 229–244.Bonfil et al. 2005

Bonfil, R., M. Meÿer, M. C. Scholl, R. Johnson, S. O’Brien, H. Oosthuizen, S. Swanson, D. Kotze, and M. Paterson. 2005. Transoceanic migration, spatial dynamics, and population linkages of white sharks. Science (New York, N.Y.) **310**: 100–3

Boustany, A. M., S. F. Davis, P. Pyle, S. D. Anderson, B. J. Le Boeuf, and B. A. Block. 2002. Expanded niche for white sharks. Nature **415**:35–36

Bradford, R.W., Bruce, B.D., McAuley, R.B. and Robinson, G. 2011. An Evaluation of Passive Acoustic Monitoring Using Satellite Communication Technology for Near Real-Time Detection of Tagged Animals in a Marine Setting. The Open Fish Science Journal, 2011, 4: 10-20

Bradford, R. W., B. D. Bruce, and A. Hobday. 2012. Identifying juvenile white shark behaviour from electronic tag data. Pages 255–270 in M. Domeier, editor. Global perspectives on the biology and life history of the white shark. CRC Press, Boca Raton, FL.

Bruce, B. D. 1992. Preliminary observations on the biology of the White Shark, Carcharodon carcharias , in South Australian waters. Marine and Freshwater Research 43:1

Bruce, B. D. 2008. White sharks: the biology and ecology of *Carcharodon carcharias*. Pages 69–81 in E. Pikitch and M. Camhi, editors. Sharks of the Open Ocean. Blackwell Scientific

Bruce, B and Stevens, J. 2004. Tracking the movement patterns of large white sharks in Australian waters. Final report to: AQWA – the Aquarium of Western Australia + the AQWA Research Foundation. CSIRO Marine Research, Hobart. May 2004. 25pp

Bruce, B.D. and Bradford, R.W. 2012. Habitat use and spatial dynamics of juvenile white sharks, Carcharodon carcharias, in eastern Australia. Pages 225–254 in M. L. Domeier, editor. Global perspectives on the biology and life history of the white shark. CRC Press, Taylor & Francis Group, Boca Raton, FL.

Bruce, B.D. and Bradford, R.W. 2013. The effects of shark cage-diving operations on the behaviour and movements of white sharks, Carcharodon carcharias, at the Neptune Islands, South Australia. Marine Biology 160:889–907;

Bruce, B. D. and Bradford, R. W. (2015). Segregation or aggregation? Sex-specific patterns in the seasonal occurrence of white sharks at the Neptune Islands, South Australia. Journal of Fish Biology 87: 1355–1370.Bruce, B.D., Stevens, J.D. and Bradford, R.W. 2005a. Identifying movements and habitats of white sharks and grey nurse sharks. Final report to Department of Environment and Heritage. CSIRO Hobart.

Bruce, B. D., Stevens, J. D. and Bradford, R. W. 2005b. Site fidelity, residence times and home range patterns of white sharks around pinniped colonies. Page 41. Final report to Department of Environment and Heritage. CSIRO Hobart.

Bruce, B. J., Stevens, J.D. and Malcolm, H. 2006. Movements and swimming behaviour of white sharks (*Carcharodon carcharias*) in Australian waters. Marine Biology **150**:161–172. Springer Berlin / Heidelberg.

Carey, F. G., J. G. Casey, H. L. Pratt Jr., D. Urquhart, and J. E. McCosker. 1985. Temperature, heat production and heat exchange in lamnid sharks. Memoirs of the Southern California Academy of Sciences **9**:92–108

Casey, J.G. and Pratt, H.L. Jr. 1985. Distribution of the white shark, *Carcharodon carcharias*, in the western North Atlantic. Memoirs of the Southern California Academy of Sciences **9**:2–14

Cliff, G., Dudley, S.F.J. and Fry, M.R. 1996. Catches of white sharks in KwaZulu-Natal, South Africa and environmental influences. Pages 351–362 in A. P. Klimley and D. G. Ainley, editors. Great white sharks: the biology of Carcharadon carcharias. Academic press, San Diego, CA.

Compagno, L. J. V. 2001. Sharks of the World. An annotated and illustrated guide of the shark species known to date. Volume 2. Bullhead, mackerel and carpet sharks (Heterodontiformes, Lamniformes and Orectolobiformes). FAO species catalogue for fishery purposes. FAO Rome.

DoF, 2004. Review and Recommendations on Shark Hazard Mitigation Activities in Western Australia. Shark Hazard Committee. August 2004. Unpublished report, Department of fisheries, Perth Western Australia.

DoF, 2012. A correlation study of the potential risk factors associated with white shark attacks in Western Australian waters. November 2012. Fisheries Occasional Publication No. 109, 2012. Department of fisheries, Perth. Western Australia.

DoF., 2014. Catch data for shark drum line deployment 25 Jan 14 to 30 Apr 14. Department of fisheries, Perth Western Australia. http://www.fish.wa.gov.au/Education-and-Partnerships/Shark-Hazard/shark-response-unit/Pages/Shark-Drum-Line-Deployment.aspx

Domeier, M. L., and N. Nasby-Lucas. 2008. Migration patterns of white sharks *Carcharodon carcharias* tagged at Guadalupe Island, Mexico, and identification of an eastern Pacific shared offshore foraging area. Marine Ecology-Progress Series **370**:221–237

Domier, M. L., Nasby-Lucas, N. and Lam, C. H. 2012. Fine-scale habitat use by white sharks at Guadalupe Island, Mexico. Pages 121–132. Global perspectives on the biology and life history of the white shark. CRC Press, Boca Raton, FL.

Duffy, C., M. Francis, M. Manning, and Bonfil., R. 2012. Regional population connectivity, oceanic habitat, and return migration revealed by satellite tagging of white sharks, *Carcharodon carcharias*, at New Zealand aggregation sites. Pages 301–318 Global perspectives on the biology and life history of the white shark. CRC Press, Boca Raton, FL.

Environment Australia. 2002. White Shark (*Carcharodon carcharias*) Recovery Plan. July 2002.

Francis, B. 2011. Before and after Jaws: changing representations of shark attacks. Honours thesis, Murdoch University, Western Australia.

Gallen, C., Bruce, B. and Harasti., D. 2013. Knowledge review and gap identification for juvenile white sharks in coastal waters of the Northern Rivers Catchment Management Authority

Green, M., Ganassin, C. and Reid, D. 2009. Report into the New South Wales shark meshing (bather protection) program. Page 142

Gubili, C., R. Bilgin, E. Kalkan, S. U. Karhan, C. S. Jones, D. W. Sims, H. Kabasakal, A. P. Martin, and L. R. Noble. 2011. Antipodean white sharks on a Mediterranean walkabout? Historical dispersal leads to genetic discontinuity and an endangered anomalous population. Proceedings of the Royal Society Biological Sciences **278**:1679–1686

Gubili, C., Duffy, C. A. J., Cliff, G., Wintner, S. P., Shivji, M., Chapman, D., Bruce, B. D., Martin, A. P., Sims, D. W., Jones, C. S. and Noble, L. R. 2012. Application of molecular genetics for conservation of the great white shark, *Carcharodon carcharias*, L. 1758. Pages 357–380 in M. Domeier, editor. Global perspectives on the biology and life history of the white shark. CRC Press, Boca Raton, FL.

Heupel, M.R. and Hueter, R.E.(2001).Use of a remote acoustic telemetry system to monitor shark movements in a coastal nursery area; in *Electronic Tagging and Tracking in Marine Fisheries*, eds J.R. Sibert and J.L. Nielsen (Dordrecht: Kluwer Academic Publishers), 217–236.

Huveneers, C., Rogers, P. J., Beckmann, C., Semmens, J. M., Bruce, B. D., Seuront, L. 2013. The effects of cage-diving activities on the fine-scale swimming behaviour and space use of white shark. Marine Biology **160**: 2863–2875.

Huveneers, C., Rogers, P. J., Drew, M. 2014. Monitoring shark species of conservation concern within the Adelaide metropolitan and Gulf St Vincent regions. Final Report to the Adelaide & Mount Lofty Ranges Natural Resources Management Board. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2013/000716-1. SARDI Research Report Series No. **754**. 89 pp.

Jorgensen, S. J., N. S. Arnoldi, E. E. Estess, T. K. Chapple, M. Rückert, S. D. Anderson, and B. A. Block. 2012. Eating or meeting? Cluster analysis reveals intricacies of white shark (*Carcharodon carcharias*) migration and offshore behavior. PloS one **7**: e47819

Kock, A., M. J. O'Riain, K. Mauff, M. Meÿer, D. Kotze, and C. Griffiths. 2013. Residency, habitat use and sexual segregation of white sharks, *Carcharodon carcharias* in False Bay, South Africa. PloS one **8**:e55048

Klimley, A. P. 1985. The areal distribution and autoecology of the white shark, *Carcharodon carcharias*, off the west coast of North America. Memoirs of the Southern California Academy of Sciences **9**: 15–40

Last, P. R. and Stevens, J. D. 2009. Sharks and Rays of Australia. Second edition. CSIRO Publishing. Collingwood, Victoria.

Long, D.J. and Jones, R.E. 1996. White shark predation and scavenging on cetaceans in the eastern North Pacific Ocean. Pages 293–307 Great white sharks: the biology of *Carcharodon carcharias*. Academic press, San Diego, CA

Lyons, K., E. T. Jarvis, S. J. Jorgensen, K. Weng, J. O'Sullivan, C. Winkler, and C. G. Lowe. 2013. The degree and result of gillnet fishery interactions with juvenile white sharks in southern California assessed by fishery-independent and -dependent methods. Fisheries Research **147**: 370–380.

McAuley, R. and Simpfendorfer, C. 2003. Catch Composition of the Western Australian Temperate Demersal Gillnet and Demersal Longline Fisheries, 1994-1999. Fisheries Research Report No. 146, Department of Fisheries, Perth, Western Australia, 78 pp.

Malcolm, H., B. D. Bruce, and J. D. Stevens. September. 2001. A review of the biology and status of white sharks in Australian waters. Page 113. CSIRO Marine Research, Hobart

Mollet, H. F., Cliff, G., Pratt, H. L. and Stevens, J. D. 2000. Reproductive biology of the female shortfin mako, *Isurus oxyrinchus* Rafinesque, 1810, with comments on the embryonic development of lamnoids. Fishery Bulletin **98**:299–318Nardi, A and McAuley, R. 2008. 2006/07 aerial shark surveillance report to the WA Government's Shark Hazard Committee. Unpublished report, Department of Fisheries, WA. 13pp.

Nardi, A. and McAuley, R. 2008. Aerial shark surveillance report, 2007/08. Unpublished report. Department of Fisheries, Perth. Western Australia. 11pp.

Neff, C. 2012. Australian beach safety and the politics of shark attacks. Coastal Management **40**: 88–106.

Neff, C. L., and J. Y. H. Yang. 2013. Shark bites and public attitudes: Policy implications from the first before and after shark bite survey. Marine Policy **38**: 545–547

Page, B., J. McKenzie and S.D. Goldsworthy (2005). Dietary resource partitioning among sympatric New Zealand and Australian fur seals. Marine Ecology Progress Series 293: 283–302.

Pardini, A. T. et al. 2001. Sex-biased dispersal of great white sharks - In some respects, these sharks behave more like whales and dolphins than other fish. Nature **412**: 139–140

Paterson, R. A. 1990. Effects of long-term anti-shark measures on target and non-target species in Queensland, Australia. Biological Conservation **52**: 147–159

Peck, C and du Plessis, M. 2011. Westpac Rescue Helicopter Service "Lifesaver 1". Department of Fisheries – Shark Surveillance Report 1011. Surf Life Saving

Pita, P. and Freire, J. 2011. Movements of three large coastal predatory fishes in the northeast Atlantic: a preliminary telemetry study. Scientia Marina, 75, No 4

Pogonoski, J. J., D. A. Pollard, and J. R. Paxton. 2002. Conservation overview and action plan for Australian Threatened and Potentially Threatened marine and estuarine fishes 2002

Reid, D.D. and Krogh, M. 1992. Assessment of catches from protective shark meshing of New South Wales beaches between 1950 and 1990. Marine and Freshwater Research **43**: 283–296.

Reid, D. D., W. D. Robbins, and V. M. Peddemors. 2011. Decadal trends in shark catches and effort from the New South Wales, Australia, Shark Meshing Program 1950-2010. Marine and Freshwater Research **62**: 676–693

Robbins, R. L. 2007. Environmental variables affecting the sexual segregation of great white sharks *Carcharodon carcharias* at the Neptune Islands South Australia. Journal of fish biology **70**: 1350–1364

Robbins, R., and D. Booth. 2012. Seasonal, sexual and size segregation of white sharks, *Carcharodon carcharias*, at the Neptune Islands, South Australia. Pages 287–299 in M. Domeier, editor. Global perspectives on the biology and life history of the white shark. CRC Press, Boca Raton, FL.

Robbins, W.D., V.M. Peddemors and S.J. Kennelly. (2011) Assessment of shark sighting rates by aerial beach patrols. Industry & Investment NSW – Fisheries Final Report Series. 35 pp.

Rogers, P. J., Huveneers, C, and Beckmann, C. (2014). Monitoring residency of white sharks, *Carcharodon carcharias* in relation to the cage-diving industry in the Neptune Islands Group Marine Park. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2014/000800-1. SARDI Research Report Series No. 818. 75 pp.

Santana-Morales, O., O. Sosa-Nishizaki, M. Escobedo-Olvera, E. Onate-Gonzalez, J. O'Sullivan, and D. Cartamil. 2012. Incidental catch and ecological observations of juvenile white sharks, *Carcharadon carcharias*, in Western Baja california, Mexico. Conservation implications. Pages 187–198 Global perspectives on the biology and life history of the white shark. CRC Press, Taylor & Francis Group.

Semmens, J. M., N. L. Payne, C. Huveneers, D. W. Sims, and B. D. Bruce. 2013. Feeding requirements of white sharks may be higher than originally thought. Nature - Scientific Reports

Skomal, G. B., J. Chisholm, and S. Correai. 2012. Implications of increasing pinniped populations on the diet and abundance of white sharks off the coast of Massachusetts. Pages 405–418 in M. L. Domeier, editor. Global perspectives on the biology and life history of the white shark. CRC Press, Taylor & Francis Group

Stevens, J.D., Last, P.R., White, W.T., McAuley, R.B. and Meekan, M.G.. 2009. Diversity, abundance and habitat utilisation of sharks and rays. Final report to Western Australian Marine Science Institute. CSIRO, Hobart. 126pp.

Weng, K. C., A. M. Boustany, P. Pyle, S. D. Anderson, A. Brown, and B. A. Block. 2007. Migration and habitat of white sharks (*Carcharodon carcharias*) in the eastern Pacific Ocean. Marine Biology **152**: 877–894.

Weng, K., and R. Honebrink. 2013. Occurrence of white sharks (*Carcharodon carcharias*) in Hawaiian waters. Journal of Marine Biology **2013**: 7.

Werry, J., B. D. Bruce, W. Sumpton, and D. Reid. 2012. Beach use by juvenile white shark, *Carcharodon carcharias*, in eastern Australia. Pages 271–286 in M. Domeier, editor. Global perspectives on the biology and life history of the white shark. CRC Press, Boca Raton, FL

Werry, J. M. Lee, S. Y., Lemckert, C. J., Otway, N. M. Natural or Artificial? Habitat-Use by the Bull Shark, Carcharhinus leucas. PLoS ONE 7(11): e49796, November 2012

West, J. G. 2011. Changing patterns of shark attacks in Australian waters. Marine and Freshwater Research, 62, 744–754