# Movement, residency and habitat use of pelagic sharks in Spencer Gulf: resolving overlaps with marine industries and community activities

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# Table of Contents

# Figures

# Tables

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# Executive Summary

*Movement and residency of White Sharks and Bronze Whalers*

This report focuses on the movement dynamics of two pelagic sharks, the White Shark (*Carcharodon carcharias*) and Bronze Whaler (*Carcharhinus brachyurus*), in South Australia. Specific aims were to: (1) determine if aquaculture activities correlated with patterns of fidelity and migration; and (2) assess and compare the use of natural foraging areas and areas used during human marine activities. Additional objectives included the development of: industry guidelines for removal and release of pelagic sharks from finfish aquaculture pontoons, and surveys to collect baseline information on perceptions of shark associations with aquaculture and other marine activities.

We used acoustic telemetry to assess fine scale (0 – 1 km) space-use of White Sharks ($n$ = 55), and Bronze Whalers ($n$ = 24) in Spencer Gulf (SG) and the eastern Great Australian Bight (EGAB). Satellite telemetry was used to quantify transit and migratory movements of ten White Sharks and their spatial overlaps with sites used by marine industries, ecotourism and the public over medium to broad (10s – 1000s of km) spatial scales.

This project provided information with which to compare patterns of daily numbers, frequency of visits, and fidelity of White Sharks at several gulf and continental shelf sites, representing a variety of habitat types. These included aquaculture zones, pinniped habitats, predicted migration paths, snapper habitats (rocky reefs and a wreck), and offshore areas used by the cage-diving tourism industry.

Among seven finfish aquaculture sites, acoustic tracking over a total of 2,280 monitoring days yielded low numbers of detections ($n$ = 73) of five White Sharks at three sites, and no detections at four sites.

Two sites in the Neptune Islands Group had the highest daily visitation (number of sharks) and fidelity (e.g. number shark days) by tagged White Sharks. Cage-diving occurs at these sites that are also large pinniped breeding colonies. This was consistent with findings at other cage-diving sites near pinniped colonies in New Zealand and South Africa.

Mixed model fits that best explained patterns of daily presence of White Sharks at sites in Spencer Gulf, included the variables of water temperature and season (autumn and winter), as well as site type factors of predicted migration paths, Snapper (*Chrysophrys auratus*) habitats, and proximity to Australian Sea Lion

(*Neophoca cinerea*) colonies and haul-outs. Variables that were not statistically significant in the model for White Sharks in Spencer Gulf included total length of sharks, sex, moon phase, and proximity to finfish farm sites.

The best mixed model that explained daily presence of White Sharks at the North Neptune Islands included mean daily bottom water temperature at the 100 m depth contour, seasons of autumn and winter, and the daily presence of cage-diving operators. The best model fit to the White Shark count data (Daily N of sharks detected) in the North Neptune Islands included, mean daily bottom water temperature at the 100 m depth contour, moon phase, and the seasons of autumn and winter.

Bronze Whalers exhibited fidelity to deep-water reef slope and sand habitats in southern Spencer Gulf. Tagged sharks exhibited strong seasonal patterns of presence in summer and early autumn. Season, water temperature, and proximity to finfish farms were significant variables in the best model fits.

Based on the analyses of satellite tracking (*n* = 10 tags, 1,491 days tracked) and acoustic telemetry data-set (*n* = 34 sharks detected, 42,647 detections over 793 days), White Sharks did not exhibit high fidelity to natural foraging areas and migration paths, some of which are areas used by diver-based fisheries for Abalone spp., or by the public during recreational activities (e.g. diving, fishing or surfing).

White Sharks monitored by satellite telemetry exhibited three distinct movement types among regions: 1) transitory within Spencer Gulf, 2) transitory in central to outer shelf and slope in the EGAB, and 3) offshore migratory, where individuals moved from tagging sites in the gulf or on the shelf, across the Great Australian Bight (GAB) to offshore areas in the Indian Ocean.

During the satellite telemetry component of the study, we examined overlap of White Sharks with spatially managed areas, including active and inactive finfish aquaculture zones, areas of diver-based fishery activity, marine parks, and areas used during recreational activities (e.g. diving, fishing, and surfing).

Overlaps with aquaculture zones by satellite tracked White Sharks were mostly limited to brief forays across the outer Spencer Gulf zone, which are near the western edge of the deep-water (≥30 m) area known as the ‘gutter’. Most finfish pontoons within aquaculture zones were located on inshore side of the core movement paths and depth ranges preferred by White Sharks (≥20 m).

Consistent foci of transitory movements by White Sharks included pinniped colonies, islands and gutters used by abalone fishers, reef edges frequented by Snapper in southern Spencer Gulf, ancient coastlines in the 80 – 130 m depth range, continental shelf-break and -slope submarine canyons, and oceanic regions of the south-west Indian Ocean.

This project provides the first direct measures of spatial overlap of satellite tagged White Sharks within and within close proximity (≤10 km) to State managed marine park sanctuary zones.

Findings suggest that avoidance of deep-water (≥20 m) movement paths of White Sharks can contribute to minimising human interaction risks and assist industry and management agencies.

*Guidelines for removal of White Sharks from aquaculture pontoons*

During the project, investigators worked with industry and PIRSA Fisheries and Aquaculture to develop guidelines for removal of White Sharks from aquaculture pontoons. This involved interviews and feedback during industry workshops, meetings with Southern Bluefin Tuna and Yellowtail Kingfish farm managers, and incorporation of input during an earlier industry workshop on sharks and aquaculture (Murray-Jones, 2004).

Industry leaders developed and introduced a pontoon headline gate method to allow White Sharks to exit pontoons when swimming near the surface. In November 2016, following the Australian Southern Bluefin Tuna Industry Association (ASBTIA) and FRDC industry workshop, farm managers, scientists and FRDC representatives discussed the draft and agreed on the final content.

The development of the industry guidelines was runner-up for the Environment Award Category at the South Australian Seafood Awards in 2017.

*Social surveys of perceptions of sharks and marine industries*

Findings of two social surveys were that industry activities and ecological factors perceived to attract sharks to coastal areas, included cage-diving operations, pinniped pupping cycles, Snapper spawning aggregations, and tuna fishing/aquaculture activities. Key findings of the social surveys included:

- General support of aquaculture developments.
- The types of aquaculture venture mattered.
- Social media, newspapers, and community newsletters were the highest used and least trusted forms of media.

- Participants suggested ‘word of mouth’ within the community was the preferred communication option.
- Marine parks, local economies, individual and community activities, and engagement with the coast mattered the most to participants.
- Relationships between sharks and aquaculture were not perceived to exist in isolation, nor were they considered to be high priorities.

Members of the public made minimal mention of factors explaining shark presence, highlighting the need for greater education and extension of science outcomes in regional and metropolitan areas.

This study will inform the public, industry and management during finfish aquaculture zoning processes, whilst also directly addressing several objectives of the *Recovery Plan for the White Shark*.

Key outcomes of the project include provision of advice to marine policy-makers regarding overlaps between sharks, marine industries and areas used during community activities (including marine parks). This project addressed important research and management questions that existed for over a decade.

# 1. Background

A Fisheries Research and Development Corporation funded industry workshop on shark interactions with finfish aquaculture was undertaken on 29 October 2003 during the Cooperative Research Centre for Finfish Aquaculture Conference. A broad range of participants identified a need to improve available information on White Sharks (*Carcharodon carcharias*) and Bronze Whalers (*Carcharhinus brachyurus*) in relation to aquaculture industry activities (Murray-Jones 2004), and to develop industry best-practice guidelines to manage shark interactions. Prior to this workshop, a risk assessment of marine finfish aquaculture (excluding Southern Bluefin Tuna, SBT) determined that the effects of industry operations on White Sharks were likely to be moderate (de Jong and Tanner 2004). At that point, the finfish aquaculture industry was predicted to expand spatially, and operations were producing Snapper (*Chrysophrys auratus*) and Yellowtail Kingfish (YTK) (*Seriola lalandii*) off Port Lincoln, Arno Bay, Fitzgerald Bay and in Franklin Harbour. Subsequent to these workshops, a single review identified Bronze Whaler interactions with finfish farms (Jones 2008), yet no new scientific data have been collected on sharks in relation to aquaculture, despite recognition from resource managers and residents in regional areas that the lack of information provided challenges during aquaculture zoning during consultation processes. The risk assessment by de Jong and Tanner (2004) discussed five reported events of entrapped White Sharks being released from finfish pontoons. During the development of the current study, these events were reviewed and the Primary Investigator worked with industry to improve processes and develop a set of agreed guidelines for removing sharks from floating aquaculture pontoons. There is a growing impetus to apply and adapt these learnings in other State management jurisdictions to minimise the impacts of shark interactions with finfish aquaculture.

The South Australian Research and Development Institute (SARDI) has recently used satellite and acoustic telemetry to assess spatial and temporal patterns of fidelity and movements of pelagic sharks in relation to cage-diving tourism in marine parks (Rogers *et al.* 2014), recreational fisheries (Rogers and Bailleul 2015), and oil and gas activities in the Great Australian Bight (Rogers *et al.* 2016). Electronic tracking of White Sharks has indicted migration between South Australian and Western Australian waters (Bruce *et al.* 2006; McAuley *et al.* 2016, 2017; Rogers *et al.* 2016). Recently, genetic methods have indicated there is distinct structuring of the Australian White Shark population (Blower *et al.* 2012), and in combination with tracking were used to provide assessments of the size of the adult component of the south-western Australian population using close-kin genetics (1,460; uncertainty range = 760 – 2,250) (Bruce *et al*. 2018).

Diver-based commercial fisheries in Western Australian and South Australian State waters operate in what approximates the centre of the distribution of the south-west population of White Sharks. Anecdotal information provided by the South Australian Abalone Fishery suggests the frequency of White Shark sightings is increasing. During this study, representatives from the fishery identified concerns associated with interactions with White Sharks, and suggested that the frequency had increased in recent years. Fishers also consistently expressed their view that modifications of white shark behaviour have occurred in relation to bait and berleying practices by cage-diving tourism at offshore islands. The South Australian Abalone Fishery became an increasingly important stakeholder during the course of the project, and their spatial areas of operations were included in the overlap analyses, and during project extension processes.

During the project, social scientists conducted two surveys to collect information on public perceptions of links between marine industry activities and sharks in regional areas. Social data will inform fisheries and aquaculture policy development, license assessments and consultation with the public by Primary Industries and Regions South Australia (PIRSA), as well as provide baseline information with which to assess perceptions regarding sharks and marine industry activities. During the project, the development of a tourism venture (swimming with tuna) at Victor Harbor led to media attention, protests and public controversy. This development generated public interest regarding tuna, sharks and aquaculture issues, and a potential source of bias in the second planned social survey. In response, the original plan to conduct perception surveys before and after the project was modified, and follow-up questions were identified by PIRSA Fisheries and Aquaculture for participants on Eyre Peninsula, the Far West Coast, Yorke Peninsula, the Adelaide Metropolitan area, Kangaroo Island and Fleurieu Peninsula.

## Need

This project addressed knowledge gaps highlighted during an industry workshop on sharks and aquaculture that was supported by the FRDC (Murray-Jones, 2004). Primary Industries and Regions South Australia (PIRSA) identified the need to improve the understanding of associations between sharks and finfish aquaculture activities. This followed recurrent comments from the public regarding site applications to PIRSA Fisheries and Aquaculture. In 2013, the need for this project was identified at meetings of the Aquaculture Advisory Council, a legislated body under the previous *Aquaculture Act 2001*, advising the State Minister for Agriculture, Food and Fisheries on matters relating to aquaculture development. The current study informs and identifies operational solutions to manage interactions between sharks and aquaculture operations in other Australian management jurisdictions. This project addresses key priorities of the *Recovery Plan for the White Shark* (2013). This project also recognised the responsibilities and implications relating to State and Commonwealth Government protection status and legislation relating to the White Shark under the *Fisheries Management Act (2007)* and the Australian Commonwealth Government, *Environmental Protection Biodiversity Conservation Act 1999 (EPBC Act)*.

Specific aims of this study were to:

- Determine if activities associated with finfish aquaculture correlate with spatial and temporal patterns of shark residency and migration;
- Assess and compare patterns of residency of pelagic sharks in ‘natural’ foraging areas, and overlaps with community activities;
- Develop a code of practice (industry guidelines) for removal and release of pelagic sharks from finfish aquaculture pontoons using information gained during the study and practical input from industry;
- Develop social surveys to provide managers with baseline information on public perception of pelagic shark interactions with activities associated with finfish aquaculture before and after the scientific study.

The aims directly supported the research needs identified during consultation with State management agencies, aquaculture zoning stakeholder meetings, and FRDC workshops (Murray-Jones, 2004), and risk assessment processes focused on spatially explicit zoning. The workshop findings of Murray-Jones (2004), in combination with aquaculture zoning public consultation processes were pivotal when identifying the priority needs and objective of the study.

# 2. Movement, Fidelity and Habitat Use of White Sharks and Bronze Whalers: Overlap with Ecologically Important Areas, Marine Industries and the Community

P. Rogers, M. Drew, M. Doubell, and A. Redondo Rodriguez.

## Introduction

Previous studies of pelagic sharks and their interactions with floating objects and infrastructure have mostly focused on fish attracting devices used to enhance fishing productivity, and impacts on non-target species (Filmalter *et al.* 2013; Davies *et al.* 2014). Despite widespread use of floating pontoons in finfish aquaculture in several countries, including Australia, the Mediterranean, Mexico, Chile, Japan and New Zealand, published studies of ecological and operational links between predatory species and this infrastructure are sparse. This lack of information forms a data gap for Australian management agencies chartered with assessing risks of threatened species interactions whilst optimising the sustainability of pelagic marine resources, and addressing public safety considerations. A single study of pelagic shark interactions with offshore finfish farms producing Pacific Threadfin (*Polydactylus sexfilis*) and Almaco Amberjack (*Seriola rivoliana*) off Hawaii focused on the Tiger Shark (*Galeocerdo cuvier*) and the Sandbar Shark (*Carcharhinus plumbeus*) (Papastamatiou *et al.* 2010). Findings included species-specific patterns of overlap durations, with the Sandbar Sharks exhibiting the highest fidelity to offshore finfish farm sites (Papastamatiou *et al.* 2010).

Satellite telemetry provides a suitable tool to investigate broad-scale movement patterns and allows researchers to address ecological questions relating to transitory and fidelity behaviours, that integrate spatial overlaps between apex predators and areas used by static (aquaculture) or mobile (fisheries) marine industries. Alternatively, acoustic telemetry facilitates calculation of fine-scale spatial parameters (e.g. site fidelity or residency) that allow researchers to quantify space- and time-use of sharks, in particular habitats, and across seasons in greater detail than can be achieved via satellite telemetry alone. In this way, when applied simultaneously, satellite and acoustic telemetry techniques can be considered complementary. Fine-scale behavioural information provided by acoustic telemetry offers important insights into the susceptibility of sharks to human marine activities, expected interaction levels with fisheries, and the selection of particular habitats (how they use space over time). Both technologies have previously been applied in Australia to investigate habitat use (e.g. Harasti *et al.* 2017) and movements (e.g. Bruce *et al*. 2006) of White Sharks across multiple spatial scales. Broad-scale movements of White Sharks from the south-western population have been assessed using acoustic (McAuley *et al.* 2016) and satellite telemetry to track transitory movements across large spatial scales (Bruce *et al.* 2006, Sims *et al.* 2012), yet no studies have analysed tracking data in relation to direct overlap with commercial marine activities managed using spatial boundaries. The focus of this study was on White Sharks and Bronze Whalers (*Carcharhinus brachyurus*), as these species were identified to interact with aquaculture (Murray-Jones 2004), and are sighted regularly in South Australian coastal areas (PIRSA, Shark Sighting Log 2017). The White Shark is a long-lived, migratory endotherm that occupies gulf, coastal, continental shelf and oceanic habitats encompassing the sub-tropical to cool temperate regions, and the Bronze Whaler is a medium to long-lived, ectotherm with a warm temperate distribution (Last and Stevens 2009; Drew *et al.* 2016).

An underlying assumption of the current study was that if human or ecological factors explained observable behaviours of the study species, then detectable signals should be observable in fidelity, mobility and affinity parameter estimates at certain sites or site types. Firstly, however, the seasonal signals of presence by species, at and within each site type/region and within their integrated habitats needed to be investigated. Prior to this study, patterns of seasonal presence and fidelity of White Sharks in South Australian waters had been examined in association with cage-diving activities around pinniped colonies, including in the Neptune Islands Group (Bruce and Bradford 2013a, 2015), the Sir Joseph Banks Group (Strong *et al.* 1996), Liguanea Island (Robbins *et al.* 2015), in western Australian shelf waters (McAuley *et al.* 2017), and in nursery areas in eastern Australia (Harasti *et al.* 2017). Significant questions remained relating to White Shark behaviours in relation to use of other sites and bioregions also used by marine industries (e.g. in Spencer Gulf, for ecotourism, by diver-based fisheries), and the public during recreational activities in South Australian waters. Specific sites of interest included southern and central gulf areas where Snapper aggregate, key offshore pinniped colonies, offshore reefs between islands, areas used by marine industries, and the array of offshore bathymetric features and submarine canyons along the shelf-slope that are known to support several pelagic shark populations (Rogers *et al.* 2016).

## Objectives and Approach

This study assessed the space-use of White Sharks and Bronze Whalers over a range of spatial and temporal scales. This allowed investigation of species-specific spatial overlaps with 28 sites of five types, including a sub-set used by marine industries, ecotourism and the public during recreational activities. The main tools used included long-term acoustic telemetry and spatial analyses that incorporated remote-sensed and sensor-derived environmental and oceanographic information.

Site selection processes incorporated sites thought to represent habitats used during broad-scale movements and periods of fidelity. These included island pinniped colonies, Snapper aggregation areas, reefs and shoals that provided important context for comparison with sites and areas used by diver-based fisheries, aquaculture and tourism. During this project phase, we were interested in patterns of habitat use within site types, and at spatial scales of 0 <10 km.

In the second phase of the study, satellite telemetry was used to elucidate the movement and habitat use of White Sharks over medium- to broad-scales of 10s – 1000s of km. This focused on determining spatial overlap over scales that approximated spatially-managed zones, including; aquaculture zones, areas used by diver-based fisheries, and areas used by the community during recreational activities (including within marine parks).

## Methods

### *Study area*

The study area included Spencer Gulf and the continental shelf waters of the eastern Great Australian Bight (EGAB) (Fig. 1). Spatially managed marine areas within the study region include South Australian State managed Aquaculture Zones, Marine Fishing Areas (MFAs) and Marine Parks (Marine Protected Areas). Spencer Gulf is a unique, seasonally subtropical, temperate ecosystem characterised by relatively shallow (mostly ≤ 55 m), thermally variably, inverse estuarine habitat that cover ~22,000 $km^2$. Spencer Gulf ecosystems support regionally significant components of Australia's commercial and recreational fisheries and aquaculture, shipping, manufacturing and tourism industries. The gulf system has a seasonal oceanographic pattern characterised by separation of water masses from those in adjacent continental shelf waters, due to salinity and water temperature frontal systems that form across its entrance between spring and early autumn (Bruce and Short 1990).

### *Acoustic telemetry: site selection and experimental design*

The location of the receivers was designed to allow spatial, ecological and operational comparisons of shark count-based, presence, and fidelity parameters within and between sites and site types for the two species. Site types selected included finfish lease areas, possible movement paths (areas consistently used during transit/directed movements), Snapper habitats, pinniped breeding colonies and haul-outs (non-breeding/resting sites), some of which included sites where tourism companies regularly conduct cage-diving, or swimming with pinniped operations (Table 1). Where logistically possible, comparative sites on the western and eastern sides of Spencer Gulf were selected to reflect areas used by marine finfish industries and those that are directly adjacent to, or within inactive aquaculture lease areas. Acoustic receivers including Vemco VR2W (https://vemco.com/products/vr2w-69khz) and VR2AR (acoustic release β model) were deployed on finfish cage infrastructure by 5 m long and 25 mm diameter drop-ropes with weights, or anchored to the benthos. The detection range of these products can vary in response to ambient noise, yet is generally reliable in the 300 to 400 m range, with maximum expected ranges of ~1 km. A summary of all receiver deployments and associated meta-data are provided in Table 1. Acoustic receivers recorded dates and times of shark tag detections (a series of tag-specific, 69 kHz pings) in UTC, which were subsequently converted to local time by adding 9.5 hours. Depending on the habitat type, receiver moorings were: marked with 70 cm surface floats with navigation beacons in offshore areas (Neptune Islands), and anchored with 50 mm diameter multi-strand rope attached to train wheels, steel or concrete blocks; or fixed on various benthic mooring and float configurations with 3 m trip lines; or fixed to star droppers hammered into the seafloor; or anchored to reef areas with heavy reef anchors and subsurface floats.

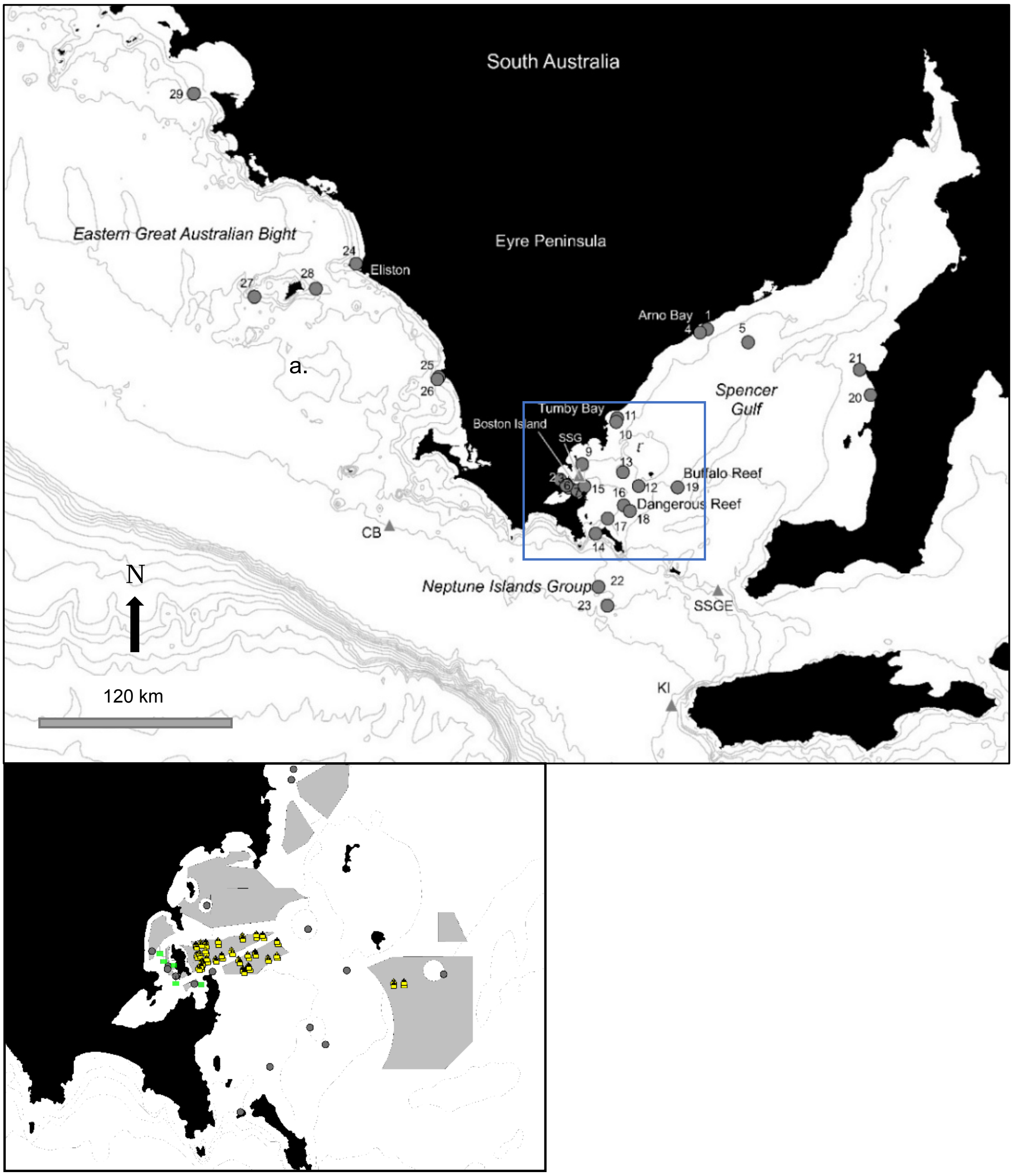



**Figure 1**. Locations and sites mentioned in the report. Sites shown as grey circle symbols show receiver deployment sites detailed in Table 1. Inset (below) shows locations of acoustic receivers (dark grey circles), aquaculture zones (grey polygons) and aquaculture lease sites (finfish – green, and SBT - yellow symbols). Sites where water temperature data were collected (triangle symbols) using ADCP sensors are shown as SSGE = SAIMOS reference station in entrance to Spencer Gulf, CB = Coffin Bay reference station at 95 m depth, KI = Kangaroo Island reference station at 100 m depth, and the ASBTIA's Southern Spencer Gulf water temperature logger at 5 m depth = SSG. Satellite tags were deployed on White Sharks at sites 1 and 23, and near 13. Acoustic tags were deployed on White Sharks at or near sites 1, 13, 16, 17, 22 and 23. Acoustic tags were deployed on Bronze Whalers near sites 16 and 17.

**Table 1**. Summary of information on individual site characteristics, ecological features and management zones, acoustic receiver deployments and detection data for tagged White Sharks and Bronze Whalers. Site type abbreviations are Aquaculture = AQUA, ** = inactive, Pinniped colonies and haul-outs = PIN, Snapper habitats = SNAP, hypothesised movement paths = MIG; Cage-diving operation site = CDO. Pinniped pup counts were sourced from Shaughnessy *et al.* (2014). In pinniped colony (PIN) details in non-italics = Australian Sea Lions and italics = Long-nosed Fur Seals. Haul-out (HO). Central Spencer Gulf (CSG), Southern Spencer Gulf (SSG), South-central Spencer Gulf (SCSG), Eastern Spencer Gulf (ESG) and the eastern Great Australian Bight (EGAB). Migration path and pinniped sites are regularly used by diver-based fisheries, Snapper and migration path sites are regularly used for fishing, and Inside Waldegrave Island (MIG) is near surfing locations.

| Receiver number | Date deployed | Date recovered | Monitoring time (d) | White Shark detections | Bronze Whaler detections | Region | Location | Depth | Site type | Pinniped colony | Spatial management zone |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 16 Feb 2015 | 23 Nov 2015 | 280 | 21 | 0 | CSG | Arno Bay | 20 | AQUA | - | Finfish Aquaculture Zone |
| 2 | 18 Dec 2014 | 1 Jun 2016 | 531 | 0 | 0 | SSG | Northern Boston Bay | 15 | AQUA | - | Finfish Aquaculture Zone |
| 3 | 1 June 2016 | 25 Jul 2016 | 54 | 0 | 0 | SSG | Northern Boston Bay | 15 | AQUA | - | Finfish Aquaculture Zone |
| 4 | 16 Feb 2015 | 19 Jul 2015 | 153 | 26 | 8 | CSG | Arno Bay | 20 | AQUA | - | Finfish Aquaculture Zone |
| 5 | 2 Mar 2015 | 19 May 2016 | 444 | 73 | 0 | CSG | Estelle Star Wreck, Arno Bay | 25 | SNAP | - | Snapper spatial closure |
| 6 | 18 Dec 2014 | 6 Jun 2015 | 170 | 0 | 0 | SSG | West Boston | 12 | AQUA | - | Finfish Aquaculture Zone |
| 7 | 6 Jun 2015 | 25 Jul 2016 | 415 | 0 | 0 | SSG | E Boston, Fanny Point | 15 | AQUA | - | Finfish Aquaculture Zone |
| 8 | 23 Jan 2015 | 1 Jul 2016 | 525 | 26 | 0 | SSG | Bickers Island | 16 | AQUA | - | Finfish Aquaculture Zone |
| 9 | 11 Feb 2015 | 20 May 2016 | 464 | 2 | 0 | SSG | Rabbit Island | 7 | PIN | HO, *HO* | **Finfish Aquaculture Zone |
| 10 | 16 Feb 2015 | 19 May 2016 | 458 | 0 | 171 | SSG | Tumby Bay 2 | 13 | MIG | - | Habitat Protection Zone |
| 11 | 16 Feb 2015 | 19 May 2016 | 458 | 0 | 44 | SSG | Tumby Bay 3 | 13 | MIG | - | Habitat Protection Zone |
| 12 | 19 Feb 2015 | 20 Jun 2016 | 487 | 25 | 63 | SSG | Bridgette Shoal | 32 | MIG | - | General Managed Use Zone |
| 13 | 3 Mar 2015 | 20 May 2016 | 444 | 96 | 37 | SSG | English Island. & Sibsey Island channel | 19 | PIN | 34 | Habitat Protection Zone |
| 14 | 22 Jan 2015 | 2 Jun 2016 | 497 | 109 | 68 | SSG/EGAB | Hopkins Island | 18 | PIN | HO | General Managed Use Zone |
| 15 | 11 Feb 2015 | 20 May 2016 | 464 | 14 | 0 | SSG | Donington Rock | 8 | PIN | HO, *HO* | General Managed Use Zone |
| 16 | 3 Mar 2015 | 20 May 2016 | 444 | 28 | 8 | SSG | West Island at Dangerous Reef | 14 | PIN | 485, *HO* | Sanctuary Zone |
| 17 | 19 Feb 2015 | 20 May 2016 | 456 | 116 | 812 | SSG | Porter Rocks | 14 | MIG | - | |
| 18 | 3 Mar 2015 | 20 May 2016 | 444 | 296 | 2,601 | SSG | Reef near Dangerous Reef | 29 | SNAP | - | |
| 19 | 3 Mar 2015 | 20 May 2016 | 444 | 21 | 4,147 | SCSG | Reef near Buffalo Reef | 37 | SNAP | - | Finfish Aquaculture Zone |
| 20 | 8 Jul 2015 | 14 Feb 2017 | 587 | 7 | 285 | ESG | Balgowan | 11 | SNAP | - | Habitat Protection Zone |
| 21 | 8 Jul 2015 | 14 Feb 2017 | 587 | 0 | 63 | ESG | Cape Elizabeth | 11 | MIG | - | |
| 22 | 1 Jul 2015 | 16 Jul 2016 | 381 | 24,957 | 0 | EGAB | North Neptune Island | 17 | CDO/ PIN | 9, *4,733* | Sanctuary Zone |
| 23 | 1 Jul 2015 | 14 Sept 2016 | 441 | 16,806 | 0 | EGAB | South Neptune Island | 23 | CDO/ PIN | 7, *3,258* | Habitat Protection Zone |
| 24 | 12 Apr 2015 | 4 Jun 2016 | 419 | 10 | 7 | EGAB | Inside Waldegrave Island | 16 | MIG | 89 | General Managed Use Zone |
| 25 | 29 Jan 2015 | 10 Feb 2015 | 12 | 0 | 0 | EGAB | Pt Drummond | 14 | MIG | - | General Managed Use Zone |
| 26 | 10 Feb 2015 | 15 Feb 2017 | 736 | 2 | 0 | EGAB | Pt Drummond | 20 | MIG | - | General Managed Use Zone |
| 27 | 12 Apr 2015 | 19 Jan 2017 | 648 | 7 | 0 | EGAB | Ward Island | 25 | PIN | 44, *151* | Habitat Protection Zone |
| 28 | 12 Apr 2015 | 4 Jun 2016 | 419 | 10 | 3 | EGAB | Topgallant Island | 26 | MIG | - | Sanctuary Zone |
| 29 | 11 Dec 2014 | 31 Jan 2016 | 416 | 0 | 0 | EGAB | Olive Island | 15 | PIN | 133, *5* | |

Receivers were attached to mooring ropes using crimped stainless steel wire at a distance of ~3 m from the seafloor. Receivers were recovered to download the datasets by abalone and aquaculture industry divers, by towing a grappling hook from a vessel in the case of moored receivers with trip-lines, or by the use of acoustic release on VR2AR receivers using the Vemco VR100 active tracking receiver (deckbox) and transponding hydrophone (https://vemco.com/products/vr100). VR2W receivers deployed at active finfish lease sites, included Arno Bay and inside Boston Bay. At aquaculture sites, VR2W receivers were attached to pontoons or feed barges. Receivers were also deployed at and/or near proposed or inactive aquaculture lease areas. Receivers were deployed at pinniped sites, including Australian Sea Lion (*Neophoca cinerea*) and Long-nosed Fur Seal (*Arctocephalus forsteri*) breeding colonies and haul-outs in southern Spencer Gulf, and the EGAB, and two cage-diving sites in the Neptune Islands Group Marine Park that are directly adjacent to breeding colonies of both species. Some of the islands sites are also used by the South Australian Abalone Fishery. Snapper habitats monitored were predominantly rocky reefs and included, Buffalo Reef, a reef slope located to the south-east of Dangerous Reef, an inshore reef near Balgowan, and the wreck of the Estelle Star. Receivers were deployed along predicted movement paths (e.g. between pinniped colonies, islands or significant reef complexes), including Tumby Bay, Bridgette Shoal, Porter Rocks near Thistle Island, Cape Elizabeth in eastern Spencer Gulf, and Pt Drummond, Inside Waldegrave Island near Elliston (adjacent to an inactive aquaculture zone and a pinniped colony), and Topgallant Island, near Flinders Island off Eyre Peninsula in the EGAB.

### *Acoustic telemetry: tagging*

Bronze Whalers

Bronze Whalers of ≤ 2.5 m total length (TL) were captured for tagging using pelagic long-lines or a hand-line in southern Spencer Gulf (Fig. 1, Table 2). Long-line captured Bronze Whalers were tagged with V16-6x tags programmed to send signals at random intervals of 50 – 110 seconds. Acoustic tags were tethered to plastic umbrella darts using a 10- to 15-cm-long stainless wire leader (1.6 mm diameter). Tethers were attached to tags using Marine Knead-it™ epoxy compound and the tag surfaces were painted with anti-fouling. Bronze whalers only had an acoustic tag ID type, e.g. Cb1 (See White Sharks). Long-line equipment comprised 8 mm floating rope main-line, with 3 m long, 2 mm diameter wire leaders attached to 16/o tuna circle hooks (60 – 100 per set) and stainless steel clips. During sets in depths >17 m, floats and weights with 5 m dropper lines were attached to the mainline at variable intervals. Hooks and leaders were baited with Western Australian Salmon (*Arripis truttaceus*) and set along the main-line at ~40 – 50 m spacings. Set durations were ~2 hours from the time of last hook set to maximise survivorship of sharks for tagging. During sets, surface floats along the main-line were monitored for movement to indicate the presence of sharks on the gear. At the end of each set, the line was retrieved on the starboard side of the vessel whilst travelling at speeds of ~1 – 2 knots. Sharks were supported next to the vessel using a sling with a solid, semi-circular aluminium frame. Once restrained, the gills of sharks were aerated using a reinforced deck-hose or via passive water flow through the sling, and the eyes of active individuals were covered with a wet micro-fibre cloth. The posture of each shark was supported using a wet, high-density foam mattress. Bolt-cutters were used to cut and remove hooks prior to the release of tagged sharks. If hooks couldn't be removed, the leader was cut as close to the hook as possible. Staff safety was always the primary consideration, and if a shark was in a position where a step could not be completed, that step was omitted. Sharks were measured by natural total length (TL cm) (Francis 2006). Sex and maturity were assessed based on criteria of Francis and Duffy (2005).

White Sharks

Free-swimming White Sharks were tagged with Vemco Ltd. (Halifax, Canada) V16-6x acoustic tags programmed to send coded sound signals at 69 kHz frequency at random intervals from 70 – 150 seconds (Table 3). Three individuals (C9 – C11) were tagged during the process of removal from a finfish pontoon in central Spencer Gulf. White Sharks were attracted to the vessel using a teaser bait on a rope and tagged using a 3 m aluminium pole. Darts were implanted in the dorsal musculature next to the first dorsal fin using a plastic umbrella dart applicator. The dart applicator point extended by 15 mm from the cone of the umbrella dart. As some White Sharks were tagged with acoustic and satellite tag types, some had an acoustic tag ID, (e.g. Cc1), and a satellite tag ID (e.g. S1), whereas others that were tagged with only one type had a single ID. Acoustic tags were tethered as for those deployed on Bronze Whalers.

**Table 2**. Details for acoustic tags deployed on Bronze Whalers.

| Shark ID | Deployment date | Deployment location | Length (TL, m) | Sex |
|---|---|---|---|---|
| Cb1 | 7 Feb 2015 | Thistle Island | 2.45 | M |
| Cb2 | 7 Feb 2015 | Thistle Island | 1.50 | F |
| Cb3 | 7 Feb 2015 | Thistle Island | 2.03 | M |
| Cb4 | 10 Feb 2015 | Bridgette Shoal | 1.77 | F |
| Cb5 | 10 Feb 2015 | Bridgette Shoal | 2.49 | F |
| Cb6 | 10 Feb 2015 | Thistle Island | 2.15 | M |
| Cb7 | 10 Feb 2015 | Thistle Island | 1.70 | M |
| Cb8 | 10 Feb 2015 | Thistle Island | 1.95 | M |
| Cb9 | 10 Feb 2015 | Thistle Island | 1.70 | M |
| Cb10 | 10 Feb 2015 | Thistle Island | 1.30 | F |
| Cb11 | 10 Feb 2015 | Thistle Island | 2.56 | M |
| Cb12 | 14 Feb 2015 | Thistle Island | 2.18 | F |
| Cb13 | 14 Feb 2015 | Thistle Island | 1.60 | F |
| Cb14 | 14 Feb 2015 | Thistle Island | 1.95 | F |
| Cb15 | 14 Feb 2015 | Thistle Island | 1.20 | M |
| Cb16 | 14 Feb 2015 | Thistle Island | 1.92 | F |
| Cb17 | 14 Feb 2015 | Thistle Island | 1.69 | M |
| Cb18 | 19 Feb 2015 | Thistle Island | 1.90 | F |
| Cb19 | 3 Mar 2015 | Thistle Island | 1.50 | M |
| Cb20 | 3 Mar 2015 | Thistle Island | 1.64 | F |
| Cb21 | 3 Mar 2015 | Thistle Island | 2.19 | M |
| Cb22 | 3 Mar 2015 | Thistle Island | 1.74 | F |
| Cb23 | 3 Mar 2015 | Thistle Island | 1.61 | M |
| Cb24 | 4 Mar 2015 | Thistle Island | 1.57 | M |

**Table 3**. Details for acoustic tags deployed on White Sharks.

| Tag ID | Deployment date | Deployment location | Length (TL, m) | Sex |
|---|---|---|---|---|
| Cc1 | 14 Sep 2013 | South Neptune Is. | 4.1 | F |
| Cc2 | 15 Sep 2013 | South Neptune Is. | 3.3 | M |
| Cc3 | 28 Sep 2013 | North Neptune Is. | 4.5 | M |
| Cc4 | 9 Oct 2013 | North Neptune Is. | 4.1 | M |
| Cc5 | 14 Oct 2013 | North Neptune Is. | 4.5 | M |
| Cc6 | 26 Oct 2013 | North Neptune Is. | 4.5 | M |
| Cc7 | 26 Oct 2013 | North Neptune Is. | 3.0 | M |
| Cc8 | 15 Nov 2013 | North Neptune Is. | 2.0 | NS |
| Cc9 | 16 Jan 2014 | Central Spencer Gulf | 2.4 | F |
| Cc10 | 16 Jan 2014 | Central Spencer Gulf | 2.4 | F |
| Cc11 | 16 Jan 2014 | Central Spencer Gulf | 2.9 | F |
| Cc12 | 29 Jan 2014 | North Neptune Is. | 3.5 | M |
| Cc13 | 29 Jan 2014 | North Neptune Is. | 4.0 | M |
| Cc14 | 29 Jan 2014 | North Neptune Is. | 3.8 | M |
| Cc15 | 23 Feb 2014 | North Neptune Is. | 4.3 | M |
| Cc16 | 24 Feb 2014 | North Neptune Is. | 2.4 | M |
| Cc17 | 26 Feb 2014 | North Neptune Is. | 4.5 | F |
| Cc18 | 28 Feb 2014 | North Neptune Is. | 3.0 | M |
| Cc19 | 19 Jul 2014 | North Neptune Is. | 3.6 | M |
| Cc20 | 19 Jul 2014 | North Neptune Is. | 3.9 | F |
| Cc21 | 20 Jul 2014 | North Neptune Is. | 3.3 | M |
| Cc22 | 20 Jul 2014 | North Neptune Is. | 3.7 | F |
| Cc23 | 21 Jul 2014 | North Neptune Is. | 4.2 | M |
| Cc24 | 18 Oct 2014 | South Neptune Is. | 4.0 | M |
| Cc25 | 19 Oct 2014 | North Neptune Is. | 3.0 | F |
| Cc26 | 19 Oct 2014 | North Neptune Is. | 4.5 | M |
| Cc27 | 15 Nov 2014 | North Neptune Is. | 3.5 | M |
| Cc28 | 15 Nov 2014 | North Neptune Is. | 3.8 | M |
| Cc29 | 16 Nov 2014 | North Neptune Is. | 3.2 | M |
| Cc30 | 24 Jan 2015 | North Neptune Is. | 3.9 | M |
| Cc31 | 24 Jan 2015 | North Neptune Is. | 3.7 | M |
| Cc32 | 24 Jan 2015 | North Neptune Is. | 2.7 | M |
| Cc33 | 2 May 2015 | South Neptune Is. | 4.2 | F |
| Cc34 | 6 May 2015 | South Neptune Is. | 1.8 | F |
| Cc35 | 6 May 2015 | South Neptune Is. | 4.2 | F |
| Cc36 | 7 May 2015 | South Neptune Is. | 4.5 | NS |
| Cc37 | 7 May 2015 | South Neptune Is. | 2.6 | NS |
| Cc38 | 6 May 2015 | South Neptune Is. | 3.0 | NS |
| Cc39 | 7 May 2015 | South Neptune Is. | 3.4 | NS |
| Cc40 | 7 May 2015 | South Neptune Is. | 2.8 | NS |
| Cc41 | 18 Jul 2015 | Southern Spencer Gulf | 3.3 | F |
| Cc42 | 19 Jul 2015 | Southern Spencer Gulf | 5.0 | F |
| Cc43 | 22 Jul 2015 | Southern Spencer Gulf | 4.2 | NS |
| Cc44 | 23 Jul 2015 | Southern Spencer Gulf | 3.8 | F |
| Cc45 | 23 Jul 2015 | Southern Spencer Gulf | 2.6 | M |
| Cc46 | 5 Aug 2015 | Southern Spencer Gulf | 2.6 | M |
| Cc47 | 7 Aug 2015 | Southern Spencer Gulf | 4.6 | F |
| Cc48 | 8 Aug 2015 | Southern Spencer Gulf | 3.5 | F |
| Cc49 | 8 Nov 2015 | North Neptune Is. | 3.9 | M |
| Cc50 | 8 Nov 2015 | North Neptune Is. | 3.2 | M |
| Cc51 | 17 Dec 2015 | North Neptune Is. | 3.0 | M |
| Cc52 | 17 Dec 2015 | North Neptune Is. | 3.0 | M |
| Cc53 | 17 Dec 2015 | North Neptune Is. | 2.8 | M |
| Cc54 | 30 Dec 2015 | North Neptune Is. | 3.4 | M |
| Cc55 | 30 Dec 2015 | North Neptune Is. | 3.5 | M |

### *Satellite telemetry: tagging*

White Sharks were fitted with a mix of five Argos-linked Smart Position and Temperature (SPOT) satellite tags (Wildlife Computers™, WC) and Sirtrack platform Transmitter Terminal tags K2F161A (Table 4), and five WC miniature pop-up archival transmitting tags (mini-PAT). Deployment of the dorsal fin-mounted SPOT and Sirtrack tags required captures of White Sharks, and Mini-PATs were deployed on sharks that were swimming next to the vessel aluminium tag pole. Two individuals (S1 and S2) were tagged during the process of removal from a finfish pontoon in central Spencer Gulf. Capture and maintenance methods used to deploy the dorsal fin-mounted satellite tags were based on those of Bruce and Bradford (2013b), with variations for sharks of larger body sizes. Captures were conducted inside and outside the finfish aquaculture lease areas in southern and central Spencer Gulf. Equipment used to capture White Sharks consisted of 100 m of 50 mm rope main-line with 30 mm backing, attached to a series of floats graduating from small (20 mm diam.) to large (70 mm diam.) spread evenly over a distance of ~8 m from the hook and leader. The leader consisted of a short length (1 m) of 50 grade chain coated in plastic tubing attached to a Mustad Perfect Circle™ hook using a stainless steel shackle. Captures were only conducted if candidate sharks were swimming at the surface at slow speeds, the PI identified the shark was not already tagged with Western Australia Department of Primary Industries and Regional Development (WA DPIRD), CSIRO or SARDI tags, and there was minimal risk of an entanglement in mooring lines. The vessel and capture floats were used to maneuver sharks boat-side and into a rubber sling positioned in the water. An important step during the captures was timing of the forward movement of the vessel approximately perpendicular to the direction the shark swam immediately following the initial hooking stage. This was done immediately after the first rapid movement ceased to reduce the risk of the sharks rolling and biting through the capture rope. As the vessel moved forward the sharks were guided toward the sling that was positioned in the water alongside the gunwale. The sling entrance next to the vessel was fastened in position under the stern, so the entry point was firmly fixed in position. Once sharks were maneuvered into the sling, the gills were aerated using a reinforced deck-hose, and the eyes were covered with a wet micro-fiber cloth. Two or three small holes were made in the dorsal fin using a cordless drill and deep socket, and satellite tags were attached to the first dorsal fin using two 3.5 mm diameter stainless steel bolts, nylex lock-nuts and washers. The posture of each shark was supported using a wet, high-density foam mattress. Sharks were measured by natural total length (cm), and where possible, sex and maturity were assessed based on criteria outlined by Francis and Duffy (2005). Mini-PATs were tethered using a plastic umbrella dart attached to 200 – 250 mm of 2 mm diameter plastic coated 316 stainless steel multi-strand wire. Umbrella darts tethered to mini-PATs were inserted into the dorsal musculature to depths of 5 – 10 cm using a stainless steel applicator attached to the tag pole.

**Table 4**. Satellite tag deployments on White Sharks in western, south-western and the approach to Spencer Gulf in EGAB continental shelf waters. Abbreviations represent: Central Spencer Gulf (CSG), South West Spencer Gulf (SWSG), South Neptune Island (SNI), Not applicable (NA), Sex – female (F), male (M), Sirtrack platform transmitter terminal (ST PTT). Information on tag types provided in materials and methods section. Wildlife Computers Hidden Markov Model generated track (GPE3), Argos platform transmitter terminal data (Argos), and No acoustic tag deployed (NATD).

| SharkID | Acoustic tag ID | Location tagged | Tagging date | Length (TL m) | Sex | Period acoustic tag detected | Duration tracked (d) | Sat. tag type | PSAT recovered | Track type |
|---|---|---|---|---|---|---|---|---|---|---|
| S1 - 134880 | Cc11 | CSG | 16 Jan 2014 | 2.9 | F | 26 Feb 2014 to 16 Jul 2015 | 221 | ST PTT, KF161A | NA | Argos |
| S2 - 115560 | Cc9 | CSG | 16 Jan 2014 | 2.4 | F | Not detected | 319 | WC Mk10A | NA | Argos |
| S3 - 148958 | Cc45 | SWSG | 23 Jul 2015 | 2.6 | M | 20 Sep 2015 to 4 Mar 2016 | 159 | WC SPOT | NA | Argos |
| S4 - 142479 | NATD | SWSG | 7 Aug 2015 | 4.1 | F | NA | 163 | WC SPOT | NA | Argos |
| S5 - 142488 | Cc48 | WSG | 8 Aug 2015 | 3.5 | F | 11 Aug 2015 to 24 Oct 2016 | 131 | WC SPOT | NA | Argos |
| S6 - 148949 | Cc33 | SNI | 2 May 2015 | 4.2 | F | Not detected | 101 | WC mini-PAT | No | GPE3 |
| S7 - 148953 | NATD | SNI | 2 May 2015 | 3.3 | M | NA | 101 | WC mini-PAT | No | GPE3 |
| S8 - 148950 | NATD | SNI | 6 May 2015 | 2.2 | F | NA | 67 | WC mini-PAT | Marion Bay, SA | GPE3 |
| S9 - 148951 | Cc38 | SNI | 6 May 2015 | 3.0 | F | Not detected | 104 | WC mini-PAT | Louth Is, SW SG | GPE3 |
| S10 - 148952 | Cc35 | SNI | 6 May 2015 | 4.2 | F | Not detected | 125 | WC mini-PAT | No | GPE3 |

### ***Data analyses***

#### Acoustic telemetry

We used Generalized Linear Mixed Models provided in the Template Model Builder package (glmmTMB) (Brooks *et al.* 2017) in R version 3.4.2 to estimate the influence of explanatory variables (Table 5) on the probability of observing daily presence and daily counts of tagged White Sharks in the Neptune Islands Group, and daily presence of White Sharks and Bronze Whalers in Spencer Gulf. Models were fitted using a log-link function that scales for binomial loss in presence data, and a Binomial error distribution (Phillips and Elith 2011). Daily count data were fitted using the Poisson error distribution. The GLMMs were fitted using maximum likelihood and the Laplace approximation. The model random effect was assigned as the Shark ID, to account for behavioural variability between tagged individuals. A range of candidate models were fitted with combinations of explanatory variables, ranging from full models with all predictors included, to single-term fits. The fits and their Akaike information criteria (AIC) were compared to those of factor free null models, e.g. ~1 + 1│SharkID (Null models are shown in results tables by shark species). Final model selections were based on the magnitude of differences (∆AIC) between the null model and the best model fit with the smallest AIC following Burnham and Anderson (2002) and Zuur *et al.* (2009).

#### Satellite telemetry

Satellite tags transmitted signals to Argos network receiver stations, which were forwarded to Argos centres in France and the USA (Argos 2008). Position estimates were downloaded in seven location quality classes (cls) ranging from highest to lowest manufacturer predicted accuracies of 3 = <250 m, 2 = 250 – 500 m, 1 = 500 – 1500 m and 0 – B = >1500 m, Z = no position (www.argos-system.org). Position errors compared to GPS positions and the 68th percentile errors were 3 = 0.49 km, 2 = 1.01 km, 1 = 1.2 km, 0 = 4.18 km, A = 6.19 km, and B = 10.28 km (Costa *et al.* 2010). In the case of the mini-PATs, the tracks were generated from raw light data using Wildlife Computers GPE3 tools. Extreme outliers, positions on land and those with unclassified error estimates (cls - Z) were removed. Positions were mapped as track-lines using MapInfo Ver. 16. software. Estimated positions from the dorsal-fin mounted satellite tags were allocated to the Austral seasons: summer = December, January and February; autumn = March, April and May; winter = June, July and August, and spring = September, October and November. Hotspot density methods utilising kernel density estimator (KDE) functions in MapInfoPro Ver. 16 were used to estimate the patterns of density of positions in 5 – 10 km cell areas using the GPE3 generated position estimates from data collected by the mini-PATs. This function estimates the density of positions within an elliptical radius of each cell. The kernel function operates within the search radius and weights each sample by distance. Satellite telemetry data collected for all White Sharks were combined and gridded into 10 x 10 km squares to match the most conservative, error estimates for the lowest quality Argos data based on Costa *et al.* 2010) (B cls = 10.28 km). Percentage overlap maps (% per grid-square with a spatial scale ≤10 km) were generated that included all satellite tracked White Sharks (n = 10), ecological and operational GIS spatial data overlays for the study region, including acoustically monitored sites, aquaculture managed zones, finfish aquaculture sites, Snapper spatial closures, commercial abalone fishing areas, cage-diving sites, marine parks sanctuary zones, and pinniped colonies.

Environmental/physical habitat and depth time-series were inspected visually to investigate habitat use by satellite tagged White Sharks. These included monthly water temperatures from ADCP on moorings at three SAIMOS/IMOS reference stations, and data loggers on the ASBTIA monitoring site in Spencer Gulf, its approach, and the EGAB at 5, 40, 95 and 100 m depths.

Remote-sensed data were linked to location estimates for dorsal-mounted and mini-PATs. Each value represents an average within a 9 x 9 km grid centred around the location estimates. Sea surface temperatures from MODIS Aqua (Level 3, 1 km resolution) were obtained from the IMOS AODN portal. Values were averaged within a 9 x 9 km grid centered around the estimated locations for dorsal-mounted and mini-PAT tags; Bathymetry depth (m) at estimated tag locations extracted from the Australian Bathymetry and Topography Grid, 2009 (Geoscience Australia, 2009, 250m resolution). Chlorophyll-*a* concentration (ug.L$^{-1}$) from MODIS Aqua OC3 algorithm (Level 3 product, 1 km resolution) obtained from the IMOS AODN portal.

Summary time series of water temperature and depth data were transmitted from floating mini-PATs following detachment from animals. High resolution archived temperature and depth data from recovered mini-PATs. Archived temperature datasets were binned and averaged to 1-minute averages of time, depth, and temperature spanning the periods from 6 May 2015 14:20 to 11 June 2015 23:27 (S8), and 6 May 2015 18:03 to 12 June 2015 03:04 (S9). Two data sets of equal size (*n* = 51,555 = 859.25 min; 35.80 days) were generated. Times were converted from GMT to ACST. For the two archived time series, temperature - depth profiles were generated using average daily temperature with depth bins with intervals of 1 m. Depth data were extracted from archival tag records and corrected for pressure-sensor drift.

**Table 5**. Predictor variables used in generalised linear mixed models for White Sharks in Spencer Gulf (SG) and the Neptune Islands Group (NIG), and Bronze Whalers in Spencer Gulf. Abbreviations: Bureau of Meteorology (BOM), Cage-diving Operators (CDO), Australian Southern Bluefin Tuna Industry Association (ASBTIA), South Australian Integrated Marine Observing System (SAIMOS), Acoustic Doppler Current Profiler (ADCP), Southern Spencer Gulf (SSG).

| Predictor variable | Unit | Abbreviation in models | Data source | Model area | Variable type |
|---|---|---|---|---|---|
| Site type description | NA | SiteType | SARDI and PIRSA data, published SARDI reports. | SG and NIG | Category / Factor |
| Shark total length | m | TL | Measured; estimated in pole-tagged White Sharks. | SG and NIG | Numeric |
| Sex | NA | Sex | Observed | SG and NIG | Category |
| Month | NA | Mon | Observed | SG and NIG | Category |
| Season | NA | Seas | Derived | SG and NIG | Category / Factor |
| Bottom depth | m | Dep | Measured | SG and NIG | Numeric |
| Longitude | Dec deg | Long | Measured | SG and NIG | Numeric |
| Latitude | Dec deg | Lat | Measured | SG and NIG | Numeric |
| Bottom temperature | °C | BTemp | ADCP at 3 SAIMOS sites in SSG 45 m depth, SW of Avoid Bay 95 m depth, and west of Kangaroo Island on the 100 m isobath. | SG and NIG | Numeric |
| Water column temperature | °C | Temp | Measured Mean daily water temperature data at 5 m in 21 m depth from ASBTIA sensor near Boston Island. | SG | Numeric |
| Wind speed | $m.s^{-1}$ | Wind | BOM; Neptune Islands. | SG and NIG | Numeric |
| Moon phase | NA | Moon | Astronomical Applications Dept. US Naval Observatory. | SG and NIG | Numeric / Scaled |
| Proximity to pinniped colony/haul-out | km | ProxLNFS, ProxASL | Measured | SG | Numeric |
| Proximity to Snapper habitat | km | ProxSnap | Measured | SG | Numeric |
| Proximity to finfish aquaculture zone | km | ProxAqua | Measured | SG | Numeric |
| Cage-diving operator presence | none | CDO | SARDI electronic logbook | NIG | Category / Factor |

## Results

### *Monitoring periods*

Acoustic monitoring times at the 28 sites varied from 153 to 736 days, with 86% of receivers deployed for >1 year. Receiver deployment information is summarised in Table 1.

### *Acoustic telemetry*

A total of 55 White Sharks ranging from juveniles to adults were tagged with acoustic tags between September 2013 and December 2015 (Table 3). Tagged sharks consisted of 32 males, 16 females of 1.8 – 5.0 m (Fig. 2) and seven unsexed sharks of 2.0 – 4.5 m.

Tags were deployed in central and SW Spencer Gulf (*n* = 11, 20%), and the North (*n* = 33, 60%), and South Neptune Islands Group (*n* = 11, 20%) (Fig. 1, Table 3). Twenty-nine tags were deployed in the Neptune Islands prior to deploying the first receivers in Spencer Gulf and the EGAB during December 2014. A total of 24 Bronze Whalers ranging from 1.5 – 2.6 m (mean = 1.9 ± 0. 4 m) were captured and tagged in SW Spencer Gulf during summer and autumn 2015 (Fig. 2). The sex ratio of tagged Bronze Whalers was close to parity and comprised 11 females of 1.5 – 2.5 m (mean = 1.8 ± 0.3 m), and 13 males of 1.2 – 2.6 m (mean = 1.9 ± 0.4 m). A total of 50,969 acoustic detections of tagged White Sharks and Bronze Whalers were recorded on receivers between 18 December 2014 and 15 February 2017.

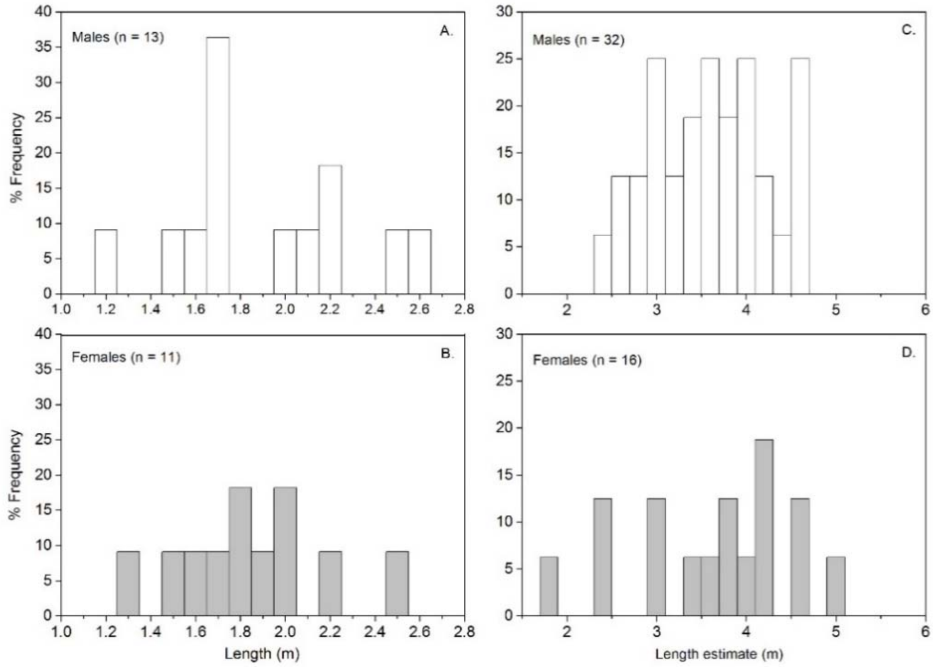



**Figure 2**. Length frequencies for male (top row) and female (bottom row) Bronze Whalers (A and B) and White Sharks (C and D) fitted with acoustic tags in Spencer Gulf and EGAB between 2013 and 2015.

### ***White Sharks***

#### Acoustic detections

A total of 42,647 detections of 34 White Sharks were recorded from 18 December 2014 to 15 February 2017. The proportion of tagged White Sharks detected using at least one site was 61%. Tagged sharks were recorded at 20 (71%) of the 28 monitored sites. Region-specific totals of 860 detections were recorded in Spencer Gulf, 41,763 detections in the Neptune Islands Group and 29 detections in the EGAB. A summary of detections by site, site type, and receiver is shown in Table 1.

#### Spatial and seasonal patterns by region

Seasonal patterns of detection frequencies were significantly different (KS-test = 2.25, $p < 0.05$) between Spencer Gulf (combined sites) and in the Neptune Islands Group (both sites), with a first peak occurring in May and a second in July at the latter sites. A third, lesser peak in detections occurred in spring-summer at the Neptune Islands that mostly comprised male sharks did not occur at sites in Spencer Gulf (Fig. 3).

An increase in detection frequencies in autumn and early winter (May – July) coincided with peaks in mean bottom water temperatures at IMOS/SAIMOS monitored sites in southern Spencer Gulf, western Kangaroo Island, SW of Avoid Bay in the EGAB. This latter oceanographic monitoring site is located in similar depth ranges and adjacent to the Neptune Islands (Fig. 3).

Insufficient detection data were collected to model seasonal and regional trends in shark counts and presence with environmental factors in the EGAB (Fig. 3).

#### Seasonal patterns by site type

*Finfish aquaculture sites*

Three of the seven monitored finfish aquaculture sites were visited by tagged White Sharks. A sum of 73 detections was recorded during 2,280 monitoring days. The mean monitoring time per receiver at this site type was 325 ± 163 days. Finfish farm sites visited by White Sharks included one in outer Boston Bay, and offshore sites located to the east of Arno Bay. Counts of detections per site were low and ranged from 0 – 34 (mean = 12 ± 15).

In this section, numbers of detections are provided following each Shark ID in parentheses. At Bickers Island, White Sharks were detected in June (Cc4 = 1) and July 2015 (Cc42 = 16, and Cc44 = 9). Two sites near Arno Bay were visited in April (Cc25 = 7) and June (Cc25 = 19), and in July (Cc42 = 5) and October (Cc45 = 16).

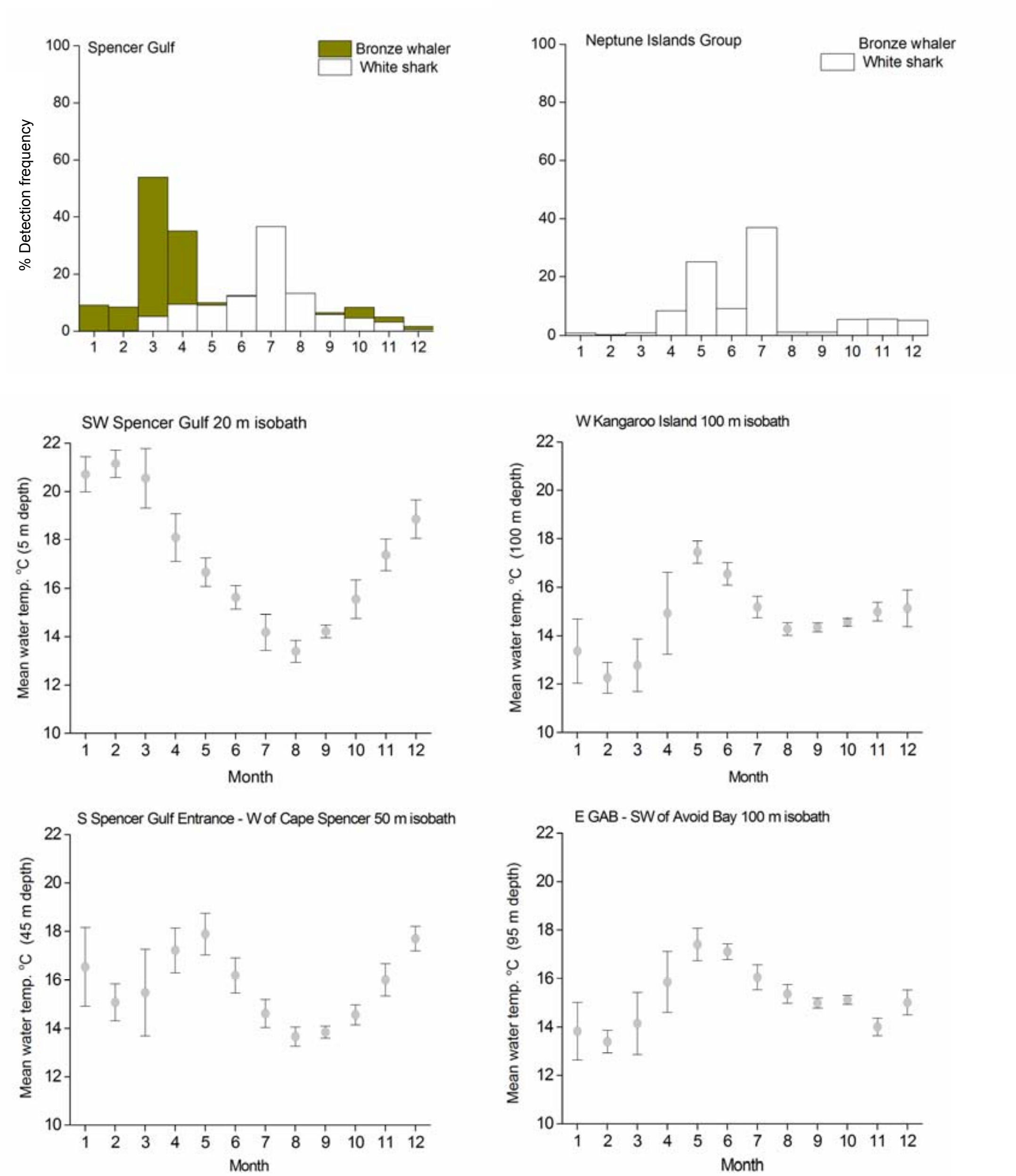



**Figure 3**. Seasonal patterns in percent detection frequency of White Sharks and Bronze Whalers (top left) at sites in Spencer Gulf (combined) and for White Sharks (top right) in shelf waters in the Neptune Islands Group. Plots with error bars show mean bottom water temperature at IMOS sites off Kangaroo Island at 100 m depth, in southern Spencer Gulf at 45 m, off Avoid Bay in the EGAB at 95 m depth, and east of Boston Island inside SW Spencer Gulf in the aquaculture zone at 20 m depth (sensor at surface: 5 m depth).

*Snapper habitats*

White Sharks visited all four Snapper habitat (reef) sites, with 397 detections recorded over 2,506 monitoring days. Mean monitoring time per receiver was 501 ± 78 days. Counts of White Shark detections per site ranged from 0 – 296 (mean = 79 ± 124). Snapper habitats visited by White Sharks included Balgowan in October 2016 (Cc48 = 7), and the Estelle Star wreck during September 2015 and March 2016 (Cc45 = 9 and 3, resp.). White Shark Cc25 visited the Estelle Star repeatedly over short periods (1 – 17 detections per month) during March-April, November-December 2015, February and April 2016. Buffalo Reef was visited briefly by several sharks in May (Cc4 = 1, Cc23 = 4), July (Cc37 = 3) and August 2015 (Cc21 = 5 and Cc25 = 5), and in May 2016 (Cc7 = 3). The site located to the south-east of Dangerous Reef was visited briefly by six sharks between May and October. Shark Cc25 visited this site briefly in May (3) and October 2015 (8), and for longer periods in July (172), August (63) and September (25). The other five sharks visited briefly in May (Cc25 = 3 and Cc16 = 4), June (Cc7 = 3), July (Cc4 = 3 and Cc41 = 1), and August 2015 (Cc48 = 6). White Shark Cc7 revisited in April 2016.

*Pinniped colonies and haul-outs*

Six of seven monitored pinniped sites were visited by tagged White Sharks. These included, Ward Island in the EGAB; Rabbit Island; Donington Rock; the channel between English Island and Sibsey Island; Dangerous Reef West Island in Spencer Gulf, and Hopkins Island near the entrance to Spencer Gulf. No acoustic detections were recorded at the largest ASL colony in the EGAB at Olive Island over a monitored period of 416 days. A total of 256 detections were recorded on 3,377 monitoring days.

Mean monitoring time per receiver was 482 ± 77 days. Detection counts at each site ranged between 0 and 109 (mean = 37 ± 46). Of the two haul-outs used by Long-nosed Fur Seals and ASL, Rabbit Island was visited by one shark (Cc4, 2) in June 2015, and Donington Rock was visited in May and June by Cc4 (1 and 2, resp.), in July by Cc42 (9) and August by Cc46 (2). The site adjacent to English Island was visited by six sharks (total = 96 detections) including: Cc11 in March and April 2015 (5 and 4); Cc4 in June 2015 (2); Cc42 (69) in July; Cc25 in August (10); Cc47 and Cc48 each in August 2015 (3 ea.).

West Island at Dangerous Reef was visited by five tagged White Sharks between April-August and November 2015, and in February and April 2016. Shark Cc7 visited in May 2015, February and April 2016, Cc11 in April 2015 (1), and Cc16 in November 2015 (4). Cc25 visited in May (8), June (5), July (2), and August 2015 (1), and Cc48 visited in August 2015 (2). The western side of Hopkins Island was visited by Cc7 in May (3), June (52) and July

(22) by Cc25 in September (3) and October (2), and by Cc16 (3) in November 2015. The site at Hopkins Island was revisited by Cc7 in March (14) and May 2016 (10). Two sharks, Cc11 and Cc31 moved westward into the EGAB in autumn and made brief visits to Ward Island in April (6) and May 2015 (1).

*Possible movement paths*

Five of seven possible movement path sites were visited by tagged White Sharks. A total of 163 detections were recorded over 3,433 monitoring days. Mean monitoring time per receiver at this site type was 490 ± days. Counts of detections per site ranged from 0 – 116 (mean = 23 ± 42). Sites visited in EGAB included Pt Drummond in April 2015 (Cc11 = 1), and February 2016 (Cc7 = 1); the channel between Inside Waldegrave Island and the mainland near Elliston in May 2015 (Cc7 = 4), September 2015 (Cc45 = 1), February 2016 (Cc33 = 5), Topgallant Island adjacent to Flinders Island during May (Cc11, 3), August 2015 (Cc39, 5), and February 2016 (Cc7 = 2). In southern Spencer Gulf, six sharks were detected briefly at Bridgette Shoal, in May (Cc36 = 5, and Cc7 = 1), June (Cc25 = 5), July 2015 (Cc44 = 1), August (Cc47 = 4, and Cc25 = 8), and September 2015 (Cc48 = 1). Four White Sharks were detected at Porter Rocks between March and October. Shark Cc7 returned to that site briefly in March, April and May of 2016; visited during five autumn months over two seasons. This highly mobile individual visited seven predicted movement path and Snapper habitat sites, in addition to the Neptune Islands Group.

*Cage-diving sites*

Cage-diving operation sites located at the North and South Neptune Islands were visited by the highest number of tagged White Sharks of the site types. A large proportion were tagged at these offshore sites (Table 3). A total of 41,736 detections of tagged White Sharks were recorded at the two Neptune Islands sites. These comprised 24,957 detections at the North Neptune Islands (19 sharks), and 16,806 at the South Neptune Islands (17 sharks). A total of 22 sharks were detected at the two sites. Several sharks visited both sites. Peaks in detections occurred in May, July and December at the North Neptune Islands, and in May, July and November at the South Neptune Islands. Of 34 tagged sharks detected during the project period, 15 (44%) individuals were not detected outside of the Neptune Islands.

## Site affinity and fidelity

A total of 12,418 days of data were used to estimate site-affinity and fidelity for 34 tagged sharks over 948 shark days. Spatial patterns of counts of sharks detected amongst sites (affinity), and number of shark days (fidelity) in Spencer Gulf and the EGAB are shown in Fig. 4. Fidelity metrics including sum of shark days, mean shark days, affinity rate (sharks per 100 days) are provided in Fig. 5, and spatial patterns of shark days at the main visited sites (with >400 monitoring days) for the ten most frequently detected sharks are shown in Fig. 6.

Of the three finfish aquaculture sites visited, counts of White Sharks detected per finfish farm site ranged from 1 – 3 (max; Bickers Island; mean = 1 ± 1.3). Rates of sharks per monitored day ranged from 0.006 – 0.007 (≈0.6 – 0.7 sharks. 100 $d^{-1}$). Site fidelity index scores for individual sharks at this site type ranged between 0.006 – 0.01 (mean = 0.004 ± 0.005) (Figs. 4 and 5). Note: low samples sizes of individuals/detections were recorded within this site type.

Of the four Snapper habitats visited, counts of individuals varied between 1 – 6. Rates of sharks per monitored day at visited sites ranged from 0.002 – 0.01 (≈0.2 – 1.4 tagged sharks. 100 $d^{-1}$) (Fig. 5). Counts of shark days per site were 1 – 28 (mean = 9 ± 11). The maximum occurred at the site the south-east of Dangerous Reef. Site fidelity index scores for sharks visiting Snapper habitat sites were 0.002 – 0.06 (mean = 0.02 ± 0.03).

Of the six pinniped sites visited, counts were 1 – 6 sharks. Counts of shark days per site ranged between 1 – 15 (max – English Island) (mean = 6 ± 5). Rates of sharks per monitored day were 0.002 – 0.01 (≈0.2 – 1.4 tagged sharks. 100 $d^{-1}$). Site fidelity index scores at this site type were 0.002 – 0.03 (mean = 0.01 ± 0.01) (Figs. 5 and 6).

Of the five possible movement path sites visited, counts of individuals detected per site ranged from 2 – 5. Rates of sharks per monitored day at visited sites ranged from 0.003 – 0.01 (≈0.3 – 1 tagged shark.100 $d^{-1}$). The estimated number of shark days per site ranged between 2 – 25 (mean = 5 ± 9) (max; Porter Rocks, Thistle Island). Site fidelity index scores at this site type (Fig. 5) for individuals (Figs. 6) ranged between 0 – 0.05 (mean = 0.01 ± 0.02).

Counts of 17 and 19 different sharks were detected at the cage-diving sites at the South and North Neptune Islands, respectively. Counts of shark days by site were 214 and 600 (max at North Neptune Island) (mean = 407 ± 273). Rates of sharks per monitored day were 0.04 (≈4 tagged sharks.100 $d^{-1}$) at South Neptune Island and 0.05 (≈5 tagged sharks.100 $d^{-1}$) at North Neptune Island. Site fidelity index scores were 0.48 at the South Neptune Islands, and 1.57 at the North Neptune Islands (mean = 1.27 ± 0.77) (Fig. 5). Notably, Cc7 was present on 50 monitored days, Cc21 on 32 days, Cc25 on 22 days, and Cc23 on 16 days at these sites.

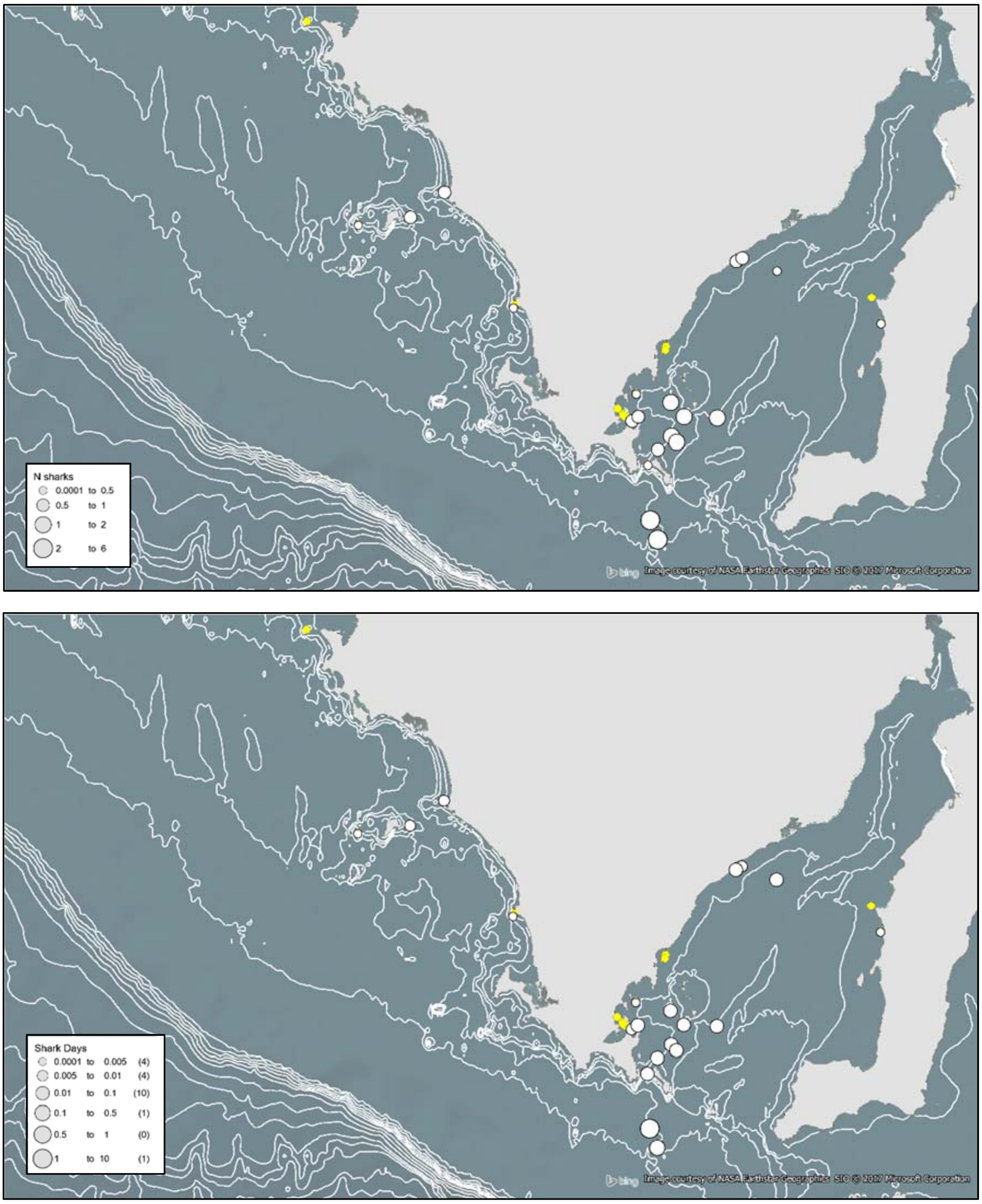



**Figure 4**. Counts of number of White Sharks (top plot) detected visiting each site and number of shark days (fidelity) (bottom plot) scaled by monitoring time for White Sharks in Spencer Gulf and the eastern Great Australian Bight. Yellow symbols indicate sites where receivers were located and no detection data were collected.

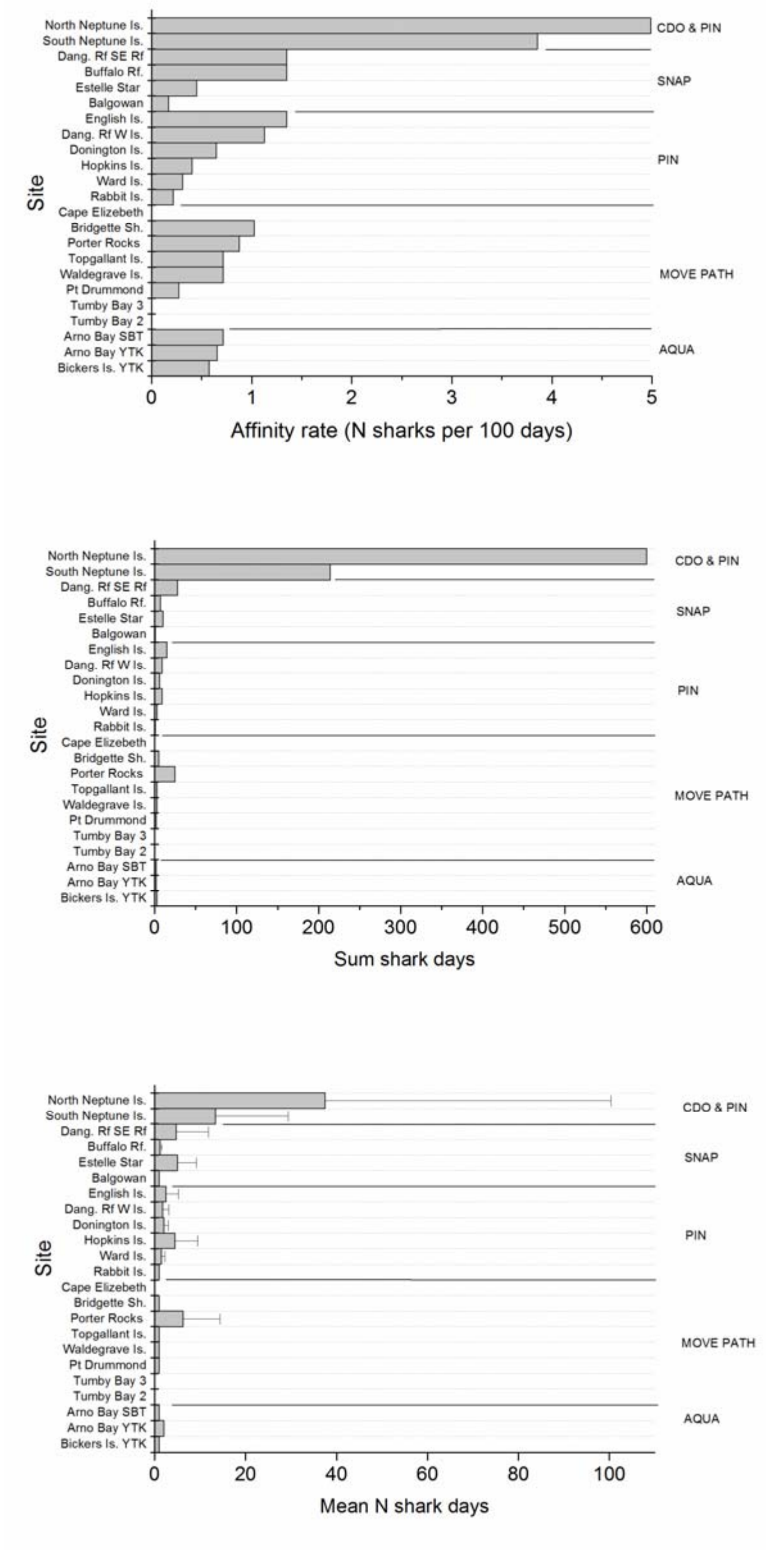



**Figure 5**. Fidelity metrics for White Sharks by site and site type in Spencer Gulf and the eastern Great Australian Bight.

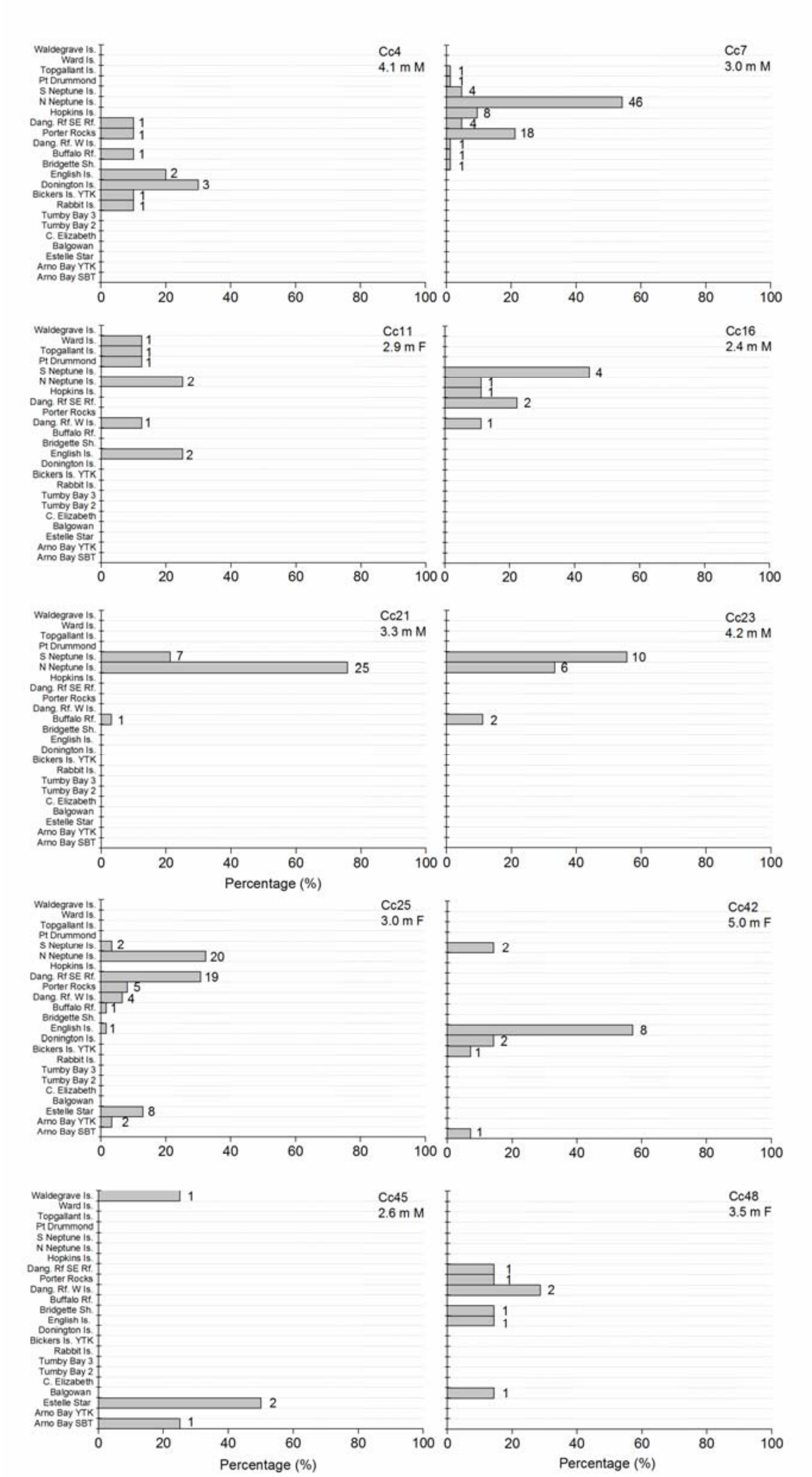



**Figure 6**. Spatial patterns of fidelity (shark days) for ten individuals at the main visited sites. Note: sites shown had >400 monitoring days except sites 1 (281d), 2 (153d) and 18 (381d) (from bottom).

### Relationships with environmental, spatio-temporal, and activity variables

Based on ΔAIC, the best glmm model fit (ΔAIC from null model = 129.8) explaining patterns of presence at Spencer Gulf sites included water temperature (slope/model coeff = -0.33, s.e. = 0.07, *p* <0.01), seasons of autumn and winter (coeffs = 2.12 and 1.5., s.e. = 0.74 and 0.83, and *p* = 0.004 and 0.07, respectively), two site type factors, including predicted migration paths (coeff = 1.25, s.e.= 0.44, *p* = 0.004), and Snapper habitats (coeff = 2.19, s.e. = 0.46, and *p* = <0.0001) (Table 6). Proximity to Australian Sea Lion colonies and haul-outs (coeff = -0.013, s.e. = 0.004, *p* = 0.001) was a significant variable, yet at the broader level of site type that included all pinniped colonies and haul-outs combined (where LNFS colonies were included), this factor was not significant (*p* = 0.74).

Model runs for the Neptune Islands datasets included cage-diving operator presence as a factor. The best glmm fit explaining presence of White Sharks at the North Neptune Islands in 2015 – 16, included a positive correlation with mean daily bottom water temperature at the western Kangaroo Island IMOS site (near the 100 m depth contour) (coeff = 0.19, s.e. = 0.04, *p* = <0.001), significant positive correlations with autumn, winter, and the broader factor of 'month', and a significant negative correlation with spring (coeff = - 0.70, s.e. = 0.16, *p* <0.001) (Table 6). Daily presence of cage-diving operators was also highly significant (*p* <0.001) in the most parsimonious fits. The best glmm fit to the daily White Shark count data (ΔAIC = 107.2), had a positive correlation with mean daily bottom water temperature at the west Kangaroo Island IMOS site (coeff = 0.06, s.e. = 0.02, *p* = <0.002), seasons including autumn (coeff = 0.33, s.e. = 0.11, *p* = 0.003) and winter (coeff = 0.62, s.e. = 0.10, *p* = <0.001) (Summer was non-sig., *p* = 0.22), and with cage-diving operator presence (coeff = 0.11, s.e. = 0.05, *p* = 0.04), and a negative relationship with moon phase (coeff = -0.26, s.e. = 0.07, *p* = 0.0003) (Table 6). Model fits were poorer when estimated total length of sharks (*p* = 0.26), sex (*p* = 0.56), moon phase (*p* = 0.66), and wind speed (*p* = 0.19) were included (ΔAIC = 178) – none of these variables were useful predictors.

**Table 6.** Generalised linear mixed model fits to daily presence and count data for White Sharks in Spencer Gulf and the Neptune Islands Group. P = presence of tagged sharks, DC = daily count of visiting tagged sharks.

| **Mixed models** | **AIC** | **ΔAIC** | **dev** | **df.resid** | **Fit** | **Family** |
|---|---|---|---|---|---|---|
| Presence of White Sharks at North Neptune Islands | | | | | | |
| P ~ 1 + 1 \| SharkID (null model) | 7114 | | 7110 | 22837 | null | Binomial |
| P ~ 1 \| SharkID + Seas + CDO + BTemp + TL + Moon + Mon + Wind + Sex | 6916.4 | 178.6 | 6892.4 | 22827 | full | Binomial |
| P ~ 1 \| SharkID + Seas + CDO + BTemp + Mon | 6910 | 181.6 | 6894 | 22831 | best | Binomial |
| Daily count of White Sharks at North Neptune Islands | | | | | | |
| DC ~ 1 + 1 \| SharkID (null model) | 2055 | | 2051 | 589 | null | Poisson |
| DC ~ 1 \| SharkID + Seas + Sex + CDO + Moon + BTemp + Mon + Wind | 1991.5 | 63.5 | 1973.5 | 582 | full | Poisson |
| DC ~ 1 \| SharkID + Seas + CDO+ BTemp + Moon | 1958.9 | 107.2 | 1931.8 | 583 | best | Poisson |
| Presence of White Sharks in Spencer Gulf | | | | | | |
| P ~1+ 1 \| SharkID (null model) | 1680 | | 1676 | 72728 | null | Binomial |
| P ~ 1 \| SharkID +Seas + Temp + Dep + TL+ Sex + Moon + Wind + ProxASL + ProxLNFS+ ProxSnap + ProxAqua + SiteType + Long + Lat | 1553.2 | 126.8 | 1513.2 | 72380 | full | Binomial |
| P ~ 1 \| SharkID + Seas + Temp + Dep + ProxASL + SiteType | 1550.2 | 129.8 | 1528.2 | 72389 | best | Binomial |

### ***Bronze Whalers***

#### Acoustic detections

A total of 8,322 detections of 21 tagged sharks were recorded across all monitored sites. The proportion detected using at least one site was 88%, and the species was present at 14 of 28 (50%) sites, with up to 15 individuals (71%) detected per site.

#### Spatial and seasonal patterns by region

Regional comparisons between gulf and shelf areas were not conducted as no Bronze Whalers were detected at the Neptune Islands sites, and low detection counts were recorded at only two EGAB sites.

#### Seasonal patterns by site type

*Finfish aquaculture sites*

One of seven monitored finfish aquaculture sites was visited by a tagged shark. The inshore site at Arno Bay was visited briefly in April (Cb18, 8). The eight detections were recorded over a combined 2,280 monitored days for the site type. No monitored sites in Boston Bay were visited by Bronze Whalers.

*Snapper habitats*

Bronze Whalers visited four of the five Snapper habitat (reef) sites. At this site type, 7,096 detections were recorded on 2,506 monitoring days. Counts of detections per site ranged from 0 – 4,147 (mean = 1,419 ± 1,869). Sites visited in eastern Spencer Gulf included Balgowan in May and October (25 and 260, respectively), and Cape Elizabeth from September to November. There were no detections of Bronze Whalers at the wreck of the Estelle Star. Buffalo Reef was visited by 13 individuals (4,147, all combined); sharks were present in all summer and autumn months; peaks in activity occurred in March (1,418 detections) and April (1,783). Bronze Whalers were detected at Buffalo Reef in November (8) and December (76). Of the 13 individuals using this reef slope, eight of the same sharks (62%) also used the reef to the south-east of Dangerous Reef. That site was visited by 15 Bronze Whalers (2,601, all combined) during the summer months, and in early autumn (April). There were no detections of the species at any site during winter. Of the 15 Bronze Whalers that were present at the site south-east of Dangerous Reef, eight of the same sharks (53%) used the reef slope near Buffalo Reef.

*Pinniped colonies and haul-outs*

Three of the seven pinniped colonies and haul-outs were visited by Bronze Whalers. An overall sum of 118 detections of nine sharks were recorded on 3,377 acoustic monitoring days. Colonies and haul-outs visited included, Hopkins Island, Dangerous Reef's West Island and English Island. Detection counts at each site were low and ranged between 0 and 73 (mean = 30 ± 33). The western side of Hopkins Island was visited by five Bronze Whalers between January and April, September and October; detection counts were low in each case and ranged from 2 – 22. The English Island site was visited briefly (2 – 11 detections) by three sharks between January and March, and in September. The western island at Dangerous Reef was visited briefly in March by two tagged sharks.

*Predicted movement paths*

Predicted movement path sites visited in the EGAB included Inside Waldegrave Island and Topgallant Island in April (7 and 3 by one shark, respectively). Bronze Whalers visited Bridgette Shoal ($n$ = 7 sharks) and Porter Rocks ($n$ = 10 sharks) between January and April in southern Spencer Gulf. There were no visits by the species during winter or spring at movement path sites in Spencer Gulf or the EGAB. Two sharks were detected at two sites in Tumby Bay (171 and 44, respectively, at sites 2 and 3) in September – November and March – April in SW Spencer Gulf.

*Cage-diving sites*

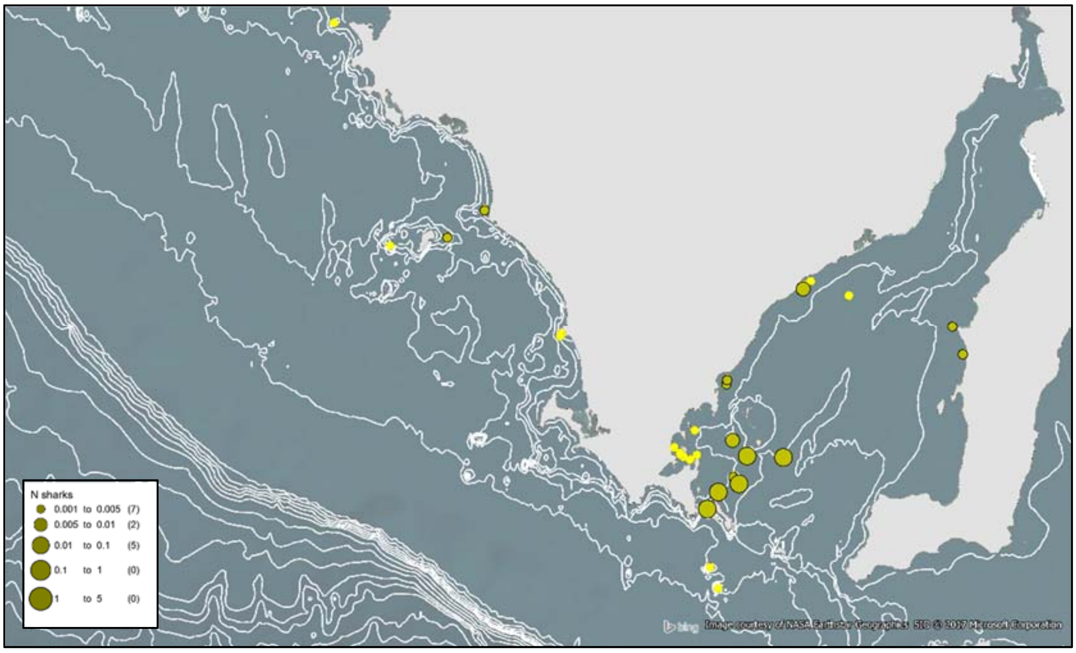
No tagged Bronze Whalers were detected on receivers at the two sites in the North and South Neptune Islands Group.

## Site affinity and fidelity

A total of 422 shark days were recorded for 21 sharks detected at 14 monitored sites. Spatial patterns of counts detected by site, and number of shark days (fidelity) in Spencer Gulf and the EGAB sites are shown in Fig. 7. Spatial patterns in fidelity and affinity metrics are shown in Fig. 8. Highest affinities and fidelity estimates (sums of shark days, and mean number of shark days) by site were recorded at the Snapper habitat and movement path sites, including a reef south-east of Dangerous Reef, Buffalo Reef, Porter Rocks and to a lesser extent, Bridgette Shoal. One shark (190 cm, F) was detected at one of seven finfish aquaculture sites. The rate of sharks per monitored day at the positive site off Arno Bay was 0.007 (0.7 shark. 100 $d^{-1}$) (Fig. 8). The count of shark days at the visited site was one. The site was visited on a single day for ~10 minutes. The site fidelity index score for the single shark at the site was 0.007. Of the four Snapper habitats, counts of tagged sharks that visited varied between 1 – 13. Sites visited by the species included Balgowan (1 shark), Cape Elizabeth (1 shark), Buffalo Reef (13 sharks), and a reef slope south-east of Dangerous Reef (13 sharks); rates per monitored day ranged from 0.002 – 0.03 (0.2 – 3 sharks. 100 $d^{-1}$) (Fig. 8). Counts of shark days per positive site ranged between 5 – 181 days (mean = 67 ± 85), with the maximum and equal maximum number of visiting sharks (n = 13) recorded at the reef slope site near Buffalo Reef. The other notable Snapper habitat site was a reef slope to the south-east of Dangerous Reef, which was visited by 13 sharks over 136 shark days. Site fidelity index scores for individuals at this site type ranged between 0 – 0.3 (mean = 0.15 ± 0.19). Bronze Whalers were detected at three pinniped colonies and haul-outs, including Dangerous Reef's West island, English Island and Hopkins Island, and counts of shark days per site ranged between 2 – 9 (max – Hopkins Island) (mean = 2 ± 3). Counts ranging from 2 – 5 sharks visited the pinniped colonies and haul-out sites. Rates of sharks per monitored day at visited sites ranged from 0.007 – 0.01 (0.7 – 1 shark. 100 $d^{-1}$) (Fig. 8). Site fidelity index scores at this site type ranged between 0 – 0.009 (mean = 0.005 ± 0.007). A total of 12 Bronze Whalers visited six predicted movement path sites. Sites visited included Inside Waldegrave Island (1 shark) and Topgallant Island (1 shark) in the EGAB, Bridgette Shoal (7 sharks), Porter Rocks (9 sharks), two Tumby Bay sites (2 sharks total), and Balgowan (1 shark) and Cape Elizabeth (1 shark). No sharks were detected at Pt Drummond in the EGAB. Rates of sharks visiting this site per monitored day ranged from 0.002 – 0.02 (0.2 – 2 sharks.100 $d^{-1}$) (Fig. 8). At predicted movement path sites, counts of shark days per site ranged between 1 – 44 days (mean = 10 ± 16) (max; Porter Rocks, Thistle Island). Site fidelity index scores for the 12 Bronze Whalers at this site type ranged between 0 – 0.1 (mean = 0.02 ± 0.03)

## Relationships with environmental, spatio-temporal, and activity variables

Based on model AIC and BIC values, the best glmm fit (binomial distribution) explaining presence of Bronze Whalers at the Spencer Gulf sites had an AIC =3643.7 (ΔAIC = 985.2), and included, seasons, water temperature (glmm = 0.30, s.e. = 0.03, $p$ <0.001), proximity to: Snapper sites (coeff = 0.09, s.e. = 0.04, $p$ = 0.01), ASL colonies and haul-outs (coeff = 0.08, s.e. = 0.02, $p$ = <0.001), and proximity to finfish aquaculture zones (coeff = 0.15, s.e. = 0.04, $p$ <0.001) (Table 7). There were negative correlations with the 'Seal' site type, (coeff = - 0.88, s.e. = 0.04, $p$ <0.001), and a positive correlation with the 'Snapper' site type, (coeff = 3.08, se = 0.56, $p$ <0.001). Daily counts of visiting Bronze Whalers were not modelled for the Spencer Gulf sites due to the low daily counts per site.



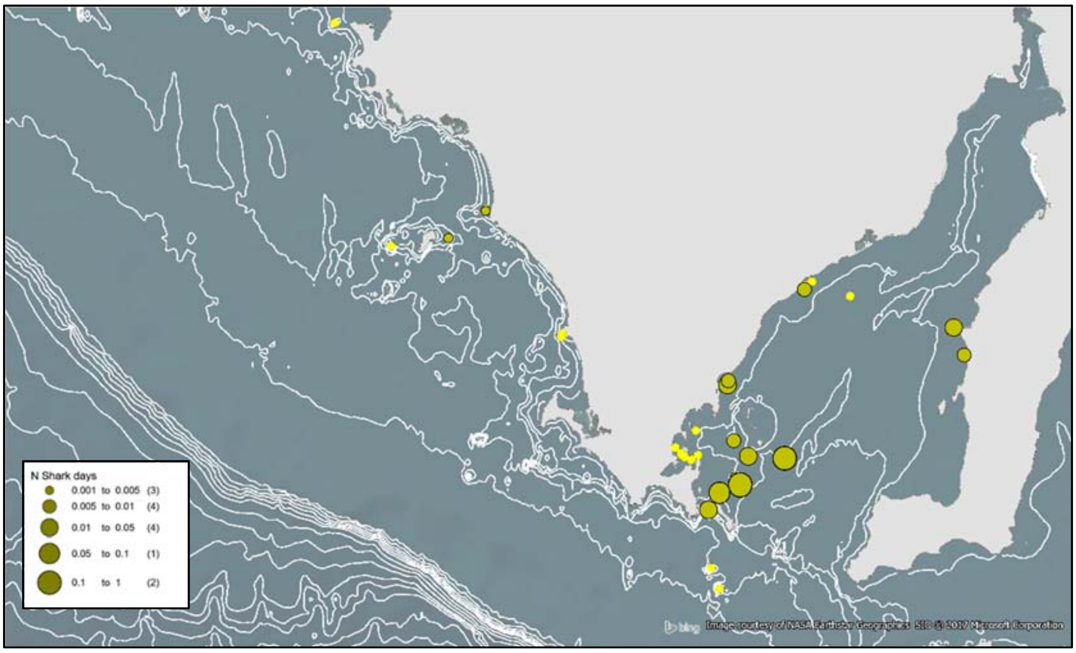




**Figure 7**. Counts of number of Bronze Whalers detected (top plot) and shark days (fidelity) (bottom plot) at each site scaled by monitoring time in Spencer Gulf and the eastern Great Australian Bight between 2014 and 2017. Yellow symbols indicate sites where receivers were located and no detection data were collected.

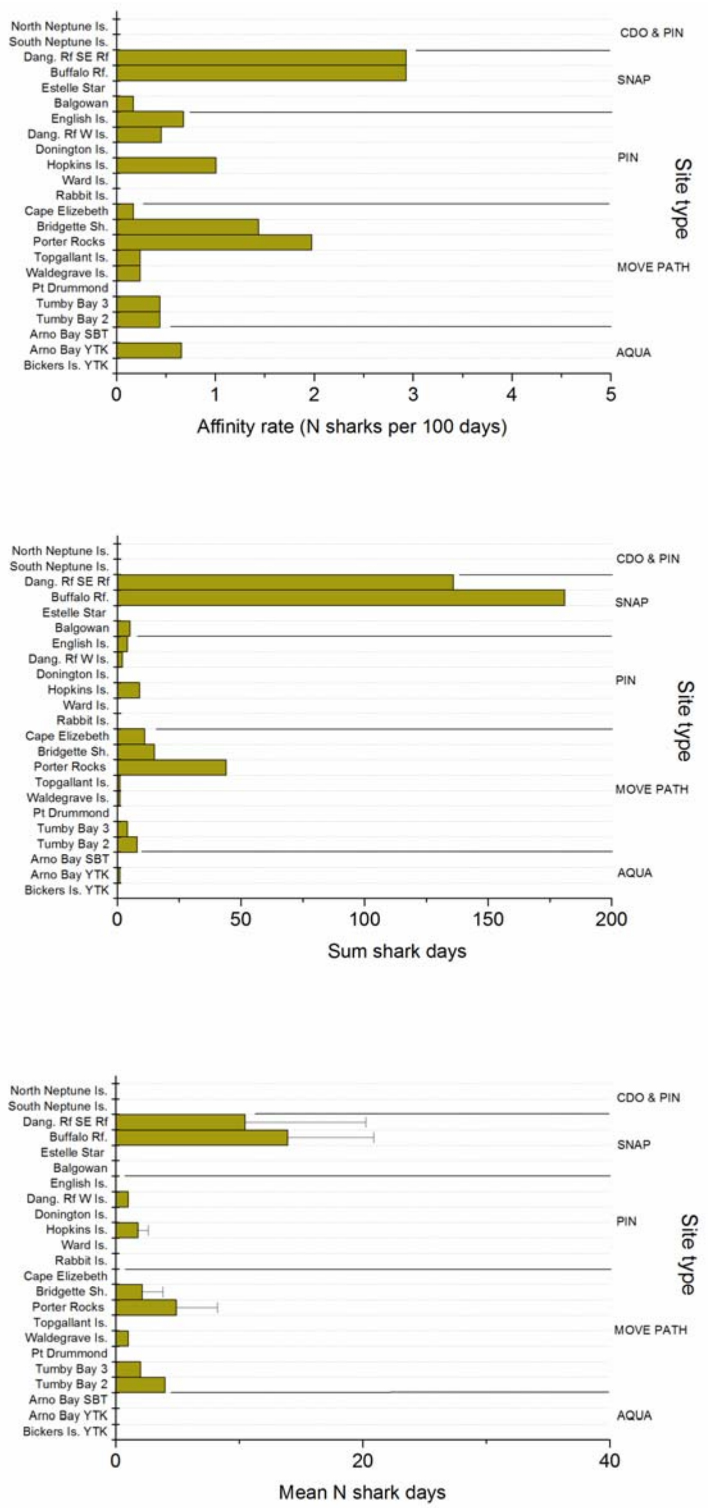



**Figure 8**. Fidelity metrics for Bronze Whalers by site and site type in Spencer Gulf and the eastern Great Australian Bight.

**Table 7.** Generalised linear mixed model fits to daily presence data for Bronze Whalers in Spencer Gulf. P = presence.

| Mixed models | AIC | ΔAIC | dev | df.resid | Fit | Family |
|---|---|---|---|---|---|---|
| Presence of Bronze Whalers in Spencer Gulf | | | | | | |
| P ~ 1 + (1 \| SharkID) (null model) | 4628.9 | | 4624.9 | 66836 | null | Binomial |
| P ~ (1 \| SharkID) + Seas + SiteType + ProxAqua + ProxSnap + proxLNFS + ProxASL + Moon + Temp | 3647.2 | 981.7 | 3621.2 | 66825 | full | Binomial |
| P ~ (1 \| SharkID) + Seas + SiteType + ProxAqua + ProxSnap + proxASL + Temp | 3643.7 | 985.2 | 3621.7 | 66827 | best | Binomial |

### *Satellite telemetry: Broad scale habitat use*

Satellite telemetry estimated positions and track-lines for White Sharks in the study area between 2014 and 2016 are shown in Fig. 9. Individual deployments of SPOT and ST PTT tags on White Sharks S1 to S5 ranged between 131 and 319 days in duration (Table 4). Mini-PAT deployments on White Sharks S6 to S10 provided individual deployments ranged between 67 and 104 days. Two Mini-PAT were subsequently recovered from southern Yorke Peninsula, and south-eastern Eyre Peninsula by members of the public, and the archived datasets were successfully retrieved (Table 4).

Information on habitat use of White Sharks collected during mini-PAT deployments (S6 – 10 over 64 – 102 days) showed individuals inhabited a diverse range of depth and thermal habitats that ranged from the shallow gulfs to the lower continental shelf slope (Table 8, Figs 10 and 11). Depths and mini-PAT surfacing locations showed southern Spencer Gulf and its entrance were key habitats for sharks S6, S8 and S9. Sharks S7 and S10 migrated offshore to continental shelf, slope and oceanic waters, and S6, S8 and S9 remained in the vicinity of the gulf and its approach, where they inhabited average depths of 17.7 ± 18 m (W4) to 32.1 ± 20.4 m (S8). Minimum and maximum depths ranging between 0 – 95 m (S9) and 0.5 – 105 m (S8) (Table 8, Fig. 10). Sharks S6, S8 and S9 experienced autumn and winter SSTs of 9.5 – 17.7°C (Figs. 10 and 11). Average SSTs by individual ranged from 14.8 ± 1.9 to 16.6 ± 0.4°C.

Average daily temperature minima recorded by tags on these three sharks ranged from 14.7 ± 1.9 to 16.4 ± 0.4°C. Lower temperatures reflected the large depth ranges traversed by sharks that visited shelf and slope habitats (13.9 – 16.1°C, for W2 and W5 respectively; estimated thermal minima = 4.7°C at 783 m (S7). Sharks S7 and S10 inhabited average depths of 103.5 ± 184.7 m and 22.5 ± 22.3 m, respectively. Depth ranges were 0 – 917 m (S7) and 0 – 163 m (S10) (Table 8). Reported SSTs experienced by these two individuals ranged from 15.8 – 20.3°C. Average reported SST experienced by shark S7 was 17.7 ± 1.1°C, as it travelled to Cape Leeuwin, WA. Shark S10 experienced SST ranging from 15.4 to 17.2°C (average = 16.1 ± 0.52°C) as it travelled north-west from the South Neptune Islands to the mid-continental shelf region to the south of Head of Bight.

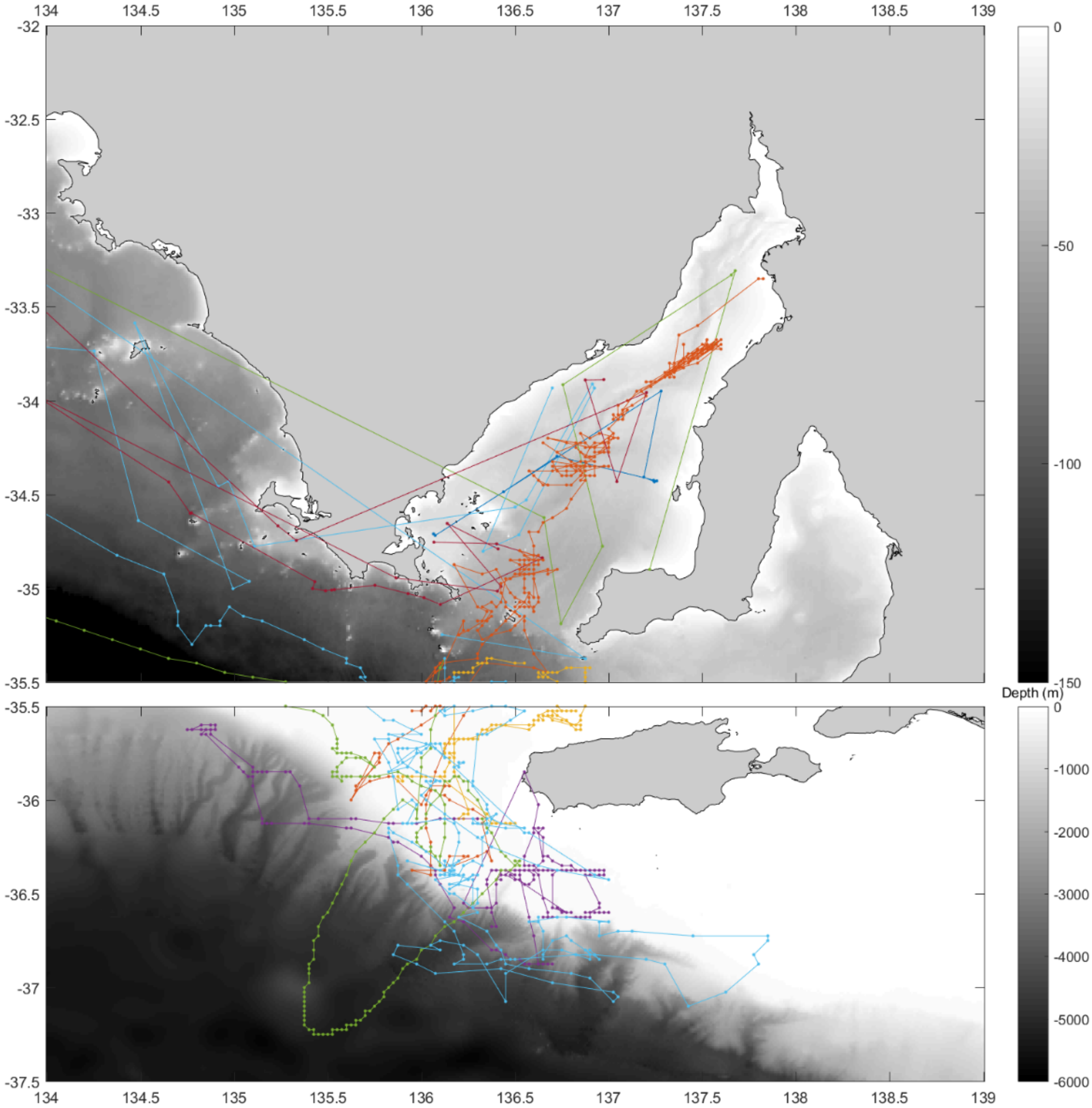



**Figure 9**. Satellite telemetry estimated positions and track-lines for White Sharks in the central study area between 2014 and 2016 over the bathymetry (Geoscience Australia, 2009). Colours indicate the different tracks of each shark. Tracks that extend across Eyre Peninsula have subsequent positions in either Spencer Gulf or the Great Australian Bight and vice-versa.

**Table 8**. Depth and temperature parameters for White Sharks S6 – S10 in 2015. Parameter estimates shown were sourced from transmitted mini-PAT data summaries.

| Parameter and statistic | S6 | S7 | S8 | S9 | S10 |
|---|---|---|---|---|---|
| N depth records | 2,077 | 26,668 | 11,362 | 19,776 | 2,413 |
| Ave depth (m) | 20.7 | 103.5 | 32.1 | 17.8 | 22.5 |
| SD depth | 18.9 | 184.7 | 20.4 | 18.1 | 22.3 |
| Min depth | 0 | 0 | 0.5 | 0 | 0 |
| Max depth | 98.0 | 916.5 | 105.0 | 95.0 | 162.5 |
| Ave SST (° C) | 14.8 | 17.7 | 16.6 | 15.7 | 16.1 |
| SD SST | 1.9 | 1.1 | 0.4 | 1.0 | 0.5 |
| Min SST | 9.5 | 15.8 | 15.9 | 13.8 | 15.4 |
| Max SST | 17.7 | 20.3 | 17.6 | 17.7 | 17.2 |
| Ave water temp minima | 14.7 | 13.9 | 16.4 | 15.1 | 16.1 |
| SD water temp min | 1.9 | 4.8 | 0.4 | 1.2 | 0.5 |
| Min water temp min | 9.5 | 4.7 | 15.2 | 13.2 | 15.3 |
| Max water temp min | 17.6 | 18.3 | 17.2 | 17.4 | 16.8 |

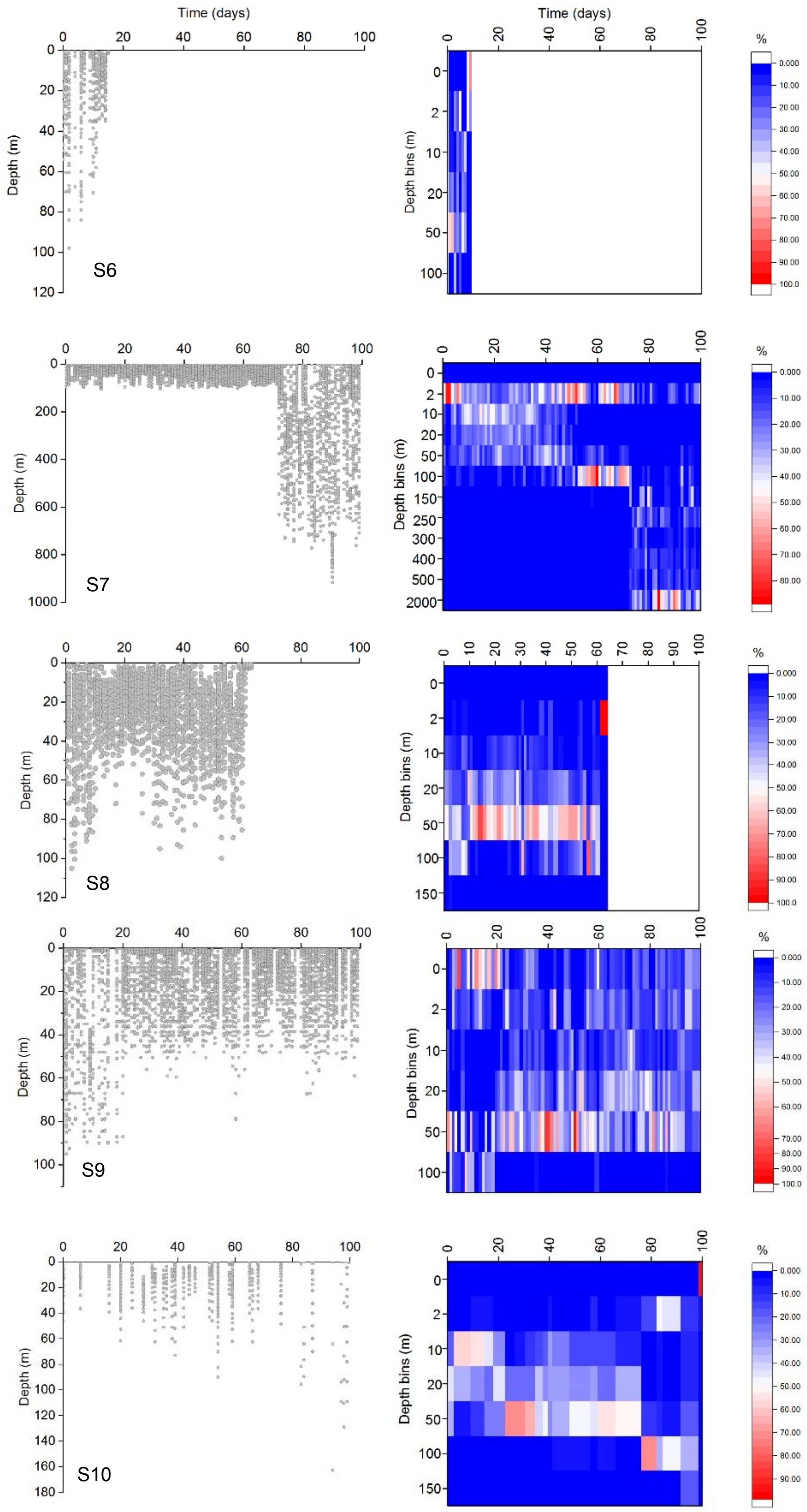



**Figure 10**. Percentage of time spent at depth by White Sharks (S6 – S10 from top to bottom) from Argos transmitted histogram summary and time series datasets.

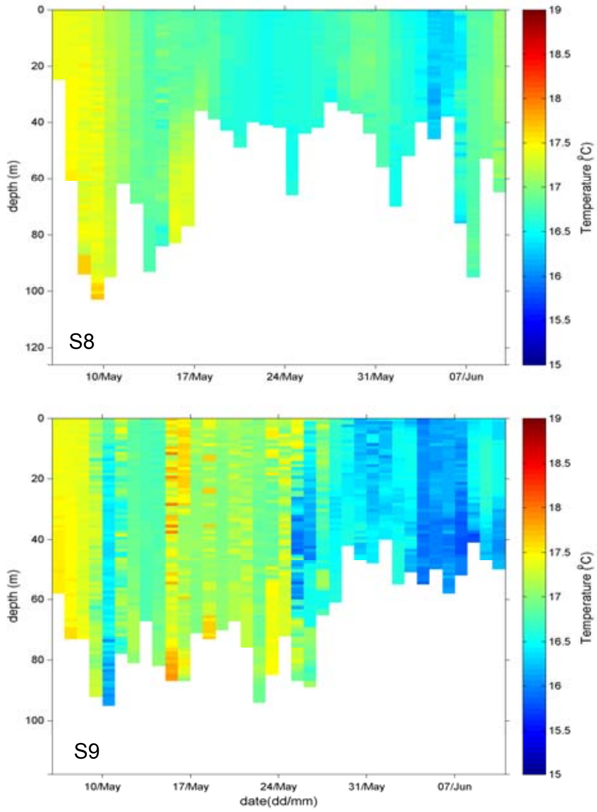



**Figure 11**. Temperature and depth habitat profiles for White Sharks S8 and S9. during autumn-winter 2015. Data were recovered from min-PAT tags and are summarised at 1 min averages and 1 m depth interval.

### ***Correlations between satellite tracks, remote-sensed environmental and physical variables***

#### Sea-surface temperature

Estimated satellite positions of White Sharks in Spencer Gulf (Fig. 10) coincided with sea-surface temperatures (SSTs) of 11.2 – 22.5°C (Fig. 12). Narrower ranges were observed when sharks were in the approach to Spencer Gulf and adjacent offshore shelf slope areas, where position estimates correlated with SST of 12.1 – 18.1°C (mean = 15.8 ± 1.2°C; median = 15.9°C) (Fig. 12). White Sharks mostly occupied mid-shelf, shelf break and slope areas of the GAB between Cape Pasley, Western Australia and Cape Catastrophe, South Australia, where position estimates correlated with SST of 11.4 – 20.1°C (mean = 15.8 ± 1.3°C; median = 15.7°C). Two sharks traversed GAB shelf waters to the area south of Western Australia, and position estimates for these sharks correlated with SST of 13.4 – 19.8°C (mean = 19.8 ± 1.1°C; median = 17.2°C). As these animals undertook these large transitory movements to the Indian Ocean, they traversed areas with SST of 16.2 to 24.0°C (mean = 19.3 ± 1.5°C; median = 19.1°C).

#### Chlorophyll-*a*

Data were considerably patchier for proxies of primary production (Chl - *a*), with data only available for 38% of the satellite position estimates (Fig. 12). In Spencer Gulf, position estimates correlated with Chl-*a* readings of 0.18 – 2.51 $\mu g.L^{-1}$ (mean = 0.59 ± 0.40; median = 0.49), however, these data have to be viewed with caution due to the proximity to land and the sensors abilities to deliver reliable information within that system. Chlorophyll-a readings correlating with White Shark satellite position estimates were higher in the approach to Spencer Gulf (0.05 – 2.34 $\mu g.L^{-1}$; mean = 0.38 ± 0.26), adjacent offshore shelf slope and submarine canyon areas of the GAB (0.03 – 2.16 $\mu g.L^{-1}$; mean = 0.33 ± 0.25), compared to shelf waters of south of Western Australia (0.04 – 0.73 $\mu g.L^{-1}$; mean = 0.24 ± 0.10). In the Indian Ocean north of Cape Leeuwin, Western Australia the satellite position estimates of White Sharks correlated with Chl-*a* values of <0.5 $\mu g.L^{-1}$ (mean = 0.16 ± 0.08 $\mu g.L^{-1}$).

#### Bottom depth

Satellite positions of White Sharks within Spencer Gulf correlated with bottom depths ranging from 1 – 79 m. The mean (30.0 ± 13.7 m) and median (29 m) reflected the preference for central gulf waters including the edges of the central and southern gutter (Fig. 9). Positions correlated with a vast range of bottom depths from 15 – 4,839 m (mean = 491 ± 1,042.74; median = 120), with the mean depth prominently influenced by the individuals that moved into oceanic near-slope habitats. When in the GAB, White Sharks mostly occupied mid-shelf to shelf break, and slope areas (mean = 926.2 ± 1,499.3; median = 141). As sharks moved through shelf waters to the south of Western Australia, satellite position estimates correlated with bottom depths of 10 – 3,897 m (mean = 287.07 ± 583.90. The median correlated with bottom depth of 80 m. Movements north and west of Cape Leeuwin traversed a broad range of bottom depths of from 45 – 3,692 m (mean = 1,540.8 ± 962.8 m), with the median = 1,359 m reflecting that shelf slope and oceanic movements were dominant.

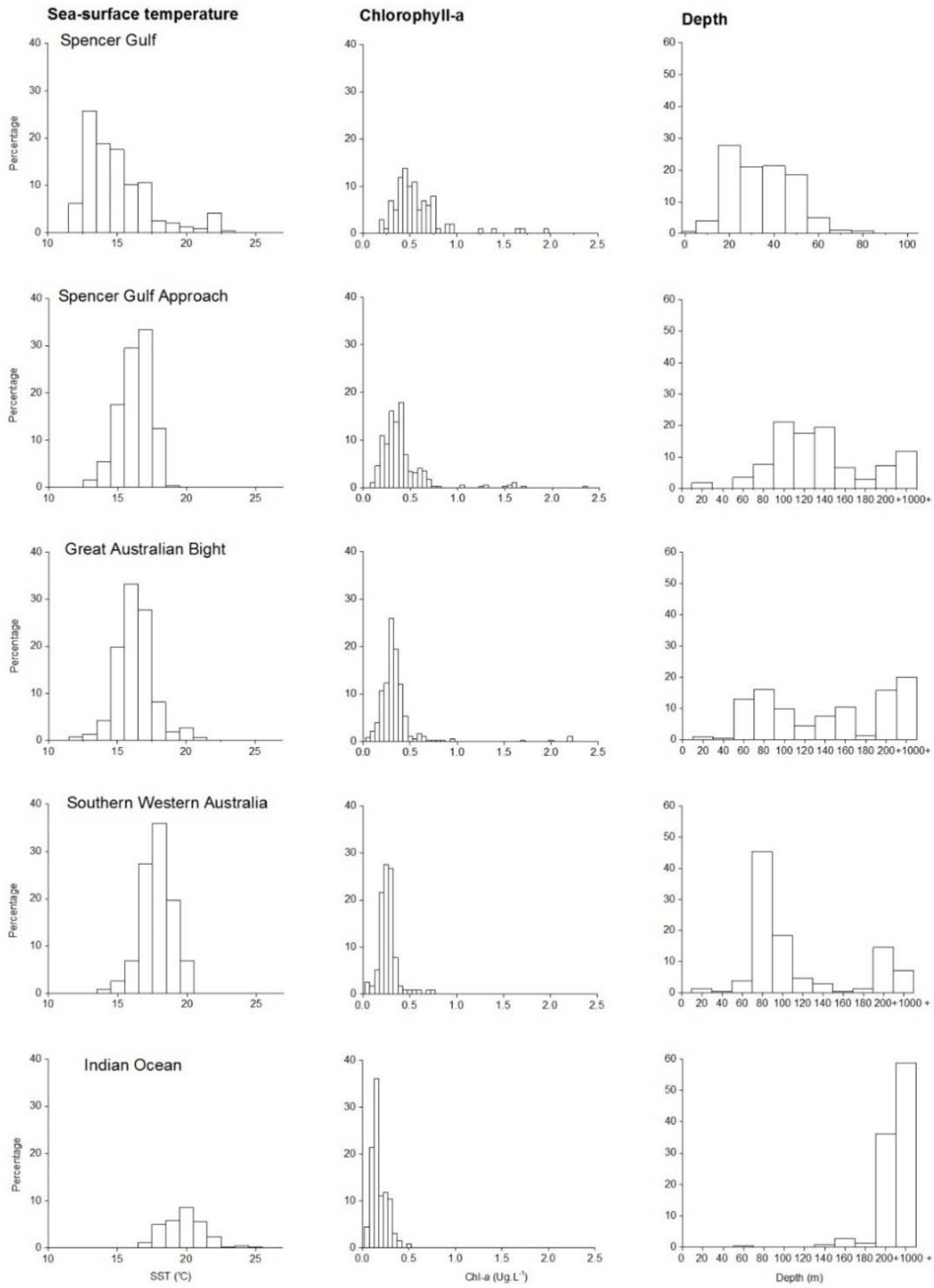



**Figure 12**. Environmental and physical correlates with satellite positions estimates for White Sharks tagged during 2014 and 2015. Remote-sensed data were sourced from MODIS Aqua (level 3, 1km resolution) via the IMOS AODN portal, and depth was sourced from Geoscience Australia (250 m resolution)

### *Spatial patterns of area use*

Spatial analyses of SPOT (S1 – S5) and mini-PAT (S6–S10) satellite tracking data (See Table 4) shown in Figs. 9, 13–17 indicated that the central 'gutter' of Spencer Gulf (>20 m depths), the continental shelf break, slope and its submarine canyons, were regions consistently used by White Sharks between January 2014 and February 2016 (Figs. 13– 17). Seasonal patterns illustrated using the satellite tagged individuals with the longest tracks (S1–S4) are shown in Figs. 13–15, and were generally consistent with patterns observed in the acoustic telemetry data, i.e. Spencer Gulf was used in autumn and winter, and to a lesser extent in summer. White Shark S4 undertook an extensive transitory movement from the tagging location in Spencer Gulf, across the GAB during winter-spring 2015 to oceanic and shelf slope waters in the Indian Ocean. The distal point of this migration was ~220 km offshore from Kalbarri, Western Australia. This shark subsequently returned to within 20 km of the tagging site in Spencer Gulf during summer, and soon afterwards, the tag ceased reporting signals to Argos (Fig. 14).

Activities and ecological features in those areas scored the highest percentages of nominal overlap (Table 9) based on the position per grid-square analyses (Fig. 18). Highest offshore area usage by White Sharks was recorded at and beyond the continental shelf-break and slope adjacent to the west and south-west of Kangaroo Island and southern Eyre Peninsula, and off south-west Western Australia in the Indian Ocean. Areas of high relief bathymetry between the 80 – 130 m isobaths were used by White Sharks during transitory movements across the GAB. Within Spencer Gulf, a total of 74% of estimated positions were correlated with depths ≥ 20 m. A total of 93% of estimated positions ($n$ = 2,956) occurred outside the gulf entrance (Cape Catastrophe – Cape Spencer). Proportional position per grid-square analyses showed the number and percentage by site types overlapping with satellite tagged White Sharks (at ≤ 10 km scale) varied considerably (Fig. 18). Spatially managed areas and their percentage overlap with satellite tagged White Sharks were: finfish aquaculture zones (5 sites; 22%), finfish farm sites (1 site; 5%), commercial abalone fishing spatial zones (45 sites; 24%), seasonal spatial closure areas for Snapper (wrecks) (1 site; 25%), cage-diving sites (1 site; 50%), and marine protected areas (36%) (Table 9). The number of marine park zones where White Sharks were observed inside marine park boundaries was 22 (23%). Only two (7%) sanctuary zones were visited by satellite tagged White Sharks, which included those at West Dangerous Reef and an offshore from Cape Borda, Kangaroo Island. Movement path sites (43%), Snapper habitats (20%), and spatial closures for Snapper (25%) that were monitored with acoustic receivers, overlapped (at scale of ≤ 10 km) with satellite position estimates of White Sharks (Table 9). Satellite tracked White Sharks passed within ≤ 10 km of 12 and 9% Australian Sea Lion, and Long-nosed Fur Seal colonies, respectively

(Fig. 18d). It is important to note when interpreting these results, that the number of sites by type, and total areas per type ($km^2$) are dissimilar, and hence, statistical between-site type comparisons were not completed.

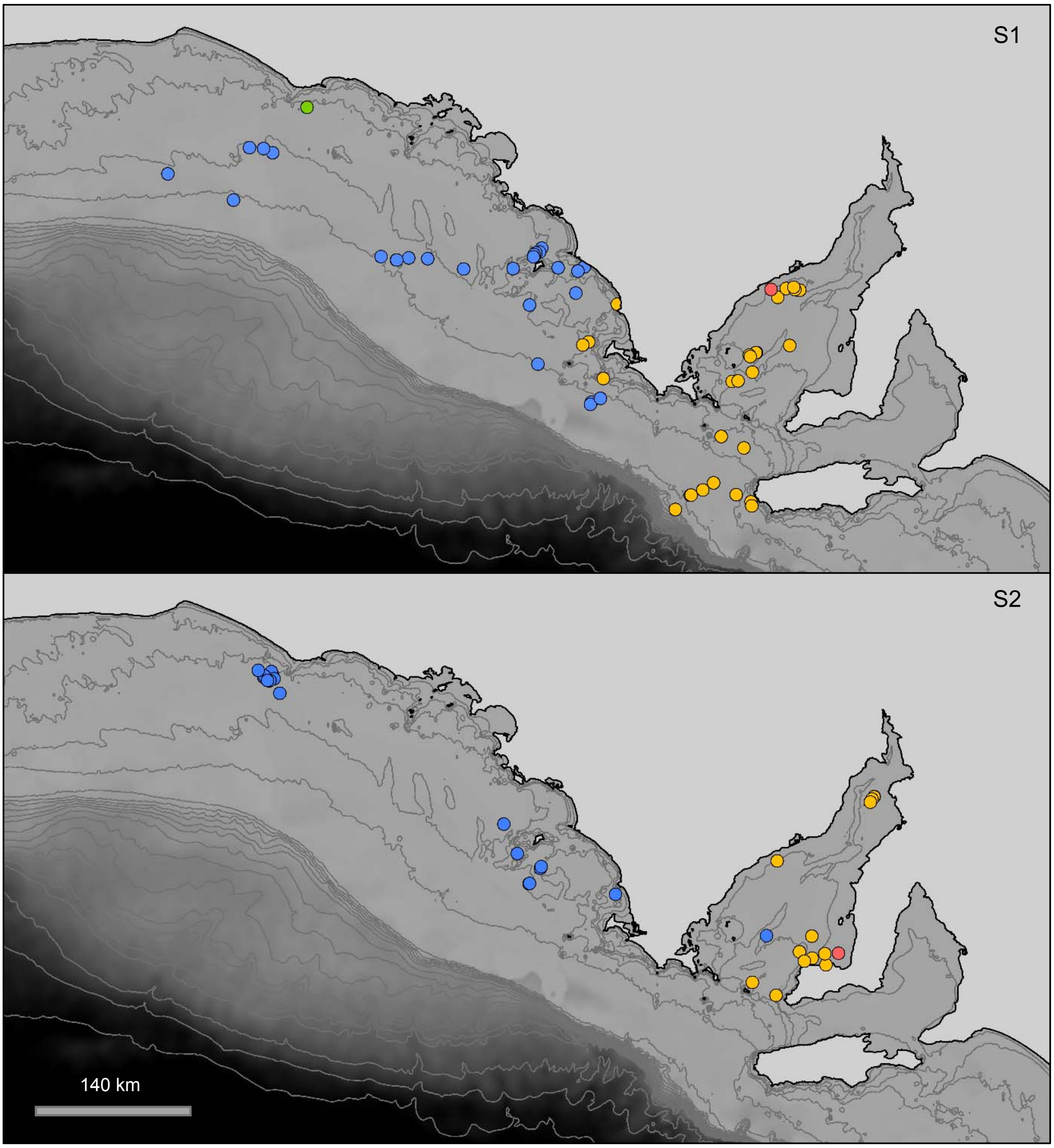



**Figure 13**. Satellite telemetry positions (SPOT tag) of White Sharks S1 (top plot) and S2 (bottom plot). Summer (Red), Autumn (Orange), Winter (Blue), and Spring (Green).

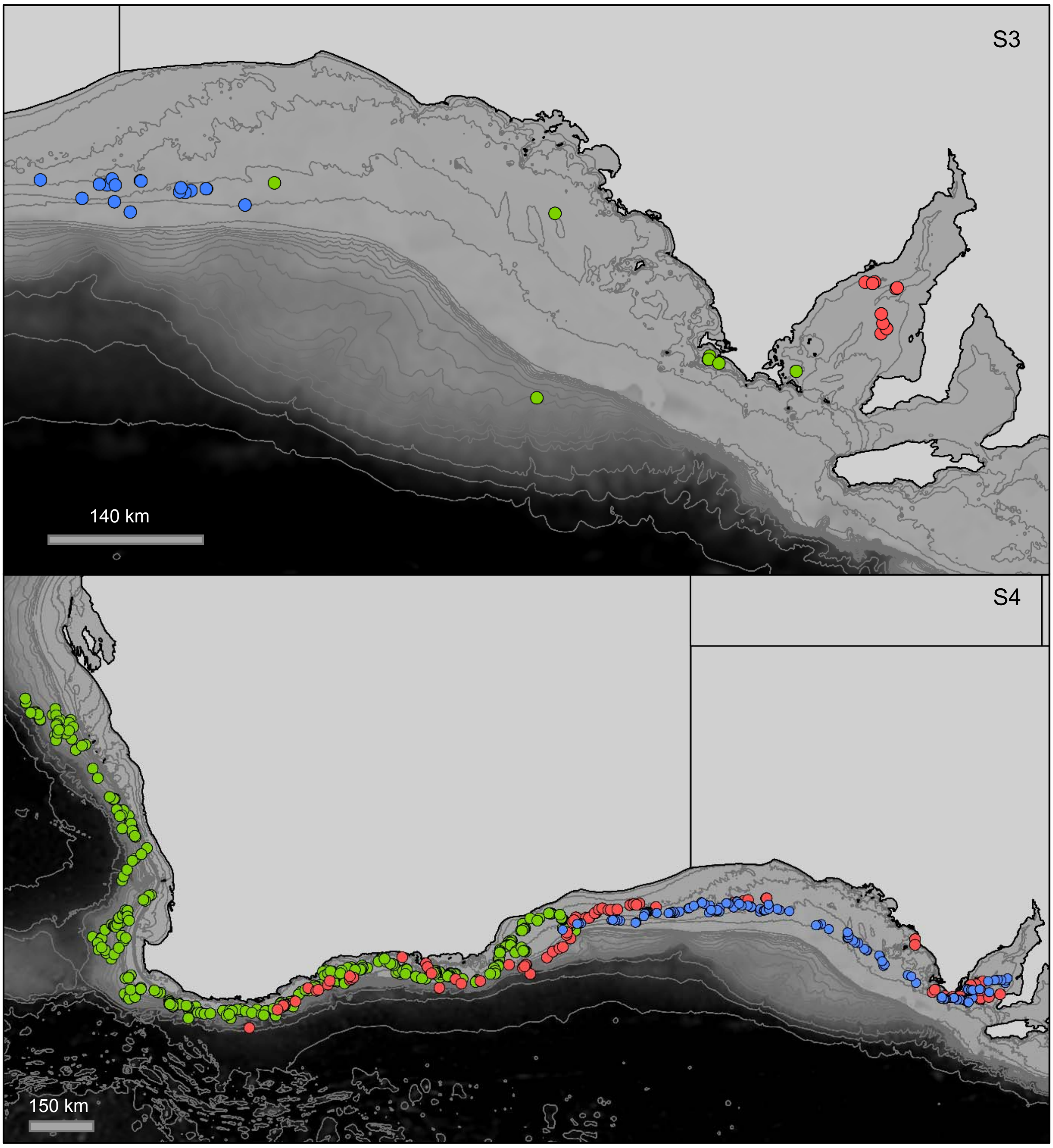



**Figure 14**. Top. Satellite telemetry positions (SPOT tag) of White Sharks S3 (top plot) and S4 (bottom plot). Summer (Red), Autumn (Orange), Winter (Blue), and Spring (Green).

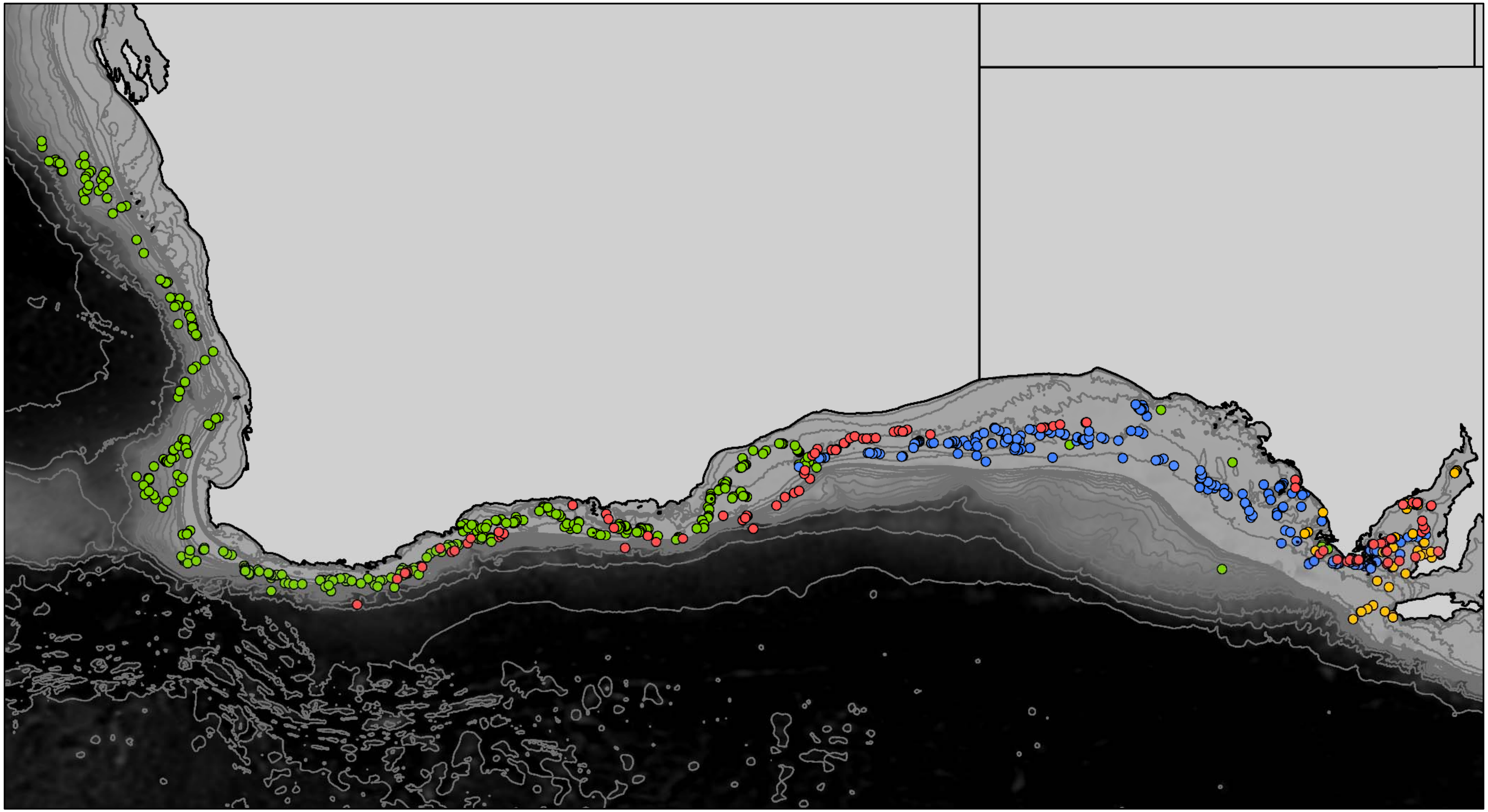


**Figure 15**. Top. Seasonal patterns in satellite telemetry positions of White Sharks S1 to S4 combined. Summer (Red), Autumn (Orange), Winter (Blue), and Spring (Green).

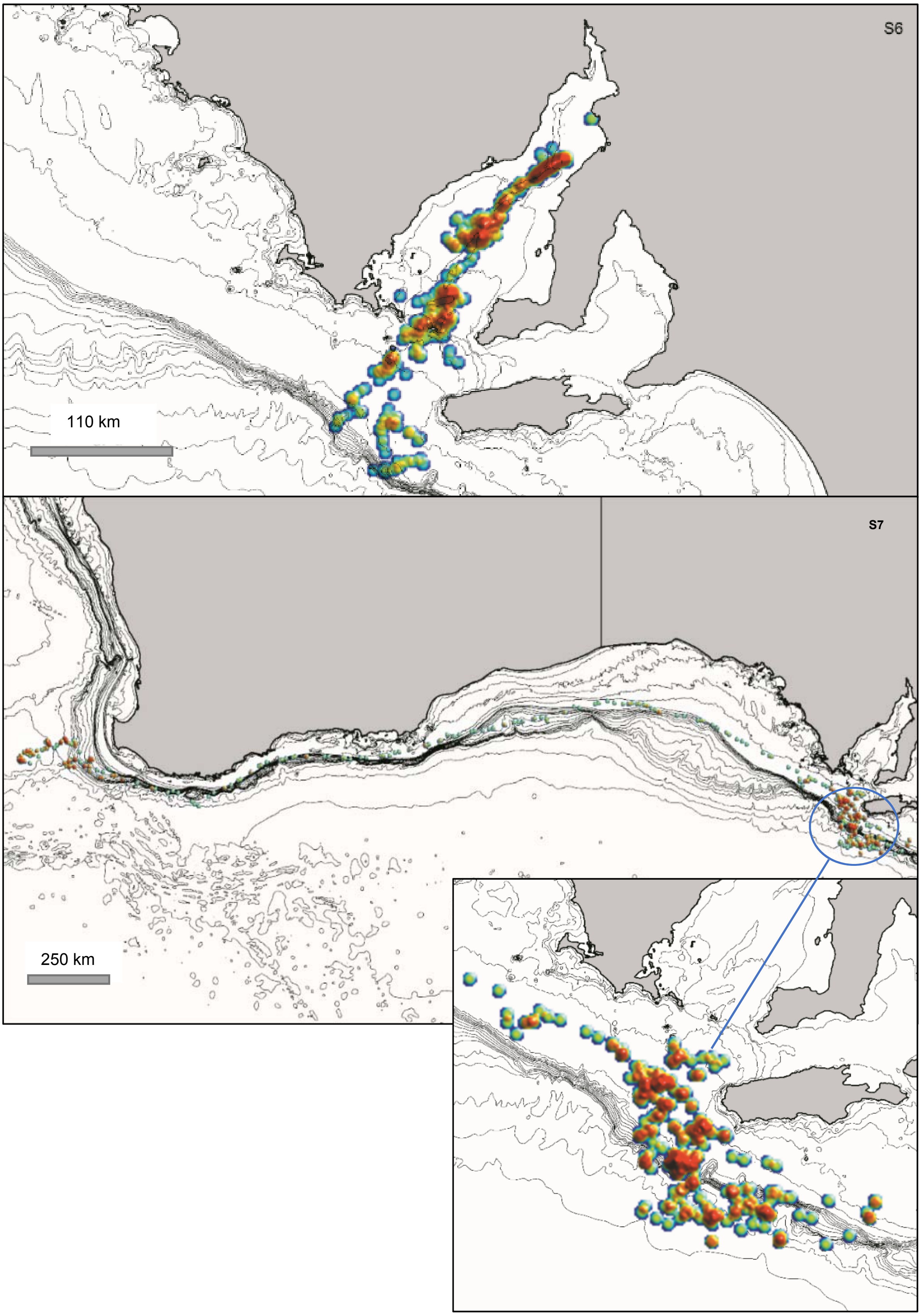



**Figure 16**. Geolocation-based position estimates from mini-PATs deployed on White Sharks S6 (top) and S7 (bottom) within KDE spherical areas.

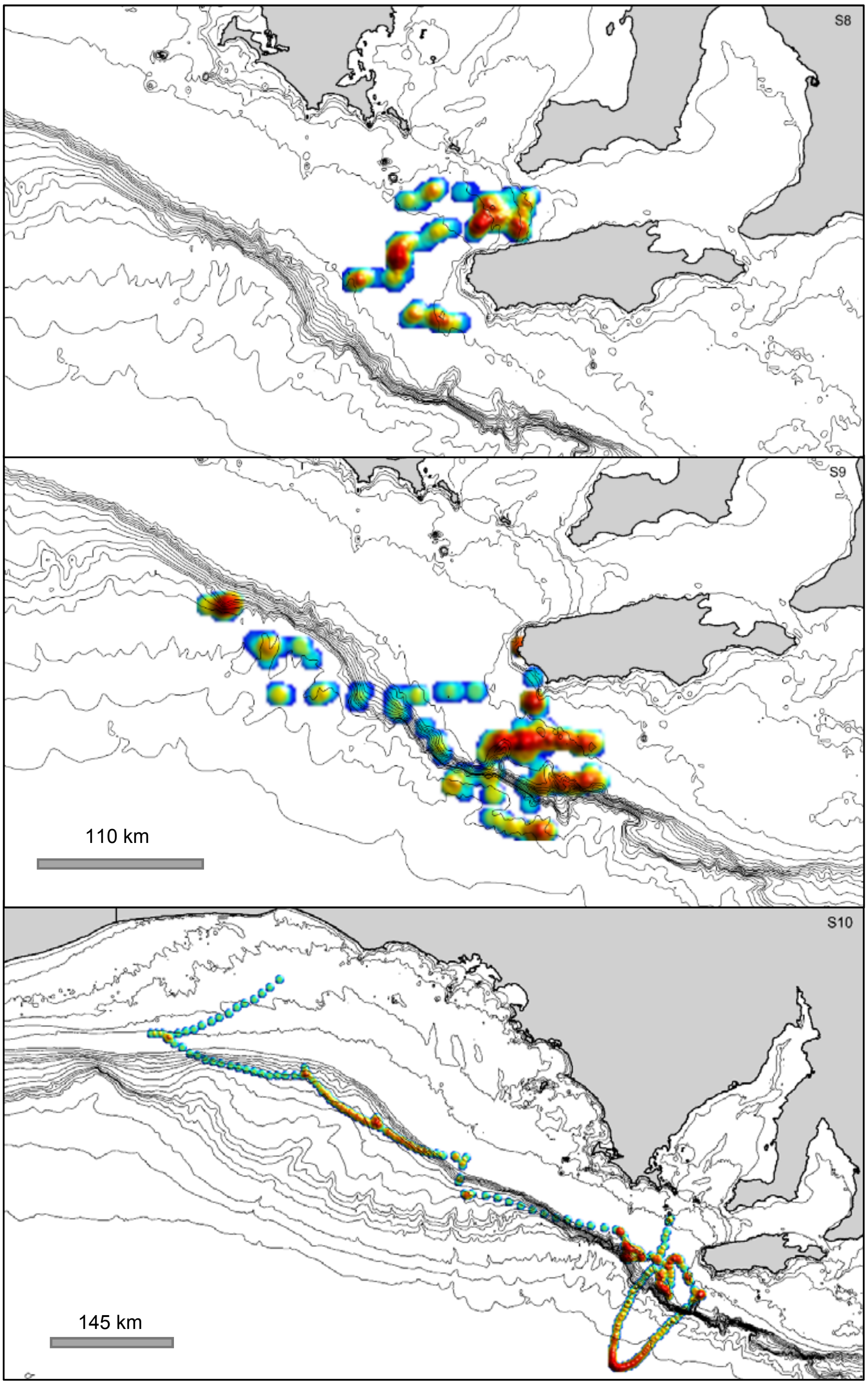



**Figure 17**. (Left). Geolocation-based position estimates from mini-PATs deployed on White Shark S8 (top), S9 (middle) and S10 (bottom) within KDE spherical areas. Scales for maps of tracks for sharks S8 and S9 are the same.

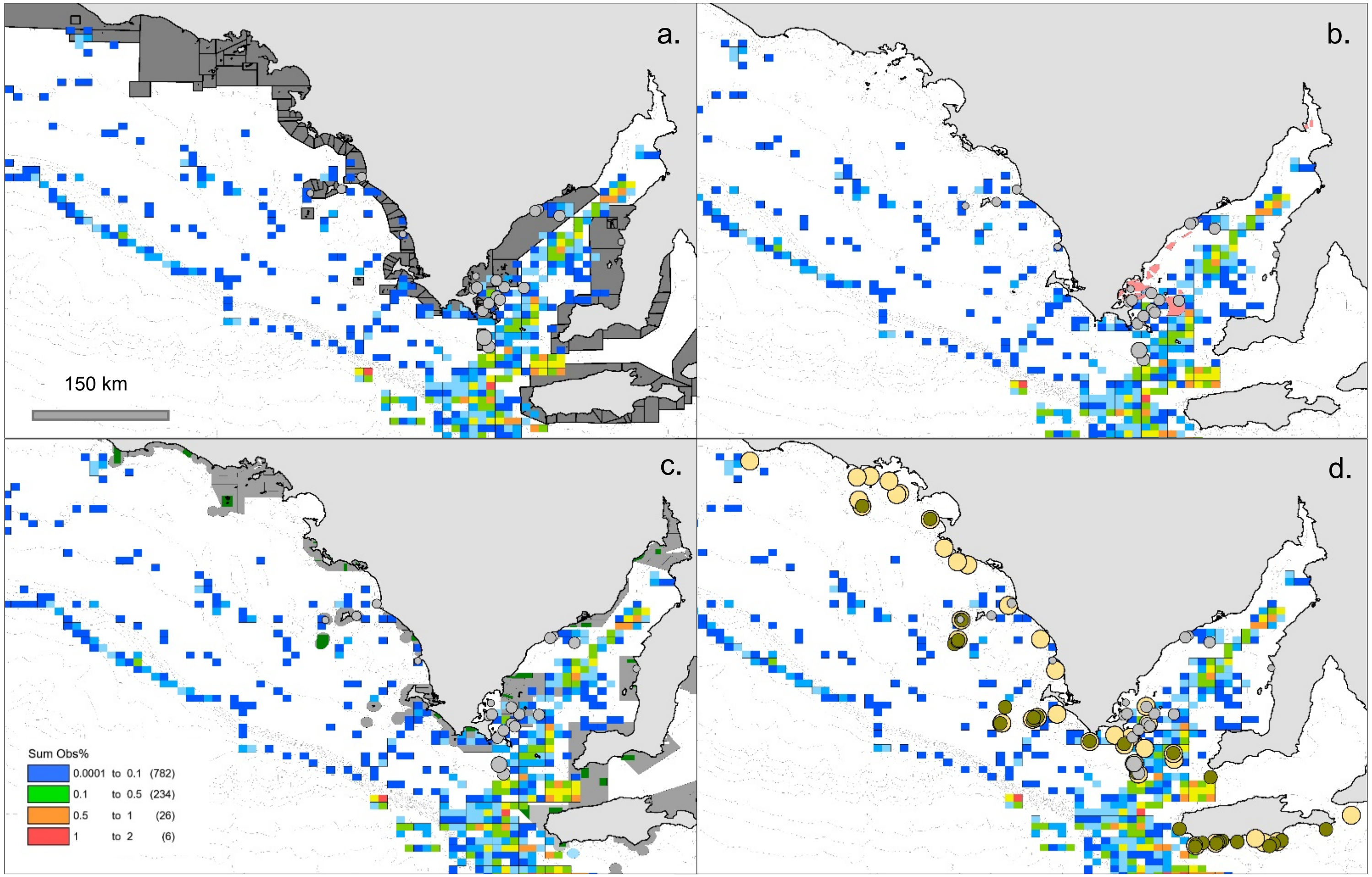



**Figure 18**. Percentage positions-per-grid-square analyses (10 km$^2$) for all satellite tagged White Sharks (*n* = 10). Grey circles show proportional number of shark days overlain on (a) commercial abalone fishing areas, (b) finfish aquaculture zones, (c) marine parks = grey, Sanctuary Zones = green shapes, and (d) pinniped colonies where yellow circles = Australian Sea Lion and brown circles = Long-nosed Fur Seal.

**Table 9**. Percentage overlap between satellite tagged White Sharks and different site types, managed marine areas and habitats. Number acoustically monitored by site type during the study is shown.

| Site type | Number and percentage of sites, managed areas and monitored habitats that satellite tagged sharks overlapped with or travelled within ≤10 km | Number acoustically monitored |
|---|---:|---:|
| Finfish aquaculture zones | 5 (22%) | 5 |
| Finfish farm sites | 1 (5%) | 4 |
| Predicted movement paths | 3 (43%) | 7 |
| Snapper spatio-temporal closures | 1 (25%) | 1 |
| Snapper habitats | 1 (20%) | 5 |
| Australian Sea Lion colonies | 5 (12%) | 5 |
| Long-nosed Fur Seal colonies | 3 (9%) | 7 |
| Cage-diving sites | 1 (50%) | 2 |
| Abalone fishery zones | 45 (24%) | 13 |
| Marine park zones (all) | 34 (36%) | 8 |
| Marine park sanctuary zone | 12 (41%) | 3 |

## Discussion

To assess overlaps between White Sharks, Bronze Whalers and marine industries, it was critical to examine the fundamental relationships between movement behaviours, and seasonal and environmental factors. To achieve this, we analysed a substantial acoustic and satellite telemetry dataset collected over a three-year period. The data-set comprised >50,000 acoustic detections and ~2,900 satellite positions, resulting from the deployment of 55 acoustic tags and ten satellite tags on White Sharks, and 24 acoustic tags on Bronze Whalers. A project of this scale was only possible due to support from finfish aquaculture, commercial fishing, marine logistics, and cage-diving tourism industries operating in Spencer Gulf and the EGAB.

Acoustic tracking showed a small number of White Sharks swam past monitored finfish pontoons in Spencer Gulf, evidenced by <100 acoustic detections at three sites, and zero at four sites. Mixed models of seasonal presence data reflected the low frequency of acoustic detections of tagged White Shark around fish farming areas, and proximity to finfish aquaculture zones was not a statistically significant variable. This was consistent with depths recorded during mini-PAT deployments (means: 18 – 32 m) that indicated the tagged White Sharks preferred the offshore southern gulf and inner-shelf habitats. Together, the satellite and acoustic tagging data support the observations of low frequency detections of White Sharks at finfish farm sites where depths were 12 – 25 m.

Initial aims of this study were to determine if activities associated with finfish aquaculture correlated with spatial and temporal patterns of shark residency and migration, and then to compare the findings with those observed in natural foraging areas, such as Snapper aggregation areas or pinniped colonies. With so few acoustic detections (<100) of White Sharks observed across the timeframe of the study at the south-western gulf sites, robust statistical explorations of linkages between fidelity and the daily timing of aquaculture industry activities wasn't feasible. The response was to introduce the broader scale minimal distance to site (proximity factor) to the mixed models during the acoustic data analyses, and this facilitated statistical comparison between the proximity from the industry and ecological sites of interest. Model fits of daily presence data clearly demonstrated that factors that drive movements of White Sharks were contextually-specific. Arrival of White Sharks in Spencer Gulf in autumn aligned with declining seasonal trends in bottom temperatures (sub-18°C), and concurrent increases in bottom temperatures in continental shelf waters of the EGAB. This was supported by mixed-model fits and aligned with the timing of intrusions of warm (17 – 18°C) Leeuwin Current and GAB Warm Pool water masses into continental shelf waters in autumn 2015 and 2016. Prior to this study, statistical quantification of the relationships between movements of White Sharks, ecological and environmental variables had mostly been limited to studies within nursery areas used by the eastern Australian population of the species (Harasti *et al.* 2017).

Best mixed-model fits to the White Shark presence data for Spencer Gulf, included water temperature, seasons of autumn and winter (peak in presence), and the possible migration pathway and Snapper habitat site types. Ecological correlates identified in the Spencer Gulf acoustic data can be used to infer that observed movements in the more temporally-limited, satellite telemetry datasets were partially explained by distribution and abundance of prey groups (Snapper, pinniped, cetacean, shark and ray spp.). These factors were identified using movement modelling approaches in a previous analysis of a small sample of White Shark tracks in the study region (Sims *et al.* 2012). The prominent offshore distributions of White Sharks observed in Spencer Gulf was generally consistent with previous telemetry studies off southern and western Australia (Bruce *et al.* 2006; McAuley *et al.* 2016, 2017). Depths inhabited by satellite tagged White Sharks ranged from those associated with the predominantly shallow areas of upper Spencer Gulf, to the deeper reefs and gutters of the southern gulf approaches, and the lower shelf slope and oceanic habitats of the GAB and south-east Indian Ocean. Deep dives of 600 – 700 m suggest these animals were foraging in, and transiting through shelf slope and submarine canyon habitats, some of which are productive (Williams *et al.* 2001), species rich deep-water ecosystems (Currie and Sorokin, 2014). During these movements, tagged White Sharks inhabited maximum depths of up to 917 m in waters off southern Western Australia, which is consistent with findings for White Sharks during migratory movements in the north-east Pacific Ocean (Weng *et al.* 2007).

Prior to this study, site fidelity of White Sharks had mostly been examined in this region in relation to cage-diving activities in the Neptune Islands Group (Bruce and Bradford 2013a), and in New Zealand (Francis *et al.* 2015), or at sites with where cage-diving had occurred, including the Sir Joseph Banks Group (Strong *et al.* (1996), Liguanea Island in the EGAB (Robbins *et al.* 2015), and Dangerous Reef (Bruce *et al.* 2005). Prior to this study there was also a paucity of published data for sites with no history of cage-diving activity, and minimal tagging at other sites in South Australia. This made it difficult to contextualise patterns in South Australia with findings in other south-west Australian regions, e.g. Western Australia (McAuley *et al.* 2016, 2017). Findings at acoustically monitored sites in Spencer Gulf and EGAB were supported by satellite telemetry data collected during this project, showing ten individuals were highly mobile and exhibited low site fidelity. In Spencer Gulf and the EGAB, small total counts acoustic detections were recorded per site (0 – 296), which was consistent with the majority of sites monitored off WA, where White Sharks mostly exhibited roaming behaviour (McAuley *et al.* 2016). There were no Snapper habitats, pinniped colonies, or areas used by marine industries where individuals exhibited fidelity as high as the maximum durations (46 shark days) observed at the North Neptune Islands, however, notable 'natural' sites in terms of fidelity, were near Dangerous Reef.

It was predicted that similar seasonal and environmental drivers would explain White Shark presence in Spencer Gulf and at the Neptune Islands. However, this was not the case, as shark presence at the latter site was best explained by combinations of mean daily bottom water temperature, the seasons of autumn and winter, and cage-diving operator presence. Similarly, best fits to the daily White Shark count data at the Long-nosed Fur Seal breeding colony at the Neptune Islands included positive correlations with mean daily bottom water temperature, moon phase, autumn and winter, and cage-diving operator activity. Importantly, we did not have receivers at comparatively large Long-nosed Fur Seal breeding colonies (due to the logistical constraints), such as those on the south-west and south of Kangaroo Island and this represents a priority for future studies. No meaningful sex- or size-based relationships could be resolved, as tagged sharks were mostly ~3 and 4 m and the sample was numerically biased towards males. These two characteristics of the sample set directly reflected the life history stages of animals that are most frequently encountered in the study area.

Robbins (2007) found a significant effect of tidal height when explaining White Shark sighting frequencies in the Neptune Islands, which was consistent with our best mixed model fit, in which moon phase was a significant predictor of daily count of tagged White Sharks. Larger tidal amplitudes associated with new- and full-moon phases may influence predation opportunities, and energy use by White Sharks around offshore islands. It is intuitive that Long-nosed Fur Seal may have access to less haul-out space on steep-gradient rocky islands during new-moon tides, and spend time away from the colony to feed on pelagic prey that tend to aggregate in tighter schools during low moon irradiance conditions. When these pinnipeds travel to and from the island they provide predation opportunities for White Sharks. Tidal amplitudes associated with new and full moons increase dispersal of berley used by cage-diving operators, and is likely to influence the fine-scale behavior of White Sharks (Huveneers *et al.* 2012; Bruce and Bradford 2013a).

White Shark distribution data collected using satellite tags showed the species undertook return- and single-transit migrations from Spencer Gulf to the Indian Ocean off WA within annual time-frames. These transits were interspersed with short-term, regional fidelity (e.g. within-gulf), a strategy likely to spread survival risks and energetic costs of spending time in areas with low probabilities of encountering suitable prey. Satellite position estimates for White Sharks in Spencer Gulf correlated with a mean bottom depth of 30 m, and low spatial and seasonal overlap with areas used by the aquaculture industry, suggesting a preference for central gulf waters. Analyses of vertical habitat data from five White Sharks showed they inhabited diverse depth and thermal habitats in southern gulf and shelf waters and conformed with findings of previous telemetry-based studies (Bruce *et al.* 2006; Sims *et al.* 2012), and those off New Zealand (Bonfil *et al.* 2010). In the Pacific Ocean, White Sharks exhibit coastal and island movement and residency phases (Weng *et al.* 2007; Domeier and Nasby Lucas 2008), interspersed with oceanic migrations during which they spend time at depths >400 m (Nasby Lucas *et al.* 2009). Tracks of White Sharks were generally consistent with those reported during previous studies (Bruce *et al.* 2006), where some shelf transitory movements aligned with the complex bathymetry of the Sahul coastline located in the 80 – 130 m depth range (Mulvany and Kamminga (1999). This depth range, approximating this submarine coastline (~25,000 years old) is also used by School Sharks (*Galeorhinus galeus*) (Rogers *et al.* 2017), and Shortfin Makos (*Isurus oxyrinchus*) (Rogers *et al.* 2015), suggesting it forms shared offshore movement pathways and/or foraging habitats. White Shark movements also extended to offshore shelf slope habitats to the south-west of Kangaroo Island, and across the GAB in autumn and winter, where suitable prey aggregate (pinnipeds and cetaceans) (Rogers *et al.* 2016).

Seasonal patterns of the presence of Bronze Whalers in the gulf were generally consistent with some of the descriptions provided by participants during the previously mentioned industry workshop (Murray-Jones, 2004). Participants suggested that Bronze Whalers moved northward during October to December (spring - summer), and southward from March to June (autumn - early winter). During this study, tagged Bronze Whalers exhibited fidelity to two main deep-water reef edges near Buffalo Reef and Dangerous Reef. Proximity to finfish aquaculture zones was a significant variable in models explaining patterns of presence of Bronze

Whalers, yet was largely driven by data from the offshore, deep-water site near Buffalo Reef, which is outside the main area used by the industry. This reef site is directly adjacent to a combination of deep-water areas used by Sardine (*Sardinops sagax*) and sloping reef fish habitats, which suggest space use is likely to be driven by prey searching and foraging behaviors (Rogers *et al*. 2012). Common Dolphins (*Delphinus delphus*) also aggregate in the nearby Sir Joseph Banks Group of Islands, and this species forms part of the diet of White Sharks (Hussey *et al.* 2012).

The study species have differing biological characteristics and life histories – White Sharks are large-bodied (~6 m) (Last and Stevens 2009), long-lived (>60 years) (Hamady *et al.* 2014), endotherms with longitudinal red muscle (Bernal *et al.* 2001), whereas the Bronze Whaler reaches medium body-sizes (~3.2 m) and longevities (~31 years) (Drew *et al.* 2016), and lacks the thermal adaptations of sharks of the family Lamnidae. Hence, it was not surprising that converse trends in seasonal and environmental factors explained the presence and distributions of the two species within Spencer Gulf. Given that Bronze Whalers prey on seasonally available small pelagic fish, demersal fishes, and squids (Rogers *et al.* 2012), it was not surprising that the best model fits explaining their presence at gulf sites included, season, water temperature, and proximity to Snapper habitats (reefs and wrecks), ASL colonies and haul-outs (islands with adjacent deep-water approaches that support baitfish aggregations in summer and autumn). Despite White Sharks and Bronze Whalers occupying similar habitats, there were seasonal differences in their patterns of presence, which may also, relate in-part to predation risk for the smaller-bodied species. In support of this application of an 'ecology of fear' hypothesis (Ripple and Beschta 2004), none of the tagged Bronze Whalers were detected in the Neptune Islands Group, which had the highest fidelity, and was the location visited by the largest number of tagged White Sharks.

# 3. Industry guidelines for managing White Sharks during static tuna aquaculture operations in State managed aquaculture zones

P. Rogers

## Introduction

The White Shark is a protected species in South Australian State managed waters, under the *South Australian Fisheries Management Act 2007*, and in Australian Commonwealth managed waters under the provisions of the *Environmental Protection, Biodiversity and Conservation Act 1999*. Beyond the established threatened, endangered and protected species reporting frameworks, these legislative instruments lack the identification of suitable approaches for on-ground management of unavoidable operational interactions with listed and/or protected species, (e.g. occasional entrapment of live sharks within floating infrastructure).

This project included an aim to develop a practical set of industry guidelines for removing and releasing White Sharks (*Carcharodon carcharias*) from Southern Bluefin Tuna (*Thunnus maccoyii*) aquaculture pontoons in South Australian State managed aquaculture zones. The occasional accidental live entrapment of White Sharks in static SBT aquaculture pontoons is an unavoidable and irregular part of operations that requires a formal, agreed response and logistical approach. Australian tuna purse seine fisheries have a Bycatch Action Plan that covers information about pelagic sharks during the capture and towing phases of the SBT fishery operating in Commonwealth managed waters (*AFMA Bycatch Action Plan, 200*5), but prior to this, no formal approaches have been developed for releasing sharks from static pontoons. Several factors need to be considered when managing entrapment of sharks in pontoons. These include but are not restricted to:

- Occupational Health, Safety and Welfare of staff;
- Potential for loss of stock through shark-related damage to aquaculture pontoons;
- Reporting of interactions with a protected species;

- Readiness to undertake steps for passive removal of sharks using industry-agreed guidelines;
- Readiness to assist SARDI and PIRSA Fisheries and Aquaculture with active removal by providing logistical support.

The approach to developing the guidelines was to integrate:

- Comments provided by industry during a workshop on sharks and aquaculture (Murray-Jones, 2004);
- Comments and input provided by industry were incorporated during 2015-16;
- Input from PIRSA Fisheries and Aquaculture, SARDI and the FRDC;
- Experiences gained during the previous release of White Sharks from inside pontoons.

The guidelines are designed to:

- Be revised as needed, based on collection of information following new cases;
- Be directly responsive to operational changes in the industry;
- Acknowledge that requirements will vary case-by-case depending on health and safety considerations, size of sharks, weather, sea conditions and unforeseen operational circumstances.

## Guidelines

These guidelines outline a practical approach for removing White Sharks from moored SBT aquaculture pontoons. They are based on the premise that an interaction with a live White Shark within a moored, static SBT pontoon in a South Australian State Aquaculture Zone has been reported by the farm manager to PIRSA Fisheries and Aquaculture.

In the event of this occurring, the license holder is to notify Fishwatch (1800 065 522) and PIRSA Fisheries and Aquaculture Reception via phone (08 8226 0900) as soon as possible (within 12 hours) after first noticing the interaction/entanglement.

**Scenario 1**: Shark is inside the pontoon and swimming around the outside perimeter at or near the surface

**Approach 1**: Industry members attach heavy weights to 18 – 20 m of the headline of the net below the pontoon and drop the rope by ~3m by whatever means appropriate to the conditions and situation (e.g. crane or ropes) to form a temporary gate. Alternatively, a gate can be created as above by using the purse line attached to a block on the stanchion. The shark is then encouraged (using a bait attached to a rope) to swim out of the temporary gate in the headline. Importantly, some sharks are more likely to swim free if the crane is turned off as the animal approaches the gate.

If approach 1 was not successful:

**Approach 2**: SARDI and PIRSA Fisheries and Aquaculture works with the industry representatives to capture and remove the White Shark from the pontoon.

**If approaches 1 and 2 were unsuccessful**: SARDI, PIRSA Fisheries and Aquaculture and industry staff seek further advice regarding other options.

**Scenario 2**: Shark is mostly swimming near the bottom of the net

**Approach 1**: If shark does not swim to the surface, or be encouraged to swim at the surface using baits, SARDI and PIRSA Fisheries and Aquaculture captures the shark which is then removed through a reduced 'gate' in the head-rope.

If approach 1 was not successful:

**Approach 2**: SARDI, PIRSA Fisheries and Aquaculture and industry staff seek formal advice regarding alternative approaches.

## Discussion

Prior to this project, no agreed formalised steps for managing direct pelagic shark interactions had been developed or applied in Australian jurisdictions where static aquaculture pontoons are used by finfish aquaculture industries. In addition, the Australian State and Commonwealth legislative frameworks lack specific caveats to facilitate management of unavoidable operational interactions with listed and/or protected species.

The guidelines directly reflected the knowledge and experience of industry members, and researchers worked with local fabrication businesses, dive companies and marine consultants in Port Lincoln to develop trial equipment and methods. The guidelines were developed through an active partnership between SARDI, PIRSA Fisheries and Aquaculture, and ASBTIA. Comments and practical input were provided by Southern Bluefin Tuna and Yellowtail Kingfish farm managers and the FRDC/ASBTIA Research Council industry to address the main working scenarios.

The guidelines outline a practical approach for conducting and managing future situations where interactions with pelagic sharks could otherwise lead to stock loss, damage to infrastructure and concern relating to safety of staff may present challenges for aquaculture industries and management agencies. Development of the guidelines addressed several priorities in the *Recovery Plan for the White Shark* and will assist reduction of potential impacts of interactions in the future.

SARDI and industry were collectively nominated for a South Australian Seafood Environmental Award in 2017 for developing the guidelines. Stakeholders in other State jurisdictions (e.g. WA) aim to implement similar guidelines in developing or existing offshore aquaculture industries, where the need to manage shark interactions has been identified.

# 4. Perception surveys

M. Nursey-Bray, M. Magnusson (University of Adelaide), M. Drew and P. Rogers (SARDI)

## Background and need

There was a need to provide baseline social information to assess perceptions regarding sharks and marine industry activities to inform PIRSA Fisheries and Aquaculture policy development.

Information on public perceptions of sharks, aquaculture, fisheries and tourism was collected before and after the completion of the study reported in Chapter 3. During this interim period there was considerable media interest in the development of a tourism venture involving tuna that is located off the southern Fleurieu Peninsula.

## Approach

Two public perception surveys were conducted between May and September 2015 (Phase 1), and December 2016 to February 2017 (Phase 2). Approaches included a literature review, media analyses, and a series of semi-structured interviews conducted during Phase 1 at Port Lincoln, Kangaroo Island, Tumby Bay, Adelaide and Wallaroo, and Phase 2 at Goolwa, Victor Harbor, Normanville, Wallaroo, Adelaide metropolitan beaches, Ceduna and Port Lincoln. Purposive sampling was used to gather data from people with commonalities, or that can reasonably be expected to provide useful insights (Patton 1990). As such, people in the marine industry who may reasonably be expected to be affected by, or have a qualified opinion about relationships between sharks and aquaculture were targeted. Media analysis supplemented the other data-sets.

### *Semi-structured interviews*

Semi-structured interviews reveal perceptions and themes surrounding issues, and provided insights and data on the socio-economic context of relationship between sharks and aquaculture. We conducted 40 semi-structured interviews of 11 women and 29 men. Interviewees were given an information sheet and signed a consent form prior to the interviews. It was agreed that adequate steps would be taken to ensure respondents would remain anonymous, and therefore all quoted statements have been removed from this report. Interviewees included people from fishing (30%), tourism (30%), recreational fishing sectors (5%), local government (10%), State government (10%) and commercial fishing agencies (15%).

### *Interview questions used in the perception surveys*

**General**
Male/Female
Where are you from and what is your history?
What do you do/stakeholder ID?
Approximate age?

**Sharks**

- What is your perception/opinion of sharks?
- What are other key marine issues that you face?
- In that context, how important do you rate the shark issue?
- Have you had had any interactions. Have stories to tell about sharks in your community?

**Aquaculture**

What is your opinion/perception of aquaculture generally?

- What is your opinion on new proposals for aquaculture?
- Do you think different types of aquaculture have different effects/impacts on sharks? Which ones and why? Why or why not?
- Have you heard of any new proposals in your region and what was community opinion about that?
- What is your opinion of the relationship between sharks and aquaculture?

**Information**

- Where did you get the information?
- What sources /forms of communication do you use to get information (go through social media, TV, newsletters, report)
- What sources do you trust/not trust and why?
- What do you think the science /scientists are saying about the impact of sharks?
- Do you believe them? Why/why not?
- How would you like to receive information about sharks /aquaculture?
- What information would you like to receive about these issues?

**Social licence**

- What do you think ‘social licence to operate’ means?
- Is there anyone else we should talk to about this, and is there anything else you would like to add/say about the issue?

**Environment**
In the second round of interviews people were asked about their views on the most pressing environmental issues and how they received communications about this.

### *Media Analysis*

Media analysis enables appropriate comparative analysis of a number of texts and is a specialised sub-set of content analysis (Macnamara 2005). Benefits of media analyses are twofold, it firstly allows for examination of a wide range of data over a long period of time and thus helps locate and identify the popular discourses about an issue. Secondly, it has the advantage of being conducted frequently, thus further enabling a detailed description of the way the issue evolves over time and changes in people's public perceptions. It provides a systematic and structured approach to content analysis of newspapers, books, radio transcripts and social media. Content analysis is a technique for gathering and analysing the content of text, and refers to words, meanings, pictures, symbols, ideas, themes, or any message that can be communicated. A review of media using the words 'sharks' and 'aquaculture', was undertaken of all media mentioning the subject. The terms were searched separately and then together in combined searches. These searches yielded hundreds of articles, but closer reading showed that the large sample was due to a large focus of items/articles about shark attacks. In sum, 32 articles over a 5-year period were chosen for analysis as they represented the issues covered across a range of media and geographical locations. The incidence of items that discussed both sharks and aquaculture together was very small in earlier years. Facebook posts were of a much smaller number and did not reveal any issues, although some posts were about shark attacks or sightings.

### *Communities of Practice*

In the second phase of the project, in late December 2016 to end January 2017, we conducted interviews across the State using a 'communities of practice' (CoP) approach. Communities of practice are instant formal and informal networks with vertical and horizontal linkages that can facilitate the flow of information and learning across cultures and boundaries. Ideally, they also have a number of enabling characteristics including: (1) committed facilitator(s); (2) a shared purpose; (3) commitment and enthusiasm from the members; (4) endorsement by key actors; (5) objectives consistent with the goals of its members' organisations; (6) self-selected membership, regular communication with, and interaction between, members; (7) development of relationships through face-to-face interactions; and (8) infrastructure to support the group's work by easing access to knowledge or evidence (Ranmuthugala *et al.* 2011). In practice, CoPs can be communities identified by the following traits: (1) the formation of group identity; (2) the ability to encompass diverse views; (3) the ability to see their own learning as a way to enhance group learning; and (4) a willingness to assume some responsibility for colleagues' growth (Grossman *et al.* 2001). In parallel, Samuelowicz and Bain (2002) argue for the idea of communities of interest (CoI), which are characterised by shared ideological and procedural assumptions, and codes, slogans, keywords accepted by that community. Wenger (2000) defines CoPs as communities that share cultural practices reflecting their collective learning. In this context, we felt that local governments in South Australia act not only as CoPs, but also provide connection points and overlap between many other CoPs such as across scales of government, fisher groups, local coastal and conservation action groups, local community service groups such as Lions Clubs or Rotary, as well as media, health, education, and tourism sectors.

All councils demonstrated clear relationships between themselves and community groups and in many instances, the CoPs overlap with each other, providing opportunities to pool resources, ideas, and people towards addressing common issues.

A total of 25 interviews were completed with community groups located at Goolwa, Victor Harbor, Normanville, Wallaroo, Adelaide metropolitan beaches, Ceduna and Port Lincoln. The CoP approach included developing a database of community groups, drawn from local governments in the study region, which was used to send interview requests. These groups included those interested in the issue, and a wider set of social and other groups and activities within each local government area. While many of the groups had logical reasons for their interest, such as surf lifesaving or sailing clubs, we also met with Rotary and other groups to gather opinions and perceptions from a wider sample of the public.

### ***Data Analyses***

Thematic analysis was used to code and categorise key results from interviews, survey and the media we collected. Thematic analysis permits the identification of patterned meanings across a data-set (Denzin and Lincoln 2005). It is a flexible method that can be used across methodologies and questions as it assists in understanding people's perceptions, feelings, values and experiences. An inductive approach to the analyses was used whereby the coding and theme development was indicated by the data, rather than assume anything before beginning. Analyses were conducted in five stages: (i) familiarisation with the data, (ii) searching for themes, (iii) coding, (iv) reviewing and amending themes, and (v) writing up. The qualitative data analysis software package NVIVO™ was used, which enabled the relative weight and emphasis different people placed on specific areas to be determined. This package also enabled thematic grouping of the information to ensure transparent verification of the data.

### *Project Evaluation*

Results from all three sources, presented similar patterns and consistent findings. In this case, triangulation ensured validity of the data collected. Triangulation is the technique adopted within the social science domain to ensure validation of data via cross verification from two or more sources (Webb *et al.* 1966). It allows for the use and combination of a number of methods to investigate the same phenomenon. This creates added confidence in the results (Denzin 1970). Three different forms of triangulation were used:

*Method triangulation*, data collected from interviews, literature, policy documents, the survey and the media analysis.

*Investigator triangulation*, where more than one investigator collected the results. In this case, two other researchers assisted in collecting information.

*Data triangulation* where similar messages and patterns are recorded across different data sources.

During the analyses, clear consistencies were identified around core themes. Interviews were conducted until it was clear there will be no new information to be obtained and interviewers could assume with confidence that the research had achieved the goals (Denzin and Lincoln 2005). The analysis was consistent with Lincoln and Guba (1985) who used evaluative criteria for establishing trustworthiness in qualitative research.

This project built on two previous projects. The first was a report written by Mazur *et al.* (2005) that focused on community perceptions of aquaculture. The key findings were that there was general support for aquaculture and strong interest in its environmental sustainability. Trust in aquaculture per se varied but people were more likely to trust those who had some familiarity with the industry and generally there was strong support for better dialogue. Overall, this project concludes that knowing communities is a vital part of building a viable aquaculture industry.

The second report was a record of Workshop Proceedings (Murray-Jones 2004), where stakeholders (~60) discussed the relationship between sharks and aquaculture. Scientists, aquaculture industry and managerial representatives and academics presented information, and the audience consisted of the same, with a few key tourism and conservation members as well. Themes covered included consideration of the nature, scale and type of shark interactions, the role of aquaculture, and means by which shark issues could be addressed. Overall workshop findings indicated that aquaculture cages did not appear to be attracting sharks to the region, and that the main factor triggering their arrival was attributed to freshly dead fish in cages. Consensus was that there was a need for improved husbandry, development of best practice guidelines, and more information about shark species, habits and populations.

The project summarised in this overview (this report) was quite different in that its target audience was a wider range of stakeholders, and secondly, focused on getting deep engagement and information not just about experiences with sharks, but on community perceptions of them and aquaculture collectively.

## Results

### *Survey Phase 1*

#### Media Analysis

Unlike media about the impact of seals on fishers, where media coverage is extensive and ongoing, there is relatively little coverage of the issue of sharks and aquaculture. Surfer and fisher blogs, shark diving web sites and publicity, a range of newspapers were reviewed, including the Advertiser, the Australian, the Sydney Morning Herald, and a range of regional papers from Kangaroo Island, Port Lincoln, Tumby Bay and Wallaroo. Information was accessed on council websites as well as alerts and warnings on government websites. A summary of the themes is presented below.

*Key theme: Shark Tourism and Aquaculture*

The relationship between shark tourism and aquaculture is reported in the media due to the fact that there is a perceived link between shark attack and shark diving operations. One example, an ABC news story from May 2015, highlights this issue. Despite shark diving attracting 15,000 tourists a year and a lot of income to Port Lincoln, residents fear that these operations will increase shark presence and hence compromise community safety.

*Key theme: Sharks and Aquaculture*

News stories about sharks and aquaculture occur rarely in comparison to the two other themes discussed above. There have been instances where the proposed or exiting aquaculture developments have raised questions over what role such operations play in attracting sharks into regions. Most of this media however occurs outside of South Australia. One instance concerns the refusal of the NSW Department of Fisheries to trial a 20-hectare fish farm off the NSW north coast on the grounds it will pollute areas and attract sharks (Hasham, 2013). Aquaculture operations in South Africa have raised concerns that they will attract sharks.

The second issue discussed most frequently in the media is the potential for technology to keep sharks away. One such device, called the Predator X is advanced by many in the media and on social media websites or companies such as Ocean Solutions as a key technique for repelling sharks and ensuring aquaculture is safe.

These are the themes that dominate the media reporting on the issue of sharks and aquaculture. Consistent with the interviews results, the issue of sharks *per se* remains a hot topic, but not when considering the relations between sharks and aquaculture.

## Interview analysis

The coded interviews highlighted a number of dominant and subsidiary themes (Table 10). In this section, each key domain is discussed and the subsidiary themes highlighted.

**Table 10.** Overview of key domains and themes identified by respondents about sharks and aquaculture during Survey 1

| Domain | Subsidiary Themes |
|---|---|
| Aquaculture | Impacts on shark behaviour<br>New proposals<br>Economics<br>Distance from shore |
| Sharks | History<br>Types<br>Numbers<br>Part of nature<br>Respect/awe/fear<br>Attacks [PI note: bites] |
| Sharks and Aquaculture | Blood<br>Attraction and Interactions<br>Views on policy<br>Social licence to operate |
| Information and Communication | Sources of information<br>Trust in information<br>Information needs |

*Aquaculture*

Aquaculture as a topic in itself was generally perceived in a very positive light by a range of respondents. Others were torn between the perceived advantages of aquaculture and the threat it might pose to environmental sustainability. Often respondents reflected on zoning issues and the importance the industry has to maintaining global food supplies. Many respondents highlighted the economic importance of aquaculture to the local economy, and in turn why this meant that management of shark impacts was so important. However, for some, the impact of sharks on aquaculture, and on shark behaviour was a key theme. Many people perceived sharks affected the quality and nature of fish production, yet new developments [aquaculture zoning] or the prospect of them were of low concern.

*Sharks*

Questions about sharks often evoked memories or stories about the history of sharks in their regions.

*Shark 'Types'*

Overall, respondents did not seem to know much about the biology of, or types of sharks in their region. People tended, when they identified sharks to talk about them to set the context of their own experience. Respondents collectively identified gummy sharks, bull sharks [PI note: not found in South Australia], White Sharks, Bronze Whalers as the key sharks being sighted – or eaten. White Sharks were almost always the species identified as being responsible for shark attacks.

*Shark Numbers*

When reflecting on shark numbers, most people had theories but were not able to substantiate their information about the numbers of sharks in their region. Again anecdotal observation was the baseline from which people operated and local observations held much greater weight than scientific estimations. Some respondents were more measured in their replies, one wryly noting that while the science is not perfect that also doesn't mean that numbers are out of control.

Some respondents were of the view that not only were numbers in fact skyrocketing and needed to be actively managed but related this increase to the fact they are protected species. These perceptions are clear in this typical observation.

*Part of Nature*

The role of the shark as an apex predator, and the need to protect them was a key refrain. Even those respondents who feared sharks or thought their numbers had increased to the point they needed managing, still construed sharks as key to nature.

*Sharks and Aquaculture*

While people were willing to discuss sharks and aquaculture as separate topics, they found it harder to discuss them together. Participants did not link sharks with aquaculture, or view them as connected, especially as the dominant talking point about sharks was either their capacity to attack people, or their inherent beauty as part of nature. There was not an automatic assertion that sharks were a policy problem, although many respondents reflected that they could be. Moreover, even aquaculture operators did not seem overly or urgently concerned about the need to manage for impact of sharks, nor convinced that their business needed to be regulated. A point of agreement amongst almost all respondents (often relying on word of mouth) was that it was logical that sharks would be attracted by aquaculture. People asserted this perception whether they believed it or not, or had any evidence, simply because it was deemed to be logical and made sense. Another key theme in people's discussions about sharks and aquaculture operations was blood. Its presence during fish feeding was considered a causal factor attracting sharks to aquaculture areas. Some respondents believed that aquaculture operations were changing shark swimming patterns.

*Safety*

Related to the discussions about aquaculture and sharks was a sub-text about ensuring that residents were safe. Hence while many respondents were not actually that worried about sharks or aquaculture, they did have views about safety on beaches, especially when employed by local government or in a position of policy responsibility. Interviewees suggested that the distance of any activity, including aquaculture, was a threat to their safety. People's view was 'the further away the better', but if managed, both sharks and aquaculture should be able to co-exist.

*Social licence to operate*

Social licence to operate refers to the acceptance of an industry, such as aquaculture, by a community to operate in a particular area (Dare *et al.* 2014; Harvey 2014; Harvey and Bice 2014; Parsons and Moffat 2014). The perceived benefits from the industry, expected by the community, are at the basis of community acceptance (Dare *et al.* 2014; Parsons and Moffat 2014). Such business advantages may include the reputation of the organisation, continued access to resources and the positive relationship between stakeholders, particularly employees (Dare *et al.* 2014). Social licence to operate is thus often linked to the organisation's legitimacy in the eye of the community (Harvey and Bice 2014). However, and interestingly, in this project, while respondent reactions to and descriptions of aquaculture implied they had secured social licence to operate, most stakeholders didn't understand what the term meant.

*Other Issues*

As interviews progressed it became clear that, while respondents were willing to discuss sharks, especially in narrating their own shark 'stories', overall sharks are not a priority when compared to other marine issues. This was especially evident by the fact that all respondents would start to talk about the issues that really matter to them. Other issues included management of Long-nosed Fur Seals, how to manage waste going into the water, the creation of marine protected areas, seismic testing and impacts of exotics on existing industries.

*Shark Tourism*

Whatever people's views on aquaculture were, the majority concurred that shark tourism had undoubtedly affected the presence of sharks in the region. Shark tourism rather than aquaculture emerged as the key dynamic in this study. Regardless of whether respondents identified as a fisher, diver or surfer, their opinion was often the same.

*Information*

One of the key aims of this project was to understand what people believed but also how they obtained information, the sources they trust and how they currently communicate. A number of observations can be made from analysing the transcripts. Firstly, it is clear that while people do use newspapers, various forms of social media and watch the news, overwhelmingly people communicate primarily via word of mouth and trust local knowledge

### *Survey Phase 2*

Findings of the Community of Practice Survey (Phase 2) were consistent with those of the first survey. An overview of key domains and themes identified by respondents in the second survey is shown in Table 11. Similar themes arose, despite the survey being conducted a year later, and using a different approach. Opinions and perceptions on topics were effectively the same between surveys, despite interviews being conducted amongst a wider cohort of participants. There were, however, a few differences relating to detail rather than substance. For example, while opinions of sharks were consistent, essentially aquaculture was not seen as an issue, more respondents in the second survey felt the type of aquaculture being proposed was a determinant of their views. Respondents generally felt that finfish aquaculture and shark tourism would have greater and more negative impact than smaller ventures, and many suggested that oyster or mussel farms were preferable.

Another nuance emerged during discussions about media and trust. Although many respondents stated they used other people and social media as their sources of information, many people also noted they used CSIRO and other qualified sources. The other interesting dimension was that almost no-one actually trusted the media they use to get information, which suggests a disjuncture between information receipt and conviction regarding its accuracy.

Finally, an additional theme arose in the second survey: how respondents related to the environment, and other issues they felt were important. People rated climate change, over-population, beach erosion, pollution, litter and marine protected areas as the key and pressing issues. They also often stated contempt for humanity and despair for the future of the planet, particularly the women interviewed. A summary of the key themes follows with an indicative quote for each so that the similarity between the first and second phases of the research reveals itself. Perceptions were summarised as follows under theme headings, as follows.

### Sharks

As with the earlier survey, when asked about sharks, most respondents indicated that they had no problem with them nor that they thought they were evil or harmful. A number of respondents argued that movies like Jaws had given sharks a ridiculous reputation. Many individuals described shark species as beautiful and fascinating. Most interviewees also referred to the fact that in their opinion they shared the marine environment with sharks and as such sharks had rights to co-exist.

Interestingly, this time, many more respondents queried the types of sharks being discussed, and made delineations between the relative dangers each species posed depending on what type it was. Many interviewees also spoke about the rights of sharks and the danger they posed in relation to areas outside of South Australia. Given the wider cohort interviewed, more of the respondents had travelled overseas or within Australia, so their comments were set in the context of this wider view and experience.

## Aquaculture and the economy

When asked their opinion on new aquaculture developments almost everyone interviewed asserted the need for economic development. Most respondents were provisionally supportive. Support was offered on two bases: (i) the perception that environmental degradation and over-fishing had caused stocks to decline, and therefore aquaculture could help fill the gap and (ii) aquaculture farms create jobs and in the current climate in South Australia, this was seen as positive, especially for their children. Some respondents talked about the development at Victor Harbor ["swim with tuna"], but did not perceive it as 'real aquaculture' and therefore viewed it as a different issue.

## Perceived impacts of aquaculture

People qualified their support by noting that it might be different if it impacted them directly, but also that it depended on the type of aquaculture. Generally, it was perceived that finfish or larger fish farms would have a larger negative effect than smaller oyster or mussel farms. It was also evident that by and large respondents stated that they were not really qualified to answer this question, which indicates a level of discomfort around it, probably an effect of the fact it has had media associated with it. Some respondents raised concern at the number of fish needed to feed aquaculture stocks, such as tuna.

## Relationship between feed in the water and sharks

While respondents did not as a rule have a negative attitude towards new aquaculture developments, they stated that it seemed logical that if there was feed or blood in the water then it would attract sharks. Some noted that this is why the tourism venture [cage-diving] is problematic because they put blood and guts in the water, which from their perspective would attract sharks. Others felt that burleying by fishers caused more problems than aquaculture. Generally, all respondents felt that if feed or blood went into the water [regardless of the purpose] it would attract sharks. Some reflected on other issues such as contamination in addition to the risk of shark presence:

**Table 11.** Overview of key domains and themes identified by respondents about sharks and aquaculture during Survey 2.

| Domain | Subsidiary Themes |
|---|---|
| Aquaculture | Support aquaculture<br><br>Plays important role in economy and fills gaps |
| Sharks | Beauty of sharks<br><br>Rights to co-exist<br><br>Species diversity matters<br><br>Respect/awe/fear |
| Sharks and Aquaculture | Logic determines there is a link between feed and shark presence<br><br>Attraction and Interactions |
| Information and Communication | Diversity in sources of information used<br><br>Trust in information low for media but high for science<br><br>Dissemination/communication of knowledge via peers preferred mode |

### Media sources

We found that there was a wider range of sources used by respondents than in the previous survey. Most used social media, science websites, and a range of community newsletters. Many cited social media as their preferred source, but most people also cited the Advertiser, Bureau of Meteorology, CSIRO website, SARDI and notifications, Coastal watch website and institutionally based community newsletters. All respondents noted their reliance on their peers, social networks and community gatherings to obtain up to date information.

### Trust in information

Interestingly, despite the wide array of media used, all respondents indicated that by and large they did not trust social media, the Advertiser or radio. Almost 80% of respondents in this case, however, did indicate a higher level of trust in scientific documents and in researchers of good repute. This is different to the other survey where almost everyone indicated lack of faith and trust in scientists and science. Everyone indicated complete faith in their peers, and people in their life (family, friends, and neighbors) and that this was the source of information and dissemination they most trusted. They also felt that researchers needed to take greater account of and value local knowledge:

### Preferred mode of receiving information

When asked how they would prefer to receive information, many suggested through informing their peers in peak or community groups, websites and information through newsletters.

### Social Licence

Respondents were asked how they felt about social licence to operate to determine if this had been contextualised in terms of changes in social acceptance of aquaculture. Consistent with the first survey, respondents had a limited understanding of what social licence to operate means, indicating that despite this being a term *de rigeur* in management, it has no resonance in the community. It was clear the social acceptance was a more appropriate term when discussing marine issues.

## Discussion

The main aim of the public perception surveys was to document stakeholder perceptions about sharks and aquaculture. A subsidiary aim was to understand whether stakeholder perceptions followed diminishing trends in relation to distance from source. Findings have implications for future communications regarding the development of future aquaculture operations, and highlight that stakeholder knowledge about sharks and/or aquaculture was generally at a low level. It was clear that while stakeholders had concerns about sharks, the general perception was that it did not rate as highly as other marine issues, e.g. marine parks and seal interactions.

Findings of the surveys have two implications for communicating information about sharks in the context of new proposals for aquaculture. The first is, there was a lack of information available about sharks within the community. Secondly, the survey indicated a need to better integrate factual information into community-based 'word of mouth' networks. In future, communications should be developed to inform the community about the level of knowledge, and risk assessments focused on aquaculture and sharks. The surveys suggest that media portrayals of shark interactions with humans can significantly influence public perception. This effect was evident in a study of the media's role in public and political responses to interactions in Western Australia, where researchers found that media dialog about sharks was influential in the policy domain, and in shaping public perception (McCagh *et al.* 2015).

As shown in a study of the public perceptions of sharks in the northern hemisphere, there are a number of specific challenges and issues in regard to sharks that may influence perceptions in this case (Friedrich *et al.* 2014). Findings highlighted that relationships between sharks and aquaculture do not exist in isolation and that other factors, including marine protected areas, local economies, individual and community activities, and engagement with the coast mattered to interviewees. In this case, it is clear that the advent of new aquaculture developments is not viewed as a high priority marine issue in South Australia, whether within the fishing and tourism communities as shown in Phase 1 of the study, nor in wider community groups (Phase 2). Results showed that distance from source of activities, in both phases did not influence perception, but that the types of aquaculture proposed, and the species of sharks under consideration did matter to participants.

The fact that many of the participants interviewed had a story to tell about sharks highlighted that the species group retains public fascination, but the positive light in which sharks are viewed is in contrast to popular media representations that are regularly fear-based and negative. Nobody interviewed advocated a cull of sharks, which directly contrasted with perceptions portrayed by some media. This is consistent with findings across the world where sharks maintain a fascination, and are financially valuable, given the potential for multiple returns to tourism industries (Richards *et al.* 2015).

# 5. General Discussion

P. Rogers and M. Drew

Based on the analyses of the satellite tracking data (*n* = 10 tags, 1,491 days tracked) and extensive acoustic telemetry data-sets (*n* = 34 sharks detected, 42,647 detections over 793 days), White Sharks studied at sites in the EGAB (excluding the Neptune Islands Group) and Spencer Gulf, exhibited highly mobile, roaming movements and did not exhibit high fidelity to natural foraging areas, inshore areas at or adjacent to locations used by diver-based fisheries, or by the public during recreational activities, such as fishing and surfing.

Spatial and temporal patterns of presence, affinity, and broad-scale movements of White Sharks were not explained by the proximity to areas where seasonal marine industry activities take place. Tracking data showed no overall, distinct patterns explaining the movements of all individuals, suggesting that seasonal presence of White Sharks in South Australian shelf and gulf environments is driven by complex combinations of factors that are operative at broad spatial scales of 100's or 1000's of km. This was consistent with the findings of a movement study with a larger sample size (including some of the same South Australian tagged sharks) throughout Western Australian shelf waters (McAuley *et al*. 2017). Despite this lack of an overarching population-wide movement and migration pattern, observed peaks in acoustic detection frequencies in winter were generally consistent between the Spencer Gulf sites and Neptune Islands sites in shelf waters. Satellite tracked individuals exhibited offshore, west-ward migrations to the GAB and WA during winter, spring and to a lesser extent summer, with others present in Spencer Gulf during summer, autumn and winter. When interpreting the trends in the satellite telemetry data, however, it is important to recognise that the overall sample size of individuals was ten and annual time series, and hence, complete seasonal movements were not examined due to the length of tag deployment times.

Aquaculture industry representatives communicated that Yellowtail Kingfish are generally harvested on a year-round basis. Seasonal patterns of presence observed in the acoustic telemetry data for Bronze Whalers aligned with comments by industry who suggested the species was observed sporadically during summer. For White Sharks and Bronze Whalers, low detection rates in gulf waters showed that overlap was more likely in offshore areas, i.e. outside most areas (>20 m depth) where finfish aquaculture leases are located. Prior to this study, residency of sharks near finfish cages had only been studied in Hawaiian waters (Papastamatiou *et al.* (2010). Findings of the Hawaiian study were based on one migratory species (Tiger Shark), and one highly mobile, predominantly coastal and shelf inhabiting species (Sandbar Shark); the latter species is also found in WA waters (Braccini *et al.* 2017). The study in the Pacific Ocean suggested there were species-specific patterns of overlap with offshore aquaculture pontoons (Papastamatiou *et al.* 2010).

Analyses of acoustic telemetry data-sets at two high detection rate sites demonstrated that marine activities have the potential to alter shark behaviours in ways that can be quantified on the basis of changes in individual movement metrics (e.g. fidelity to a site, area or region). The scaled metric of 'shark days' was used to provide new information on the significance of several pinniped colonies, Snapper habitats and other physical features to White Sharks and Bronze Whaler, that had not been previously examined in detail in South Australia. Whilst several pinniped colonies were visited over short durations by acoustically tagged White Sharks, notable results were that the largest Australian Sea Lion colony in the EGAB was not visited by a single tagged White Shark, and no satellite tagged White Sharks transmitted from areas at or near pinniped colonies on the southern coastline of Kangaroo Island. Some of the sites monitored were nested within spatially-managed fishery and aquaculture areas, marine parks, and corridors linking patches of reef, sand and seagrass in gulf waters. In Spencer Gulf, three key sites of interest to White Sharks were identified where individuals exhibited brief, repeated visits, including two reef slopes offshore from Dangerous Reef and Buffalo Reef, and a channel near English Island in the Sir Joseph Banks Group. These features are adjacent to granite-capped islands where pinnipeds haul out or breed, and are located along movement paths near the edges of the central 'gutter' in Spencer Gulf. This was supported by the satellite tracks, and a previous study of Bruce *et al.* (2006).

Highest use of offshore areas by satellite tagged White Sharks occurred at and beyond the continental shelf-break and slope adjacent to the west and south-west of Kangaroo Island and southern Eyre Peninsula, and off SW WA in the Indian Ocean. Areas of high relief bathymetry between the 80 – 130 m depth contours were used by White Sharks during transitory movements across the GAB. Proportional grid-based overlap analyses of the satellite telemetry data showed the number and percentage of site types that White Sharks overlapped with at the ≤ 10 km scale varied considerably; the following spatially managed areas and their percentage scores were - finfish farm sites (5%), finfish aquaculture zones (22%), commercial abalone fishing areas (24%), seasonal spatial closures for Snapper (wrecks) (25%), state marine parks (36%), and cage-diving sites (50%). It is important to note when interpreting these findings, that the number of sites and total area per type ($km^2$) are inequal, and hence, any between-site type comparisons can't be statistically supported. The Snapper habitats (20%), Snapper spatial closures (25%), and predicted movement paths that were acoustically monitored (43%), were in the vicinity of several satellite position estimates. Notably, 12% and 9% of Australian Sea Lion, and Long-nosed Fur Seal colonies, respectively were passed by satellite tracked sharks, indicating that hypothesized directionality towards or near these habitats did not explain a substantial percentage of the movement stages exhibited. In summary, the proportional grid-based analyses of White Shark satellite tracking data indicated that central Spencer Gulf (>20 m depths), continental shelf break, slope and associated submarine canyons, were the key regions used by White Sharks. Within Spencer Gulf, 74% of the estimated satellite positions correlated with depths ≥ 20 m, and 93% of the estimated positions ($n$ = 2,956) occurred outside the entrance to Spencer Gulf, between Cape Catastrophe and Cape Spencer. As a result, the activities and ecological features in those areas and depth ranges scored the highest nominal overlap percentages, and there was minimal overlap between areas used by White Sharks and inshore coastal areas used by the public for recreational activities. It is likely that this partially explains the low frequency of harmful and fatal interactions between White Sharks and humans in South Australian waters.

Shark behaviour in response to human activities needs to be considered in light of the new information collected during this study. Of importance are the potential implications of the differences we found in fidelity behavior of White Sharks exhibited at the Spencer Gulf, EAGB (off western Eyre Peninsula) and Neptune Islands sites. White Sharks are typically highly mobile. The exception to this is during visits by some individuals to the Neptune Islands Group, where some White Sharks exhibited high site-fidelity within the scale of weeks to months at cage-diving sites in the embayments adjacent to Long-nose Fur Seal breeding colonies. Importantly, other individuals either did not exhibit high fidelity at these sites, or did not return following tagging during the study period, suggesting individualistic susceptibility behaviors to routine human stimuli (input of bait and berley) may be operative, and this warrants further investigation and management consideration. There are continuing uncertainties surrounding the potential implications of these findings in context of safety of marine user groups in areas adjacent to these sites, including the diverse migration pathways of this species, some of which were identified (or confirmed) during this study.

During this project, preliminary scientific outcomes combined with the findings of the two social surveys were used to provide advice in relation to a tourism development application process at Victor Harbor. A tourism development led to sporadic public interest regarding potential links between tuna, sharks and aquaculture. In response, the social survey plans were structured to avoid potential participation biases predicted to be driven by polarised opinions in social and other media, and within vocal minority groups, and follow-up questions were applied to interviewees across the scale of the South Australian survey area. These two surveys found that social media was not widely viewed as an important, trust-worthy or reliable source of information with regard to sharks, and that sharks and aquaculture together were considered lower order priorities than marine parks, or seal impacts on the seafood industry.

Throughout the project, the investigators worked in partnership with industry representatives to develop operational solutions to resolve interactions between sharks and marine industries in South Australia in a safe, practical and humane manner, which will provide flow-on benefits to other Australian management jurisdictions, including WA and Tasmania. Considerable interest in this component of the project has been communicated from the WA Aquaculture Council.

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# 7. Recommendations

It is recommended that the results of this study be broadly disseminated to the aquaculture and commercial fishery sectors, Government of Western Australia Department of Primary Industries and Regional Development, Victorian Fisheries Authority (VFA), Queensland Department of Agriculture and Fisheries; NSW Department of Primary Industries, Tasmanian Government (DPIPWE), Australian Fisheries Management Authority (AFMA), Department of Agriculture and Water Resources (ABARES), national and international fisheries scientists and the general public.

# 8. Extension and Adoption

- Considerable engagement between SARDI, PIRSA Fisheries and Aquaculture and the fishing and aquaculture industry.
- Advice to PIRSA Fisheries and Aquaculture on shark movements and Oceanic Victor tourism application.
- Contributed to South Australian Senate on Shark Mitigation Measures.

The Principle Investigator presented findings at:

- ASBTIA and FRDC SBT Industry Workshops in Port Lincoln in November 2015 and 2016.
- ASFB Conference in Hobart in September 2016.
- PIRSA Fisheries and Aquaculture in March 2017.
- Australia Abalone Industry Committee meeting at Glenelg in June 2017.
- Discussions with Tina Thorne (Executive Officer of Western Australian Aquaculture Council) in July 2016 and February – March 2017.
- Discussions with Steve Nel (Aquaculture manager) in July 2016, and Fiona Rowlan (Senior Management Officer) of WA DPIRD in February and July 2017.
- South Australian Shark Risk Round Table Parliament House presentation in December 2017.
- Findings were presented at the AMSA Conference in Adelaide in July 2018.

# 9. Project coverage

FRDC Fish magazine article in June 2017. *Shark Smart*, pages 14 – 16. Vol 25 (2).

Posted on the IMOS Website http://imos.org.au/news/newsitem/shark-smart/

Posted on FRDC and IMOS Facebook pages.

# 10. Project materials developed

Peer-review publications currently in preparation that incorporate data from this project:

Rogers, P.J., Drew, M., Doubell, M., and Redondo Rodriguez, A. *Movement dynamics of White Sharks in Spencer Gulf and the Great Australian Bight: overlap with areas of ecological significance, marine industries and tourism.*

Rogers, P.J., and Drew, M, Doubell, M., and Redondo Rodriguez, A. *Environmental and ecological drivers of presence of a temperate reef shark, the Bronze Whaler (Carcharhinus brachyurus) in a seasonally sub-tropical gulf ecosystem.*

## Data-sharing and provenance:

This project led to the development of formalised cross-jurisdictional data-use and sharing agreements with CSIRO and WA DPIRD, and draft formal agreements with NSW DPI.

It is anticipated that acoustic detection data will be stored in the IMOS program data portal by December 2018.

Data collected by SARDI will be amalgamated with data collected during other programs in NSW DPI and WA DPIRD to assess connectivity of White Shark populations at the National level.