Galapagos shark movement patterns and interactions with fishing vessels in the marine parks surrounding Lord Howe Island

A report for Parks Australia

Australian Government
Parks Australia

Australian Marine Parks

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Table of contents

List of figures

List of tables

List of abbreviations

BP	Ball's Pyramid
FAD	Fish Aggregating Device
GAMM	Generalised Additive Mixed Model
GLMM	Generalised Linear Mixed Model
IMOS	Integrated Marine Observation System
KDE	Kernel Density Estimation
KUD	Kernel Utilisation Distribution
LHI	Lord Howe Island
NSW DPI	New South Wales Department of Primary Industries
NTZ	No-Take Zones (includes Sanctuary Zones in State waters and National Park Zones in Commonwealth waters)
VMS	Vessel Monitoring System

1. Executive summary

Galapagos sharks (*Carcharhinus galapagensis*) are a key indicator species in the World Heritage listed marine parks surrounding Lord Howe Island (the Lord Howe Island Marine Park in NSW State waters and the Lord Howe Marine Park in Commonwealth waters), yet, very little is known about their movement patterns or residency. This Galapagos shark population may be genetically distinct from others across the southwest Pacific Ocean and the marine parks surrounding Lord Howe Island (LHI) appear to be an important nursery for the species. There is a pressing need to understand the movement ecology of Galapagos sharks in these marine parks, because they regularly interact with fishers where they are inadvertently captured as bycatch and/or consume bait and hooked fish (depredation), leading to negative outcomes for both fishers (social and economic) and sharks (altered natural behaviour, injury or death). The combination of acoustic telemetry to collect data on shark movements and Vessel Monitoring Systems (VMS) to track fishing vessel activity, provides a unique opportunity to identify how shark movements and fishing activity overlap and where key 'hotspots' of overlap occur. This detailed spatial information is valuable for fishers and marine park managers for determining areas and times at which the likelihood of shark interactions is greater, and thus can help to identify strategies to reduce these human-wildlife conflicts.

To investigate Galapagos shark movements, 30 juvenile sharks (18 females and 12 males, total lengths from 96 – 177 cm) were internally tagged with acoustic tags in January 2018. Twelve acoustic receivers were deployed around the LHI and Ball's Pyramid (BP) shelves, both in areas where fishing occurred regularly and in no-take zones (NTZs; which are called Sanctuary Zones in the NSW State Marine Park and National Park Zones in the Commonwealth Marine Park) where no fishing is allowed. These acoustic receivers collected data on the movements of tagged sharks across a three-year period (January 2018 – January 2021). Ten of the acoustic tags also recorded depth and temperature data concurrent with the sharks' presence at each site. Fishing vessel activity was determined using VMS data for six vessels from January 2018 to November 2019 and two vessels from December 2019 to January 2021. Detection patterns were analysed to investigate individual variation in shark movements and seasonal changes and to generate a residency index. Generalised Linear Mixed Models (GLMMs) were applied to investigate whether residency was affected by shark sex, total length and/or tagging location. Kernel Utilisation Distribution (KUD) was used to estimate the core and extent areas of Galapagos shark space use in the marine parks. Kernel Density Estimation (KDE) was applied to VMS data to determine spatial variation in fishing activity. Maps of shark space use and how it overlapped with fishing activity were generated to identify key 'hotspot' areas of overlap. A Generalised Additive Mixed Model (GAMM) was utilised to quantify how fishing activity and environmental variables influenced the number of shark detections. The depth distribution of Galapagos sharks was also investigated, using GLMMs to determine how season, diel period, total length and sex influenced depth ranges. A survey of local charter and recreational fishers was conducted to collect detailed information about shark-fisher interactions, such as where and when they occur most frequently, what impacts they have, and whether fishers currently use any mitigation/avoidance techniques. Logbook catch data for sharks from 2015 to 2018 were also analysed to determine the overall shark catch per year, the percentage of sharks released and retained and the size distribution.

Between 2018 and 2021, acoustic receivers recorded 24,933 detections from 28 of the 30 tagged Galapagos sharks, with a substantial level of individual variation in the detection patterns. Number of detections per shark ranged from 8 – 8,636, with a mean of 890, and sharks were detected at 1 – 8 different acoustic receivers around the marine parks (mean = 3.8). Galapagos sharks were detected in every month of the three-year study period, with five individuals showing high and consistent numbers of detections all year round, indicating that at least part of the Galapagos shark population within the marine parks is resident. This supports findings of high levels of residency for this species around other oceanic islands, including Hawaii and islands in the eastern tropical Pacific Ocean. One individual was, however, detected on 03/02/2021 by an acoustic receiver on a Fish Aggregating Device (FAD) close to the Hunter Marine Park (Commonwealth) and Port Stephens – Great Lakes Marine Park (NSW) and approximately 30 km offshore from Port Stephens (32.78278°S, 152.41171°E) in mainland New South Wales, representing a distance of 653 km from the original tagging location. This would be the first documented movement of a Galapagos shark from LHI to mainland Australia, however it is possible that these detections resulted from the tagged Galapagos shark being predated upon by a larger shark (e.g. a white shark *Carcharodon carcharias* or a tiger shark *Galeocerdo cuvier*) at another location, with this larger shark then retaining the tag in its digestive system. Highest numbers of Galapagos shark detections in the LHI array occurred in spring and summer months, possibly due to more favourable environmental conditions and a greater level of fishing activity in these seasons. The tagged Galapagos sharks were recorded moving up to 12.2 km per day (mean = 6.8 km per day), travelling up to 36.3 km away from their original tagging locations (mean = 12.2 km), apart from the individual detected in mainland NSW offshore waters. Residency index values varied from <0.01 – 0.57 with most individuals having a low residency index (i.e. <0.1). However, three sharks tagged at a site where fish are commonly 'cleaned' (i.e. where the head and guts are removed and disposed of at sea) had notably higher residency index values, likely because this consistently available food source led to changes in their behaviour and movement patterns over time. When interpreting the results for the detection patterns and residency levels of the tagged sharks, we acknowledge that there was a relatively low coverage of acoustic receivers across the marine parks surrounding Lord Howe Island (distances between receivers were between 5 and 15 km), and detection ranges were relatively small (400 – 600 m). Therefore, we are unable to determine whether gaps in detection patterns and low residency index levels for some individuals represented migration away from the area for periods of time, or whether they were simply outside of the detection range of receivers but still within the marine parks.

Space use areas were only able to be calculated for nine out of 28 Galapagos sharks, i.e. those that were detected at ≥5 acoustic receivers. The KUD areas of these sharks were highly variable, ranging from 0.28 km^2 – 217.65 km^2 (mean = 75 km^2) for core KUDs and from 1.59 km^2 – 1342.63 km^2, (mean = 496 km^2) for extent KUDs. Three sharks with the smallest space use areas were those that displayed high residency at the site where fish waste was disposed, further supporting the theory that this readily available food source has led to a change in their behaviour. Some of the sharks' core KUD areas also closely overlapped with areas of highest fishing activity, particularly at shelf edges in the northeast and southeast LHI shelf and the northern BP shelf. This overlap was likely related to the formation of behavioural associations in the Galapagos sharks, where they have learnt to associate the sounds of fishing vessels with a food source in areas that are frequently fished, as has been recorded for other shark species elsewhere in Australia. The overlap also likely occurred because fishers and sharks both targeted shelf edge areas where there is higher productivity and greater density of bait fish and yellowtail kingfish (*Seriola lalandi*), the key target species of the LHI charter fishery.

GAMMs also indicated that the number of Galapagos shark detections was positively influenced by the level of fishing activity and that detections peaked in summer, reflecting the experiences of LHI fishers, who reported higher rates of shark bycatch and depredation in summer. Galapagos sharks ranged from 0 – 94 m depth (mean = 25.2 m), similar to findings in Hawaii and Ascension Island (in the equatorial South Atlantic Ocean). Diel period significantly affected depth distribution, with sharks moving shallower at night, indicative of diel vertical migration, which has been recorded for Galapagos sharks at other locations and is hypothesised to be linked to changing prey distributions. Temperature data indicated a clear seasonal pattern, with most detections occurring when sea temperatures ranged from 19 – 21°C. In addition to tagged Galapagos sharks, the acoustic receivers also detected a white shark and a tiger shark originally tagged in Australian coastal waters. The white shark was detected 93 times across six receivers on both the LHI and BP shelves, between 15/05/2019 and 02/07/2019. The tiger shark was detected 24 times on two acoustic receivers, from 14/12/2020 – 16/12/2020.

Results from a survey of LHI fishers indicated that shark depredation resulted in the loss of 50.6 ± 26% of fish hooked per trip, with generally higher depredation rates in summer months. In the majority of cases (72.2 ± 22.8%), the whole fish was lost due to shark depredation, with the fish head being retrieved for only 27.7 ± 22.8% of depredation events. Loss of bait and fishing gear to sharks was also reported to occur, with bait lost 8.7 ± 3.9 times per trip and lost gear costing $96.9 ± 3.9 per trip. Depredation rates were reported to be highest on the LHI shelf, followed by the BP shelf and then shelf edges. Lower levels of depredation were noted to occur in near shore and lagoon areas. Fishers reported almost zero shark depredation in areas >150 m deep, although they did occasionally encounter larger shark species, such as silky (*Carcharhinus falciformis*) and shortfin mako (*Isurus oxyrinchus*) sharks, at these depths. Rates of Galapagos shark bycatch were 7.7 ± 4.2 sharks per trip, with 70% of fishers stating they released all bycaught sharks, while the other 30% sometimes retained sharks for sale to restaurants or for use as bait. Only one fisher removed hooks from all sharks before releasing them, with the others mainly cutting the line. Reporting rates for shark interactions were low, with only 10% of fishers reporting all interactions, including both bycatch and depredation and the percentage of sharks kept and released. The remainder of fishers stated that they only partially reported shark interactions, for example just the number of sharks that were bycaught but not depredation events, and that these figures provided were estimates.

Logbook data submitted by charter fishers indicated that 4441 sharks were caught between 2015 and 2018, with a mean of 1114 ± 500 per year. Of those caught, 98.13% were released and 1.87% were retained by fishers. While the vast majority of sharks caught were likely Galapagos sharks, a small number of individuals from other species would also have been caught, for example silky and shortfin mako sharks and small deep-sea *Squalus spp.* The size distribution of sharks caught ranged from <50 cm to 250 cm, with a mean total length of 92.86 ± 61.08 cm. Because Galapagos sharks are born at 50 – 70 cm, it is likely that those recorded in the <50 cm category were other, smaller species, such as *Squalus spp*. Additionally, some of the larger sharks >2 m could have been silky, shortfin mako or tiger sharks.

This research generated important new insights into the movement ecology and behaviour of Galapagos sharks, which have not previously been studied in the southwest Pacific region. The results from the spatial analyses of shark movements and fishing activity identified four key 'hotspot' areas where fishing activity and Galapagos shark habitat use overlapped. This key finding will enable fishers to make more informed decisions about where they can fish to potentially reduce shark interactions. Combined with information gathered through surveys of LHI fishers, these outputs have facilitated the development of best-practice guidelines to help fishers reduce negative shark interactions in the marine parks. Key recommendations include avoiding hotspots where shark movements and fishing activity were found to overlap the most, moving location regularly when fishing, avoiding fishing in the same area on consecutive days and fishing in deeper (>100 m) or shallower (<30 m) water where possible, all of which will help to reduce the chance of encountering sharks and reinforcing the behavioural association of sharks with vessels. Bringing back fish waste for disposal on land at the LHI waste management facility, instead of cleaning at sea, will also help to reduce the chance of sharks being attracted to vessels. In terms of fishing gear, using electric reels and/or handlines instead of rod and reel will enable hooked fish to be retrieved quicker, limiting the time available for sharks to depredate them, and jigs and lures will be less likely to attract sharks compared to bait. Diversifying the fish species targeted to include more demersal species instead of yellowtail kingfish may also help to reduce depredation rates, because demersal species are reported by fishers to be less attractive to sharks and there is less spatial overlap in the distribution of some demersal species with the Galapagos sharks, compared to yellowtail kingfish and other pelagic fish. Improved data collection in the LHI artisanal fishery via an electronic logbook system and regular onboard fisheries observer coverage is also recommended, to address existing uncertainty/underreporting issues around the level of shark bycatch and the occurrence of depredation. Working with local residents and authorities to install fish cleaning tables and bins, as well as the establishment of a fish waste composting business, is also strongly encouraged. Further research is also recommended, including the testing of two new shark deterrents designed to reduce shark depredation and bycatch, to assess if they can provide a cost-effective technological solution to negative shark-fisher interactions. Collecting further data on shark movements and habitat use by continuing the deployment of the current acoustic receiver array in the marine parks and tagging a small number of Galapagos sharks with satellite tags, is also recommended to better identify spatial and temporal ‘hotspots’ of overlap between shark movements and fishing activity. Overall, this collaborative research project has used a multi-disciplinary approach and worked closely with the LHI fishing community to provide detailed insights into the behaviour and movement ecology of this little understood species and how it interacts with fishing activity in the marine parks. This research represents a critical first step towards informing future research and management strategies to reduce negative shark-fisher interactions in the marine parks surrounding LHI.

2. Introduction

The marine parks surrounding LHI, which includes the Lord Howe Island Marine Park managed by New South Wales (NSW) State Government and the Lord Howe Marine Park managed by the Commonwealth Government, are located approximately 700 km north-east of Sydney and are part of the Lord Howe Island Group World Heritage site listed in 1982 (Director of National Parks, 2018). These marine parks contain a unique mix of sub-tropical and temperate species, including a number of endemic fish and invertebrates, as well as the world’s most southerly true coral reef (Director of National Parks, 2018). The marine parks aim to manage and protect the unique biodiversity whilst also providing opportunities for a range of different uses and activities including recreational and charter fishing (Director of National

Parks, 2018). The vast majority of fishing that occurs in the marine parks uses hook and line, although fishing is not allowed in NTZs, which make up 27% (12,500 hectares) of the NSW State Marine Park and 8% (927,300 hectares) of the Commonwealth Marine Park. There are bag limits and minimum size limits for key target species such as yellowtail kingfish, doubleheader wrasse (*Coris bulbifrons*) and bluefish (*Girella cyanea*) (NSW Department of Primary Industries, 2020). As part of a voluntary agreement with Parks Australia, some charter fishing vessels (six vessels from January 2018 – November 2019 and two vessels from December 2019 onwards) also provide high resolution spatio-temporal fishing activity data through Vessel Monitoring System (VMS) devices.

Galapagos sharks (*Carcharhinus galapagensis*) are distributed at oceanic islands and seamounts throughout temperate and sub-tropical waters worldwide (Ebert et al., 2021) where they primarily inhabit epipelagic waters from 0 – 100 m depth and tend to be resident year-round (Wetherbee et al., 1996; Kohler et al., 1998; Meyer et al. , 2010). However, some larger scale movements >300 km have also been documented (Lizardi et al., 2020). The Galapagos shark is a key indicator species for the management of the marine parks surrounding LHI (Edgar et al., 2010) and occurs in high abundance throughout these marine parks (Heagney et al., 2007; Neilson et al., 2010; Rees, 2013; Davis et al., 2017). The waters surrounding LHI, along with Elizabeth and Middleton Reefs and Norfolk Island, are the only known locations where Galapagos sharks occur in Australian waters (Kyne et al., 2019). The population of Galapagos sharks in the waters surrounding LHI is believed to be genetically distinct from those at Norfolk Island and Elizabeth and Middleton Reefs and other locations across the southwest Pacific (van Herwerden et al., 2008).

This species regularly interacts with charter and recreational fishers in the marine parks surrounding LHI, where they consume bait and hooked fish (a process known as depredation – see Figure 1) (Robbins et al., 2011; Mitchell et al., 2018b). The frequency of depredation by Galapagos sharks has increased in the last 5 – 10 years, possibly due to a change in shark behaviour, whereby they have likely become accustomed to boat engine noise, associating this with the availability of a food source in the form of hooked fish, as well as bait, released fish that are injured and discarded fish waste (Mitchell et al., 2018b; 2020). Shark depredation causes extra mortality for targeted species, e.g. yellowtail kingfish, injury to sharks from fishing gear and costly loss of fish and gear for fishers. Such interactions are also causing a broader shark-fisher conflict in the marine parks, which is resulting in fishers deliberately injuring and killing sharks, with some local fishers also advocating for a cull of the species. Large numbers of Galapagos sharks are also caught as incidental bycatch in the LHI charter fishery, ranging from 559 – 1,328 animals per year, and whilst >95% of sharks are released, post-release mortality can occur from hook injuries and stress (Figueira & Hunt, 2017). These marine parks constitute a possible nursery area for this species, as reflected by the large number of juveniles <1.5 m caught in the charter fishery (Figueira & Hunt, 2017), the frequent observation of juvenile sharks on baited camera surveys (Neilson et al., 2010; Rees, 2013; Davis et al., 2017) and the capture and sighting of sharks <60 cm with a visible umbilical scar present (Mitchell & Camilieri-Asch, pers. obs.). Therefore, in combination with the possible genetic localisation or high residency of this population, the presence of a potential nursing area in these marine parks increases the vulnerability of the local shark population to declines caused by culling and high levels of bycatch. Such declines have previously been observed at Saint Paul's Rocks in the Atlantic Ocean, where the resident population of Galapagos sharks was reduced to very low levels due to large catches in longline and hand line fisheries (Luiz & Edwards, 2011; de Queiroz et al., 2021).

Figure 1. A Galapagos shark approaching a hooked yellowtail kingfish prior to consuming it, a process known as 'depredation'.

Because of the socio-economic and biological impacts associated with the occurrence of shark depredation in the marine parks surrounding LHI, there is a need to investigate potential solutions for mitigating this human-wildlife conflict. Previous research tested magnetic deterrents as a means of reducing Galapagos shark interactions with fishing gear in the marine parks, showing partial success when few sharks were present, but low effectiveness when shark density was higher and intra-specific competition occurred (Robbins et al., 2011). To build on this previous deterrent research and generate potential solutions for mitigating depredation, it is important to understand more about the biology and ecology of Galapagos sharks, specifically by identifying their movement patterns, seasonal presence, depth range and residency around the LHI marine parks. For example, collecting data on the times of year and depths at which Galapagos sharks are most likely to occur can inform fishers about the potential likelihood of encountering sharks and experiencing depredation. Additionally, identifying how shark movement patterns and residency overlap with fishing vessel activity is of substantial value for producing detailed spatial information about where shark interactions are currently occurring most frequently and identifying potential causes.

Acoustic telemetry has been widely used for investigating the movement ecology of sharks in Australia and worldwide, offering the ability to track the movements of sharks for long timescales (up to 10 years) (Heupel & Simpfendorfer, 2005; Papastamatiou et al., 2010), at broad and fine spatial scales (Braccini et al., 2017; Bruce et al., 2019; George et al., 2019), and provide detailed information on habitat use and residency (Espinoza et al., 2015). Also, the ability to investigate overlaps between shark movement patterns and fishing vessel activity has increased in recent years, due to advances in satellite and acoustic tag technology, as well as satellite-based VMS. The combination of these two technologies allows high-resolution analysis of the spatial and temporal dynamics of shark-fishing interactions on fine and broad scales. A recent large-scale study used this approach to determine the overlap between pelagic shark movements and longline fishing vessels globally, finding that 24% of the space used by these sharks overlapped with fishing activity (Queiroz et al., 2019). Specifically, high overlaps occurred in locations with strong temperature gradients and high productivity, due to sharks and fishers targeting the same fish resources (Queiroz et al., 2016). Jacoby et al. (2020) used acoustic telemetry data from 101 tagged reef sharks and fishing activity data from interceptions of illegal fishing vessels in the British Indian Ocean Territory (BIOT), to construct movement networks to predict the long-term movements of sharks and identify the extent to which this would expose them to risk of being caught by illegal fishing activity. Other studies have also used acoustic telemetry to assess how provisioning of sharks by ecotourism operations affects their movement patterns, depth use and home range size (Fitzpatrick et al., 2011; Brunnschweiler & Barnett, 2013; Huveneers et al., 2021). These studies highlight the potential of technology for investigating the overlap of shark movements with fishing activity, however, the occurrence of human-shark conflict driven by depredation is yet to be explored using this approach.

3. Aims and objectives

This research sought to use acoustic telemetry to investigate the movement patterns of Galapagos sharks in the marine parks surrounding Lord Howe Island (LHI) and how they overlap with fishing vessel activity as monitored by VMS tracking of charter fishing vessels. The specific objectives of the research were as follows:

1. To identify the movement patterns of Galapagos sharks in the marine parks surrounding LHI over a three year timescale, using an array of 12 fixed acoustic receivers;
2. To determine the space use and residency of Galapagos sharks within the marine parks, and how this may be influenced by fishing activity and environmental factors;
3. To collect baseline ecological data for this species, particularly on its depth range and temperature preferences;
4. To quantify the extent to which shark movement patterns overlap with fishing vessel activity in time and space and identify key overlap ‘hotspots’;
5. To provide recommended strategies to fishers and marine park managers for reducing negative interactions between fishers and Galapagos sharks.

This research provides the first detailed investigation of Galapagos shark movement patterns, space use and residency in the southwest Pacific region, contributing vital ecological knowledge on this species, which has received little research attention to date. This information has substantial value for improving our understanding about the role this predator and key indicator species plays in the food webs and ecosystem dynamics of the marine parks of LHI. The use of acoustic telemetry and VMS data to determine how the spatial overlap of shark movements and fishing activity influences shark depredation is the first such application of this technology regionally, and will therefore provide key insights into this topical human-wildlife conflict that will have value to other locations where shark depredation is occurring.

4. Methods

4.1 Study location

Data collection occurred in the marine parks surrounding LHI, located ~600 km east of the Australian mainland (Figure 2). The marine parks surrounding LHI covers both the LHI and BP shelves, which are separated by a deep-water (>500m) trench. Shelf waters reach a maximum of 100m before dropping steeply to >2000m.

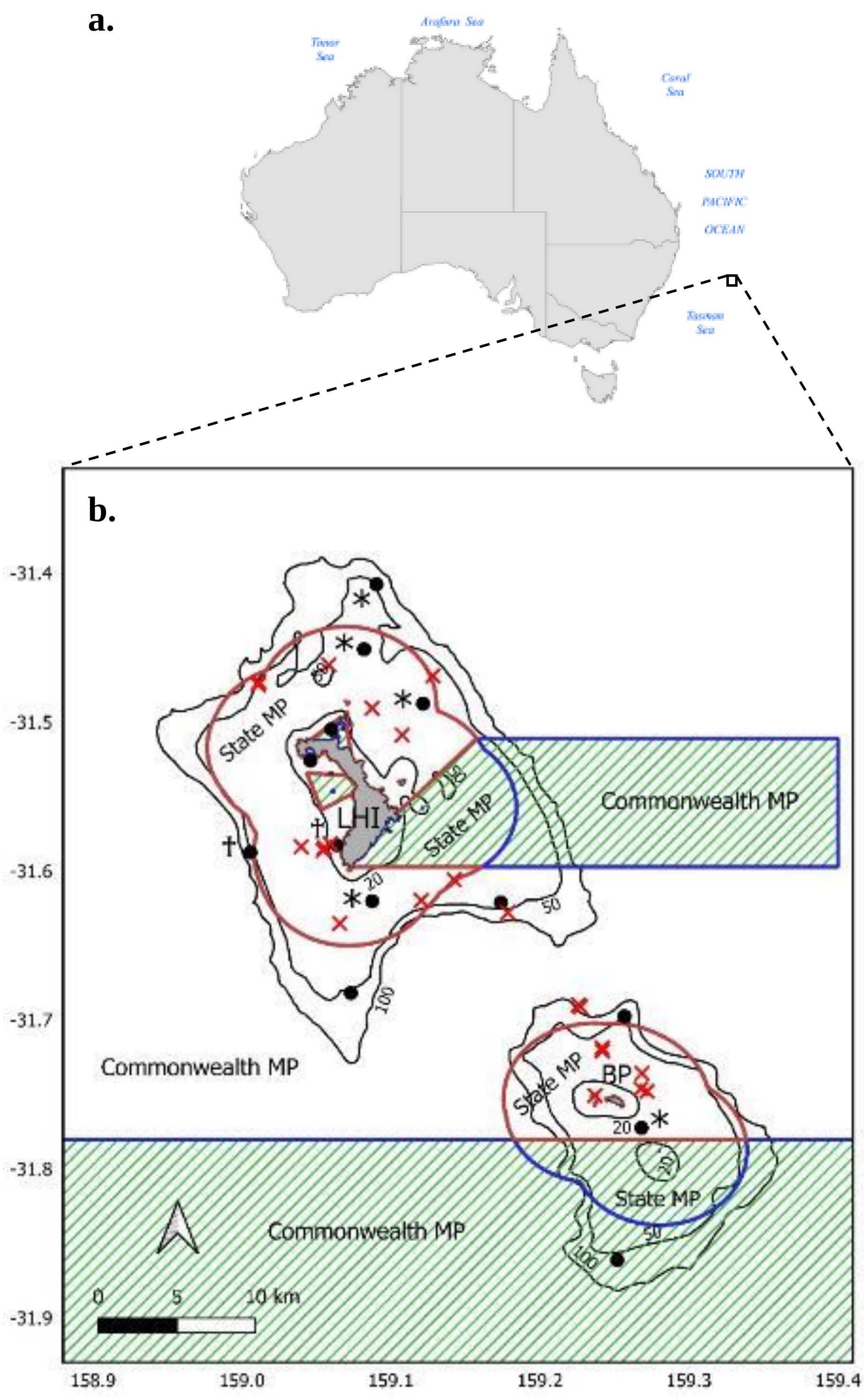


Figure 2. (**a**) Map of Australia showing the relative position of Lord Howe Island; (**b**) Detailed map showing acoustic receiver locations (black circles) and shark tagging locations (red crosses). Solid dark red lines show the boundaries of the NSW State Marine Park and blue lines indicate the Commonwealth Marine Park. No-take zones are marked with hashed green lines. Solid black lines indicate the 20, 50 and 100 m depth contours. LHI = Lord Howe Island, BP = Ball's Pyramid. * denotes receivers which were only deployed between January 2018 and January 2019 and † indicates receivers which were deployed from January 2019 to January 2021.

4.2 Acoustic telemetry data collection

To collect data on the movement patterns of Galapagos sharks, 30 individuals ranging in total length from 96 – 177 cm (12 males, 18 females; Table 1) were captured in a range of different locations throughout the marine parks surrounding LHI (Figure 2) via a combination of line fishing methods, including handlines, an electric winch and hand-operated Alvey reels. Fishing gear consisted of barbless 14/0 Mustad™ non-offset circle hooks (where the barb was also crushed) baited with squid and/or pilchards, attached to a 1.5 m stainless steel wire trace, which was attached to a monofilament mainline, which ranged in breaking strain from 100 – 400 lbs. Sharks were captured and brought onto the vessel for acoustic tagging (Figure 3), where they were secured in a custom-built cradle device lined with foam. Water was continuously circulated over the gills of the shark throughout the tagging process, enabling ventilation. Prior to internally implanting the acoustic tags, the total length of the shark was measured and a small (2 cm) triangle of skin was clipped from the trailing edge of the dorsal fin for use in later genetic studies. The shark was then rotated onto its dorsal surface to induce tonic immobility, after which a small (3 cm long) incision was made in the abdominal portion of the shark, off the midline. The V16 acoustic tag was inserted into the peritoneal cavity (Figure 3b) and the wound closed with 3 to 4 interrupted, dissolvable sutures. The wound was then disinfected with betadine as a preventative measure against infection. A yellow dart tag (NSW Department of Primary Industries Game Fish Tagging Program) was then inserted into the dorsal musculature of the shark to enable fishers to report if it was recaptured. Following removal of the hook (Figure 3c), the shark was then returned to the water (Figure 3d) and its condition recorded. The tagging process took between 8 – 14 minutes, from when the shark was brought onto the boat, to when it was released.

Table 1. Tagging details for Galapagos sharks in the marine parks surrounding Lord Howe Island. LHI = Lord Howe Island, BP = Ball's Pyramid. V16 = standard acoustic tag, V16TP = acoustic tag combined with temperature and pressure sensors.

Tag ID	Model	TL (cm)	Sex	Date (UTC)	Time (UTC)	Location	Latitude (°S)	Longitude (°E)
1280540	V16	96	F	21/01/2018	03:45	Northwest LHI shelf	31.473267	159.011283
1280541	V16	128	M	21/01/2018	04:15	Northwest LHI shelf	31.473267	159.011283
1280542	V16	137	F	21/01/2018	04:45	Northwest LHI shelf	31.47515	159.010833

1280543	V16	116	F	21/01/2018	05:35	Northwest LHI shelf	31.4618	159.05825
1280544	V16	121	M	23/01/2018	02:36	East LHI shelf	31.490867	159.087333
1280559 *	V16TP	127	M	23/01/2018	05:44	South LHI fish cleaning area	31.5818	159.059283
1280560	V16TP	155	F	23/01/2018	06:05	South LHI fish cleaning area	31.583833	159.039833
1280561	V16TP	146	F	23/01/2018	06:15	South LHI fish cleaning area	31.58435	159.055383
1280562	V16TP	136	F	23/01/2018	06:30	South LHI fish cleaning area	31.5863	159.054533
1280563	V16TP	117	M	23/01/2018	21:52	South LHI shelf	31.6198	159.120267
1280564	V16TP	121	M	23/01/2018	22:19	South LHI shelf	31.6198	159.120267
1280565	V16TP	116	M	23/01/2018	22:45	South LHI shelf	31.6198	159.120267
1280566	V16TP	117	F	23/01/18	23:00	South LHI shelf	31.6198	159.120267
1280567	V16TP	136	F	24/01/2018	00:45	South LHI shelf	31.6353	159.0656
1280568	V16TP	141	M	24/01/2018	04:15	East LHI shelf	31.508833	159.1075
1280545	V16	116	F	24/01/2018	05:45	East LHI shelf	31.469067	159.128217
1280546	V16	115	M	24/01/2018	06:20	East LHI shelf	31.469067	159.128217
1280547	V16	156	F	26/01/2018	05:10	North BP shelf	31.689983	159.2259
1280548	V16	177	F	26/01/2018	05:47	North BP shelf	31.69145	159.227183
1280549	V16	152	M	26/01/2018	06:05	North BP shelf	31.69145	159.227183
1280550	V16	138	F	3/02/2018	01:30	Close to BP	31.750883	159.237
1280551	V16	121	M	3/02/2018	02:21	Close to BP	31.746417	159.267733
1280552	V16	114	M	3/02/2018	03:03	Close to BP	31.74805	159.27185
1280553	V16	133	F	3/02/2018	03:19	Close to BP	31.74805	159.27185
1280554	V16	137	F	3/02/2018	03:42	Close to BP	31.7359	159.268467
1280555	V16	125	F	3/02/2018	05:14	North BP shelf	31.721017	159.241917
1280556	V16	125	F	3/02/2018	05:44	North BP shelf	31.71885	159.241633
1280557	V16	129	M	3/02/2018	22:41	Southeast LHI shelf	31.605917	159.14235
1280558	V16	115	F	4/02/2018	00:47	Southeast LHI shelf	31.628033	159.17845
1280539	V16	138	F	4/02/2018	01:16	Southeast LHI shelf	31.628033	159.17845
1280559 †	V16TP	146	F	29/01/2019	02:50	South LHI fish cleaning area	31.584283	159.0595

*shark caught and killed by fisher in October 2018, † tag re-deployed in January 2019

Figure 3. Images of the tagging process for Galapagos sharks. (**a**) hooked shark about to be brought onto the vessel; (**b**) inserting an acoustic tag into the body cavity of a shark whilst it is restrained in the purpose-built cradle device for tagging; (**c**) removing the hook prior to releasing the shark; (**d**) shark swimming away after being tagged and released. Image credit Justin Gilligan (**a, d**) and Ian Hutton (**b, c**).

Acoustic tags were programmed to emit an acoustic signal every 30-90 seconds, providing an approximate battery life of 10 years. Ten of the 30 tags deployed on sharks had temperature and pressure sensors which pinged in an alternate pattern and had operating ranges between -5 to 35°C and 0 to 680 m, respectively. An array of VEMCO VR2W acoustic receivers (which were provided on loan by the IMOS Animal Tracking Facility) were deployed around the marine parks of LHI to detect tagged sharks (Figure 2, Table 2), with 12 receivers deployed in year one (January 2018 – January 2019), nine in year 2 (January 2019 – January 2020) and six in year three (January 2020 – January 2021), due to loss of receivers from acoustic release failure in years 1 and 2 and other equipment limitations. The receivers were located mostly in areas identified by fishers to be popular fishing grounds, apart from two which were deployed in no-take zones to act as control sites (Figure 2). One receiver was also located in a location at the south of LHI where fish waste is regularly disposed. Acoustic receivers were attached to seafloor moorings deployed in depths ranging from 14 – 76 m. Moorings included a concrete block, steel beam or chain anchor, 1.5 – 2 m of riser chain to which a SubSeaSonic AR-60 acoustic release was attached (apart from for two shallow water moorings at approximately 15 – 18 m depth in year one and one shallow water mooring at 14 m depth in years two and three), followed by 1 m of rope to which the acoustic receiver was attached in-line (Figure 4a). The mooring was maintained upright by a 15-litre solid plastic float approximately 2 m above the acoustic receiver. Acoustic receivers were retrieved (Figure 4b) and serviced every 12 months for the duration of the project, before being re-deployed. Data was downloaded and processed in the VEMCO User Environment (VUE) software (Innovasea, Bainbridge Island, WA, USA; https://www.innovasea.com/) where the 'FDA Analyser' tool (VEMCO, 2015; Pincock, 2012) was used to identify and remove any false detections. Range testing was conducted in January 2021 by deploying a V16-6x-BLU-2 acoustic tag from a vessel at waypoints located every 200 m from the receiver, starting at 200 m and ending at 1200 m. The effective detection range was then calculated by cross checking the timestamp and distance of the vessel from the receiver as recorded in the GPS waypoints, with the pings detected by the receiver. Detection ranges of 400 to 600 m were recorded for receivers in deeper water (>30 m), with the one shallow receiver having a detection range of 400 m.

Table 2. Acoustic receiver deployment details. LHI = Lord Howe Island, BP = Ball's Pyramid, NTZ = no-take zone.

Station Name	Date (UTC)	Time (UTC)	Bottom Depth (m)	Seabed type	Latitude (°S)	Longitude (°E)	Date deployed until	No. months data
North lagoon passage	7/01/2018	22:55:00	19.3	Sand	31.5323	159.042	15/01/2019, not redeployed in year 2	12
Admiralty Islands NTZ (North LHI)	7/01/2018	01:00:00	18.7	Sand	31.5094	159.051	15/01/2019, not redeployed in year 2	12
Northeast LHI shelf 1	23/01/2018	22:38:00	50.5	Unknown	31.4076	159.09	17/01/2019, then lost in year 2	12
Northwest LHI shelf	22/01/2018	02:00:00	57.4	Unknown	31.5185	158.976	Lost in both years 1 and 2	0
Northeast LHI shelf 2	12/01/2018	04:30:00	43.5	Algal reef	31.4513	159.082	17/01/2019, not redeployed in year 2	12
East LHI shelf	12/01/2018	04:05:00	30	Algal reef	31.4878	159.122	19/01/2019, then lost in year 2	12
South LHI shelf	11/01/2018	23:30:00	30	Sand and coral reef	31.6203	159.087	16/01/2019, not redeployed in year 2	12
Southwest LHI shelf	12/01/2018	00:44:00	49	Sand and coral reef	31.682	159.073	23/01/2021	36
Southeast LHI shelf	12/01/2018	02:40:00	45.5	Sand, sponges urchins	31.6212	159.174	17/01/2020, then lost in year 3	24
Northeast BP shelf	12/01/2018	02:00:00	50	Sand and urchins	31.6977	159.257	17/01/2020, then lost in year 3	24
Central BP shelf	22/01/2018	00:02:00	34.5	Sand with rocky reef	31.7726	159.268	17/01/2019, not redeployed in year 2	12
South BP shelf (NTZ)	21/01/2018	23:24:00	54.5	Sand	31.8578	159.25	15/01/2021	36
West LHI shelf	20/01/2019	23:23	75.8	Unknown	31.58759	159.0056	16/01/2020, then lost in year 3	12
South LHI fish cleaning area	20/01/2019	23:42	14.8	Sand and rocky reef	31.58283	159.0635	26/01/2021	24

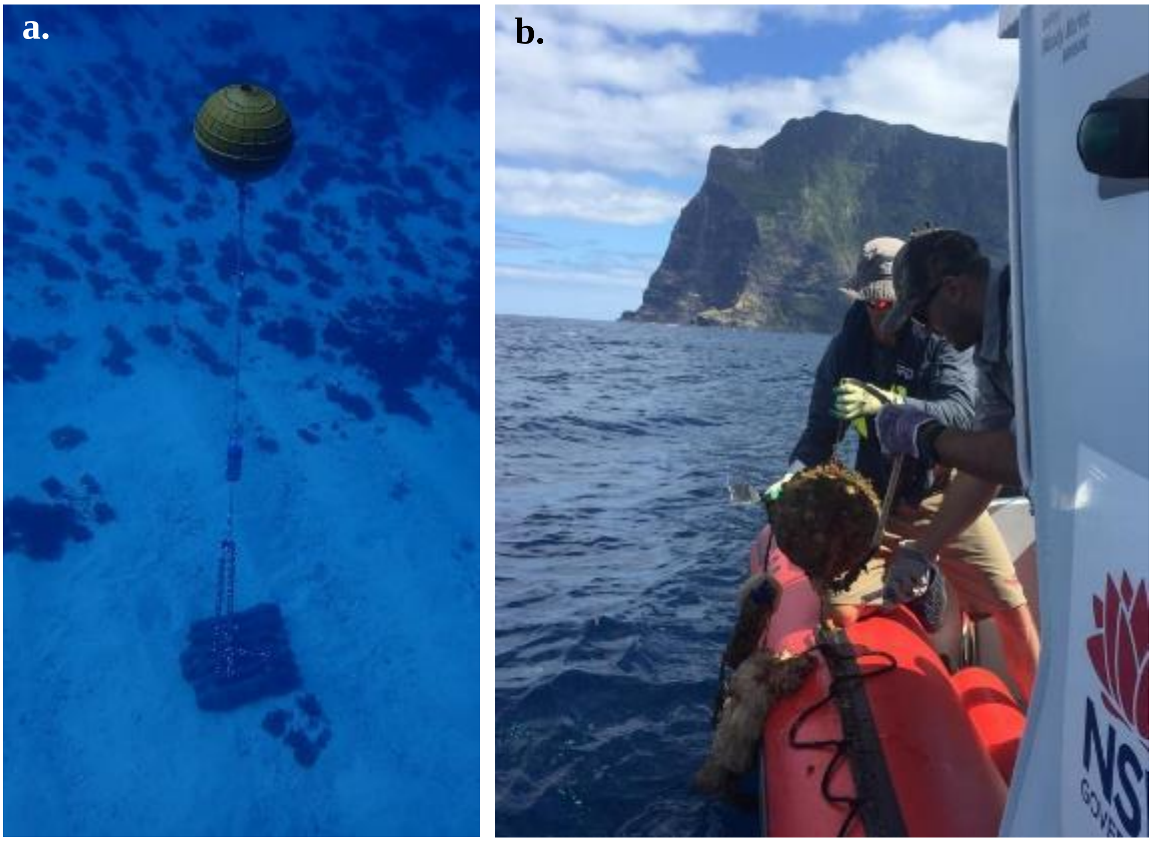


Figure 4. Images of the acoustic receiver mooring setups. (**a**) Newly installed shallow water acoustic receiver mooring; (**b**) recovered deep-water acoustic receiver mooring. Photo credits: Emma Henry (**a**) and Sallyann Gudge (**b**).

4.3 Environmental data

Remotely sensed sea surface temperature (SST) data were downloaded from the Australian Integrated Marine Observing System (IMOS) via the Australian Ocean Data Network (AODN; https://portal.aodn.org.au/) portal. The L3C SST data used were derived from the Advanced Very High Resolution Radiometer (AVHRR) instrument on the NOAA-19 satellites, which has a resolution of 0.02° x 0.02° (Beggs et al., 2013). Night-time data were used to reduce the variability in temperatures that can occur from solar heating of the surface skin of the water. SST values for the closest grid cell to each acoustic receiver location were used. Chlorophyll-*a* data were also sourced from AODN, in the form of daily mean values at a resolution of 0.01° x 0.01°, which were provided by the MODIS sensor on the Aqua satellite platform (IOCCG, 2006). This sensor infers Chlorophyll-*a* concentrations based on multi-spectral measurements at the surface layer of the ocean (IOCCG, 2006). Percentage lunar illumination (between 0 and 100) was determined using the 'getMoonIllumination' function in the 'suncalc' package for R (Agafonkin & Thieurmel, 2017). Bathymetric data were derived from a series of multibeam surveys, which were collated to form a high-resolution grid (5 m cell size) of the marine parks surrounding LHI (Linklater, 2009; Brooke et al., 2010; Mleczko et al., 2010; Linklater et al., 2018). Bathymetric variation values, representing the standard deviation in bathymetry across an area of 1 km radius from each acoustic receiver location, were derived as a metric to encompass variation in seabed topography, following the methods of Wilson et al. (2007), Rees et al. (2014; 2018).

4.4 Vessel Monitoring System data

To determine the activity of registered charter fishing vessels in the marine parks surrounding LHI, Vessel Monitoring System (VMS) data was utilised. This data has been collected since October 2015 as part of NSW Department of Primary Industries' and Parks Australia's Pilot of a Vessel Monitoring System for Commercial Operators, under a voluntary agreement. VMS data was available for six vessels from January 2018 to November 2019, after which it was only available for two vessels for the remainder of the study period until January 2021. This reduction occurred because some small fishing vessels were not eligible for Commonwealth Commercial Tourism Licences, and because one vessel ceased operation after November 2019. VMS data was collected by the Collecte Localisation Satellites (CLS) Triton Advanced VMS units (https://www.iridium.com/products/triton-advanced/), which record positional information (latitude and longitude), speed, date and time for each vessel every three minutes whilst underway (i.e. speed >0 $km.hr^{-1}$). Each datapoint was then assigned to the marine park zone it was located in and a depth value was assigned to each point in ArcGIS (ESRI 2019, Redlands, CA) using a high-resolution bathymetric map of the marine parks surrounding LHI (Linklater et al., 2018). The data were then further filtered to remove any points where speed was >3 $km.hr^{-1}$, to leave just points which were attributed to be passive drift fishing (anchoring is not allowed in the marine parks surrounding LHI and strong currents prevent it). However, it is possible that fishing was not occurring during a small number of these VMS points <3 $km.hr^{-1}$, for example if the occupants of the vessel were opportunistically viewing fauna such as whales, dolphins and/or seabirds, or taking a break from fishing. Locations inside the shallow LHI lagoon (<20 m depth) were also filtered out because this study was focused on deeper, mid-shelf waters where interactions between Galapagos sharks and fishing vessels occur frequently. All VMS data was aggregated to avoid identification of individual vessels.

4.5 Statistical analysis

4.5.1 Seasonal presence of sharks and residency index

A range of parameters were used to investigate the seasonal presence of Galapagos sharks in the marine parks surrounding LHI, including the detection patterns of each individual across the three-year study period, the number of months that each shark was detected and the mean number of detections per day. The number of detections per month for all sharks combined was also used as a measure of seasonal presence in the acoustic receiver array. The detection span, calculated as the number of days between the first and last date of detection, was also determined for each shark, as well as the total number of days they were detected. A residency index was calculated for each shark by determining the proportion of days from the total study period (1060 days) on which the shark was detected. To identify how sex, total length and tagging location affected the residency index, Generalised Linear Mixed Models (GLMMs) were applied using the 'lme4' package in R (Bates et al., 2015), with a binomial response distribution and with tag number as a random factor to account for individual variation between sharks. Predictor variables were checked for correlation so that any variables having a correlation coefficient >0.4 were removed from the same model. A forward stepwise approach was used to identify the best-fitting model, based on Akaike's Information Criterion (AIC) (Akaike, 1974) values. The best model was determined to be that with the lowest AIC value and only including significant predictor variables. The goodness of fit of the final model was assessed based on the distribution of the residuals and the relationship between the observed and model fitted values.

4.5.2 Space-use patterns of Galapagos sharks

To examine the space-use of sharks within the marine parks surrounding LHI, Kernel Utilisation Distribution (KUD) analysis was applied, using the package 'adehabitatHR' in R (Calenge, 2021). The 50% core and 95% total KUD areas were calculated for nine of the 30 sharks tagged, with the remaining 21 sharks only detected at less than five receivers, preventing the algorithm from generating KUD areas for these animals. GLMMs were applied to investigate how the 50% and 95% KUD areas of sharks were potentially influenced by season, total length and sex of the sharks. A Gaussian distribution was applied to the response data, which was normally distributed after being log + 1 transformed. Tag number for each of the sharks was included as a random factor in the GLMM, to account for any individual variation in movement behaviour. Predictor variables were checked for correlation and a forward stepwise process was used to identify the model with the lowest AIC and significant predictor variables. Goodness of fit was confirmed by assessing model residuals and r^2 values.

4.5.3 Spatial patterns of fishing activity

The spatial variation in fishing activity across the marine parks surrounding LHI was quantified by applying a Kernel Density Estimation (KDE) function ('kde2' in R), which produced a surface of KDE values based on the density of spatial fishing points recorded by VMS units from all vessels combined (i.e. six vessels from January 2018 to November 2019 and two vessels from December 2019 to January 2021). KDE values were then calculated for each acoustic receiver location, based on the mean of all KDE values within a 1 km radius of the acoustic receiver, which was judged to be the theoretical maximum limit of the detection range. Heatmaps of fishing activity were created in QGIS (QGIS Geographic Information System, 2019) for the overall study period, and winter (April – September) and summer (October – March) months. Heatmaps were generated using KDE and represented the number of VMS points per 1km radius, with a pixel size of 50 m x 50 m. Maps were also generated in QGIS to assess the overlap of shark space use (50% and 95% KUD areas) and fishing activity.

4.5.4 Assessing the influence of fishing activity and environmental variables on shark detection rates

To quantify how fishing activity and a range of environmental and biological factors (Table 3) affected shark presence in the form of number of detections per day, full-subsets Generalised Additive Mixed Models (GAMMs) were applied using the 'fssgam' package in R (Fisher et al., 2018). GAMMs are an advanced form of Generalised Additive Models (GAMs) (Hastie & Tibshirani, 1986; Wood, 2006), which use smoothing to address non-linear distributions of predictor variables (Craven & Wahba, 1978; Wood, 2008). Due to the range of continuous predictor variables that were being investigated in this study, and the likelihood of them having non-linear distributions, GAMMs were chosen instead of GLMMs to allow for smoothing of these continuous predictors. The response variable used was the number of detections per day at each acoustic receiver, which ranged from 0 to 217. This response variable was log + 1 transformed to create a more even distribution, although it still remained left-skewed after transformation, due to the large numbers of zeros. As a result, the Tweedie distribution was applied because it was most suitable for this response data (Tweedie, 1984; Tascheri et al., 2010; Coelho et al., 2016).

A range of predictor variables were tested using the full-subsets approach, which tests all possible combinations of potential predictor variables and determines the best-fitting, most parsimonious model (McLean et al., 2016; Fisher et al., 2018; Mitchell et al., 2018a). To prevent high levels of correlation between predictor variables, only combinations of variables which had Pearson's correlation coefficient values <0.4 (Zuur et al., 2009) were included in the GAMMs. Site was included as a random factor in the GAMM to account for any spatial variation between the acoustic receiver locations. The number of receivers deployed in each year was included in the GAMM as an offset, because there was a reduction in the number of receivers deployed and recovered, from 11 in year 1 (2018) to six in year 2 (2019) and three in year 3 (2020) (see Table 2). Additionally, the acoustic receivers that were deployed at north lagoon passage and Admiralty Islands NTZ were removed from the GAMM analysis as they did not record any detections, likely because of the ambient (background) noise from the reef and cliffs drowning out any pings from acoustic tags. Keeping these receivers in the analysis would otherwise have introduced a large number of zeros to the dataset and compromised the accuracy of the analysis.

To identify which predictor variables produced the best-fitting model, all variable combinations were ranked by AIC values. The most parsimonious model was determined as being within two AIC values of the lowest AIC and having the least predictor variables (Burnham & Anderson, 2002; Fisher et al., 2018). A maximum of three predictor variables were allowed in this approach to prevent overfitting (Burnham & Anderson, 2002; Zuur et al., 2009). AIC weights (wAIC) (Burnham & Anderson, 2002) were also used to increase the robustness of model selection (Fisher et al., 2018). The full-subsets approach also generated predictor variable importance values (Fisher et al., 2018) to quantify the relative importance of all predictor variables tested. Chlorophyll-*a* was also included as a predictor variable in the initial GAMMs, however due to gaps in data availability caused by cloud cover, this variable was not included in the final models.

Table 3. Predictor variables included in the Generalised Additive Mixed Models (GAMMs) applied to investigate the presence of sharks in the acoustic array, and their hypothesised importance.

Predictor variable	Hypothesised importance
Smoothed continuous predictor variables	
Depth (m)	Depth has been reported to have a substantial influence on Galapagos shark movements, distribution and catch rates in Hawaii

	(Wetherbee et al., 1996; Meyer et al., 2010) and off Ascension Island in the South Atlantic Ocean (Madigan et al., 2020), likely because of the influence it has on habitat availability and prey dynamics. Because of this, it would also be expected to influence shark movements and distribution in the marine parks surrounding LHI.
Percentage of moon illuminated	The level of lunar illumination has been shown to influence the movements and feeding behaviour of some shark species, due to variation in light levels and changing tidal dynamics (West & Stevens, 2001; Hammerschlag et al., 2017, Niella et al., 2021).
Sea surface temperature (°C)	Temperature can influence the metabolic activity levels and feeding behaviours of sharks (Carey et al., 1990; Stevens et al., 2010), therefore it can affect their spatial distribution and the chance of being detected at each receiver location.
Spatial fishing activity (kernel density)	Higher levels of fishing activity in discrete areas can lead to the formation of behavioural associations in sharks, where they associate the cue of boat engine noise and fish blood with the availability of hooked fish to depredate on, thus leading to them spending a greater amount of time in these areas (Madigan et al., 2015; Mitchell et al., 2018a; 2020).
Bathymetric variation	Higher abundance and diversity of pelagic predators can occur in areas of complex seabed topography (Bouchet, 2015, 2020). Specifically, higher seabed complexity has been shown to support greater abundances of yellowtail kingfish, a probable prey species of Galapagos sharks, in the marine parks surrounding LHI (Rees et al., 2018).
Categorical factor predictor variables	
Season	Time of year can influence shark presence and distribution through variation in a range of environmental factors not implicitly included in the model, for example current dynamics, seasonal prey aggregations and thermal stratification of the water column.

4.5.5 Depth distribution

To determine the effect of environmental and biological variables and fishing activity (Table 4) on the depth distribution of Galapagos sharks, a GLMM was applied. The distribution of the response variable (depth) was Gaussian, therefore this distribution was used for the GLMM. Correlation between predictor variables was assessed, with those having a correlation >0.4 being removed from the model. Tag number and site were included in the GLMM as random factors, to account for any random variation between individual sharks and between receiver locations. The depth of receiver stations was included as an offset in the model because it had an influence on the depth at which sharks were detected, particularly because the shallow (14.8 m) south LHI fish cleaning area station had by far the highest number of detections. A stepwise approach based on AIC values was applied to identify the best model, which had the lowest AIC value and contained only significant predictor variables. Model fit was checked by examining the distribution of residuals and the r-squared value. All data analyses were conducted in the R language for statistical computing (R Development Core Team, 2015).

Table 4. Predictor variables included in the Generalised Linear Mixed Model (GLMM) used to assess the depth distribution of Galapagos sharks, and their hypothesised importance.

Predictor variable	Hypothesised importance
Continuous predictor variables	
Percentage of moon illuminated	The level of lunar illumination may influence the depth distributions of Galapagos sharks due to variation in light levels and the effect it has on the diel vertical movement patterns of their prey species (West & Stevens, 2001; Campana et al., 2011; Vianna et al., 2013; Niella et al., 2021).
Bathymetric variation	More complex and varied seabed topography can lead to dynamic vertical movements of sharks in the water column and thus more changeable depth distributions (Sleeman et al., 2007; Rogers et al., 2015).
Total length	Total length of Galapagos sharks may influence their depth distribution due to segregation between smaller and larger animals, as is seen in other pelagic sharks species (Camhi et al., 2009), and ontogenetic changes in diet are known to occur in Galapagos sharks (Wetherbee et al., 1996), which may influence the depth at which they are foraging on prey species.
Spatial fishing activity (kernel density)	Provisioning activities have been found to alter the depth distributions of reef sharks (Fitzpatrick et al., 2011). Greater fishing activity in a specific area may lead to a shallower depth distribution of Galapagos sharks due to them swimming up to the surface to investigate vessels and pursue hooked fish prior to depredating them.

Categorical factor predictor variables	
Season	Season could influence Galapagos shark depth distributions through the changing temperature and stratification of the water column. Galapagos sharks may alter their depths to remain within an optimal thermal range at different times of year. Additionally, surface heating in summer and storm activity in winter can lead to changes in the stratification of the water column and depth of the thermocline, which are known to influence pelagic sharks (Howey-Jordan et al., 2013; Ketchum et al., 2014), including Galapagos sharks (Madigan et al., 2020).
Sex	Spatial segregation based on sex is known to occur in some pelagic shark species (Camhi et al., 2009), with some evidence of this occurring for Galapagos sharks in Hawaii, where females displayed a shallower depth distribution (Wetherbee et al., 1996). Sex may therefore be expected to have an influence on depth for Galapagos sharks in the marine parks surrounding LHI.
Diel period	Some sharks display diel vertical migration in response to the movements of their prey species (Heard et al., 2018) and for thermoregulation (Howey-Jordan et al., 2013), whereas others show reverse diel vertical migration (Madigan et al., 2020) or a mix of the two strategies (Queiroz et al., 2012). Diel period would therefore be expected to have an important influence on Galapagos shark depth distributions.

4.6 Survey of Lord Howe Island charter and recreational fishers

To collect further information about the interactions of fishers with Galapagos sharks in the marine parks surrounding LHI, a survey was conducted with both charter fishing operators (*n* = 6) and selected recreational fishers (*n* = 4), who together, constituted the majority of fishing effort in this local, artisanal fishery. This survey involved 25 open ended questions to collect information on fishing practices, fishing gear used, as well as the occurrence of shark interactions, including either capture of sharks or depredation, and strategies that fishers currently used to reduce shark interactions. Other fishing parameters, such as the average number of crew and passengers per trip over a year, and the estimated loss of targeted catch and gear, were included – see Appendix 1 for the full list of questions. The data and information collected from this survey was collated anonymously to identify key themes in the results.

For questions with answers containing continuous variables, we calculated mean and standard deviation values. For questions with categorical variables, we generated the summation values and/or the proportions of answers, as percentages (%), across the fishers (*n* = 10). The last question (No. 25) was an open question to add further comments, specifically designed to bring any other aspects to the conversation, which were not covered in previous questions; therefore, we presented a summary of this extra information.

4.7 Analysis of Lord Howe Island shark catch data 2015 – 2018

To quantify the occurrence of Galapagos shark bycatch in the LHI charter fishery in both State and Commonwealth waters, catch return data collected and maintained by NSW DPI as a condition of the NSW Marine Park permit was utilised.

A previous report is available for this catch data (including shark catch data) between 2004 and 2015 (Figueira & Hunt, 2017). Here, we analysed only additional years of data available i.e. between 2015 and 2018, and compared some calculated metrics with the previous report. Data was only available until the end of 2018, as a new reporting system has been implemented and is still being tested since early 2019. This additional data still provides more recent knowledge, in line with the start of our research (2018).

The key metrics calculated from this data included: the number of logged fishing trips and sharks caught; the number of trips where shark catches were reported; the mean shark catch per trip (including all trips or only those reporting a shark catch); the average size (total length) of caught sharks; the number of sharks caught according to size ranges; and the percentage of sharks that were retained or released. This data contributes to the acoustic telemetry and VMS fishing activity mapping aspects of this project by providing further detail on the frequency of shark-fisher interactions in the marine parks surrounding LHI.

5. Results

5.1 Detection patterns

Between January 7th 2018 and January 26th 2021, there were 24,933 detections for the tagged Galapagos sharks. Of the 30 sharks tagged during this research, 28 were detected, with a minimum of eight detections for shark 1280540 ranging to 8636 detections for shark 1280561 (Table 5). Sharks 1280544 and 1280555 were not detected across the study period. The number of sites at which each tagged shark was detected at ranged from 1 – 8, with a mean of 3.8 and the detection span varied widely between individuals, ranging from just three days to 1011, from a total study period of 1060 days (Table 5). The mean detection span was 576 days, with 21 of the 28 sharks having a detection span greater than one year. The number of individual days on which each shark was detected was generally <100, apart from six sharks, the highest of which was detected on 603 out of the 1060 days in the study period (Table 5). The mean number of days when sharks were detected was 74.1.

Table 5. Summary of key detection metrics for the 30 Galapagos sharks tagged in the marine parks surrounding Lord Howe Island in January 2018.

Tag ID	Total length	Sex	No. sites detected at	Date of first detection	Date of last detection	Total no. detections	Detection span (days)	No. days detected	Residency index
1280540	96	F	2	21/01/2019	25/01/2019	8	4	2	0.002
1280541	128	M	4	13/06/2018	03/12/2020	403	904	20	0.02
1280542	137	F	3	05/11/2018	27/08/2019	69	295	7	0.01
1280543	116	F	3	27/05/2018	13/01/2019	237	231	10	0.01
1280544	121	M	0	-	-	0	-	0	0
1280559*	127	M	0	-	-	0	-	0	0
1280560	155	F	7	04/06/2018	31/01/2020	2410	606	225	0.21
1280561	146	F	5	21/01/2019	26/01/2021	8636	736	603	0.57
1280562	136	F	6	05/06/2018	23/01/2021	1104	963	206	0.19
1280563	117	M	4	31/01/2018	07/11/2020	3427	1011	164	0.15
1280564	121	M	5	25/01/2018	24/08/2020	144	942	24	0.02
1280565	116	M	2	26/01/2018	29/01/2018	23	3	2	0.002
1280566	117	F	3	24/08/2019	12/12/2019	35	110	4	0.004
1280567	136	F	8	09/06/2018	18/12/2019	369	557	19	0.02
1280568	141	M	6	15/04/2018	04/12/2019	1481	598	60	0.06
1280545	116	F	2	22/06/2018	20/11/2019	34	516	3	0.003
1280546	115	M	5	24/01/2018	05/12/2019	312	680	20	0.02
1280547	156	F	1	05/02/2018	29/03/2019	45	417	13	0.01
1280548	177	F	4	27/01/2018	01/08/2020	1847	917	234	0.22
1280549	152	M	6	26/01/2018	27/04/2020	387	822	24	0.02
1280550	138	F	2	20/02/2019	14/01/2020	13	328	3	0.003
1280551	121	M	3	03/12/2018	30/01/2020	53	423	5	0.005
1280552	114	M	2	28/08/2019	16/03/2020	243	201	18	0.02
1280553	133	F	4	03/06/2018	19/03/2020	306	655	27	0.03
1280554	137	F	4	18/05/2018	06/03/2020	495	658	42	0.04
1280555	125	F	0	-	-	0	0	0	0
1280556	125	F	4	27/05/2018	07/11/2020	408	895	31	0.03
1280557	129	M	6	05/02/2018	14/01/2020	274	708	29	0.03
1280558	115	F	2	04/02/2018	17/01/2020	1697	712	216	0.20

1280539	138	F	2	11/05/2018	18/12/2019	194	586	14	0.01
1280559†	146	F	4	17/03/2019	24/12/2020	279	648	51	0.05

*shark caught and killed in October 2018, † tag redeployed in January 2019

The frequency and seasonal pattern of detections varied substantially between individual Galapagos sharks, with six sharks showing frequent detections throughout the study period, compared to more sporadic and infrequent detections for the remaining 22 individuals (Figure 5). Six of the 28 sharks were only detected in the second and third year of the study period (Figure 5).

The mean number of detections across the 28 tagged Galapagos sharks was 890, with a substantial degree of variation across individuals. Eight sharks were detected <100 times across the whole three years study period, whereas seven sharks were detected >1000 times (Figure 6). The sharks with the highest number of detections were 1280561 with 8636 detections, 1280563 with 3427 detections and 1280560 with 2410 detections (Figure 6).

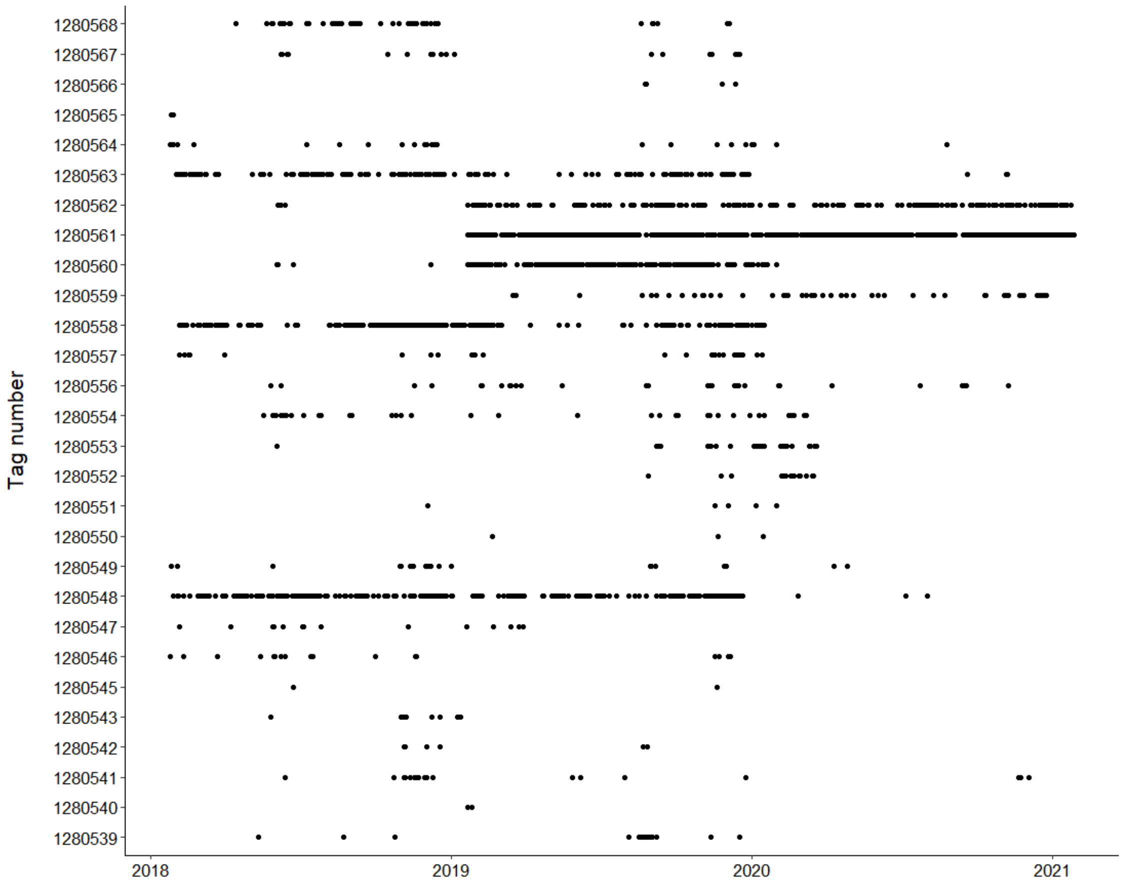


Figure 5. Detection patterns of 28 tagged Galapagos sharks from January 2018 – 2021.

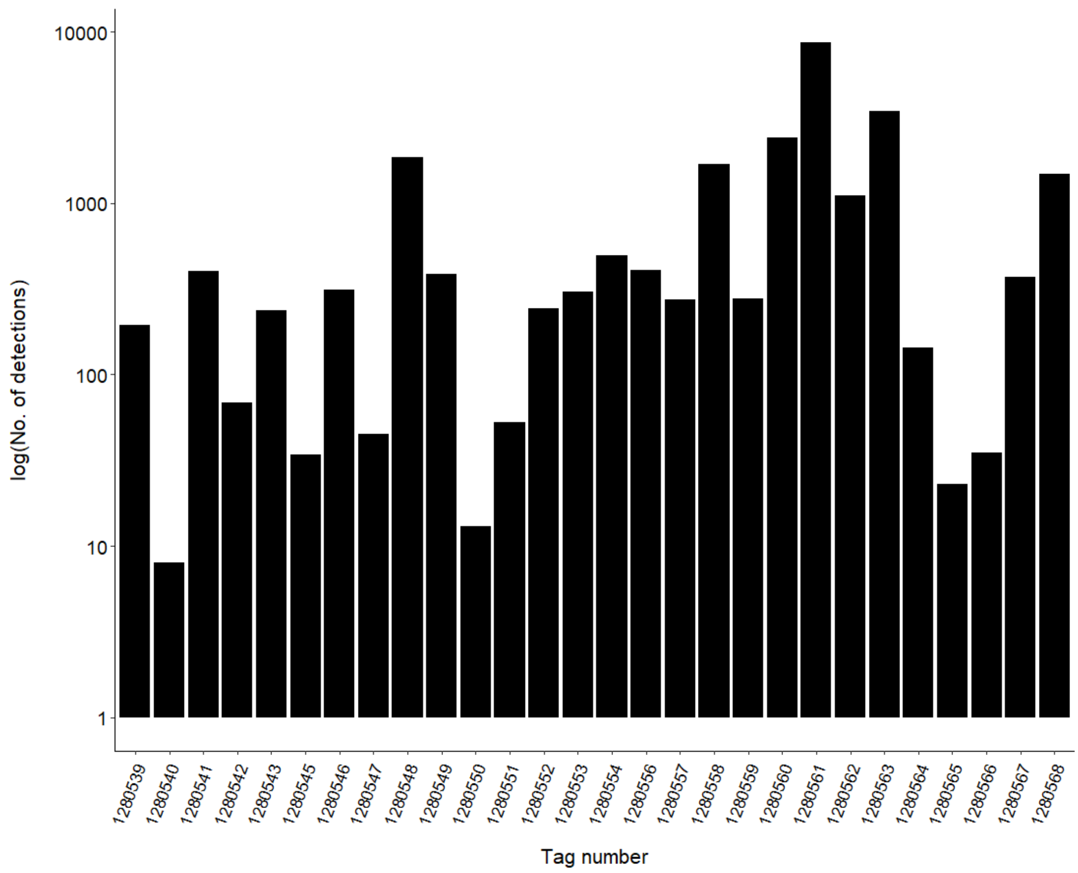


Figure 6. Number of detections for each of the 28 tagged Galapagos sharks that were detected in the marine parks surrounding Lord Howe Island between January 2018 – 2021. Number of detections is presented on a log10 scale.

Galapagos sharks were detected in all months of the year across the study period, with detections ranging from a minimum of 59 in January 2018 to a peak of 1761 in November 2018 (Figure 7). June 2018 and October 2019 also had relatively high numbers of detections, with 1277 and 1710, respectively (Figure 7). April had notably lower numbers of detections (<400 per month) in all three years. The number of tagged sharks detected per month also displayed a similar seasonal pattern, with the highest number of tagged animals (21) detected in Austral spring/early summer, particularly November and December 2019 (Figure 8). The number of tagged sharks detected in Austral autumn were low (<10 tagged sharks detected per month, apart from May 2018) (Figure 8). The mean number of sharks detected per month was 8.5 across the whole three-year study period.

The percentage of months in which each of the 28 individual Galapagos sharks were detected, ranged from 3.0 - 75.8 % (mean of 28.8%), across the three-year study period (Figure 9). In addition to shark 1280548, which was detected across 75.8% of months, sharks 1280558, 1280561, 1280562 and 1280563 were also detected in >60% of months (Figure 9). However, 10 sharks were only detected in <20% of months, highlighting the variability in this metric (Figure 9).

Of the 28 tagged Galapagos sharks that were detected, all had a median number of detections per day <50, with a range of <5 to 36 (Figure 10). However, there were a number of outlier points where Galapagos sharks were detected >100 times in a single day, for nine different tagged sharks. The highest number of detections in a single day was 220 for shark 1280560 (Figure 10).

The number of tagged sharks detected at each of the acoustic receiver locations across the whole study period was notably variable, from a minimum of two at the central BP shelf location to 18 at both the southeast LHI shelf and west LHI shelf locations (Figure 11). Greater than 10 different sharks were also detected at the southwest LHI shelf, northeast BP shelf and south BP shelf locations (Figure 11). No tagged sharks were detected at the acoustic receivers located in the north lagoon passage and Admiralty Islands NTZ, potentially because high ambient noise levels from nearby reefs and cliffs prevented detection of acoustic tags. The acoustic receiver at the northwest LHI shelf location was not recovered in either years 1 or 2 and thus did not provide any data.

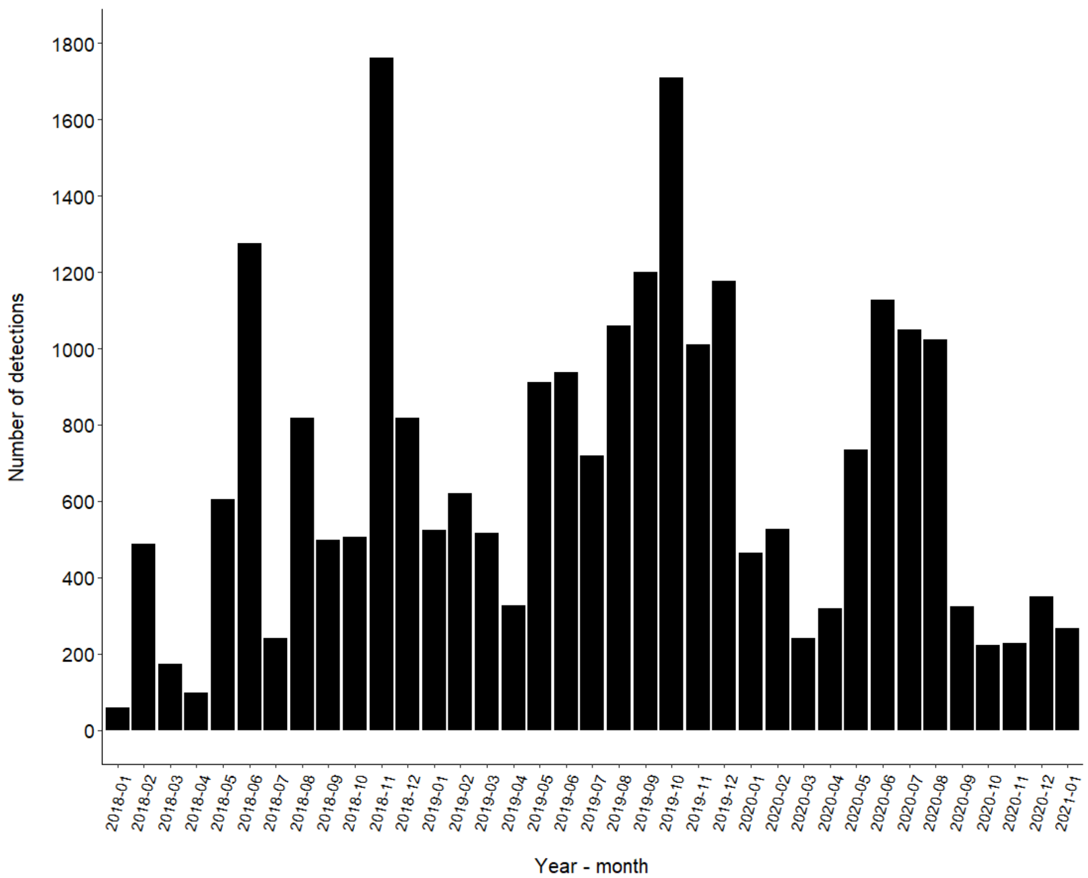


Figure 7. Number of detections per month for all tagged Galapagos sharks combined, between January 2018 – 2021.

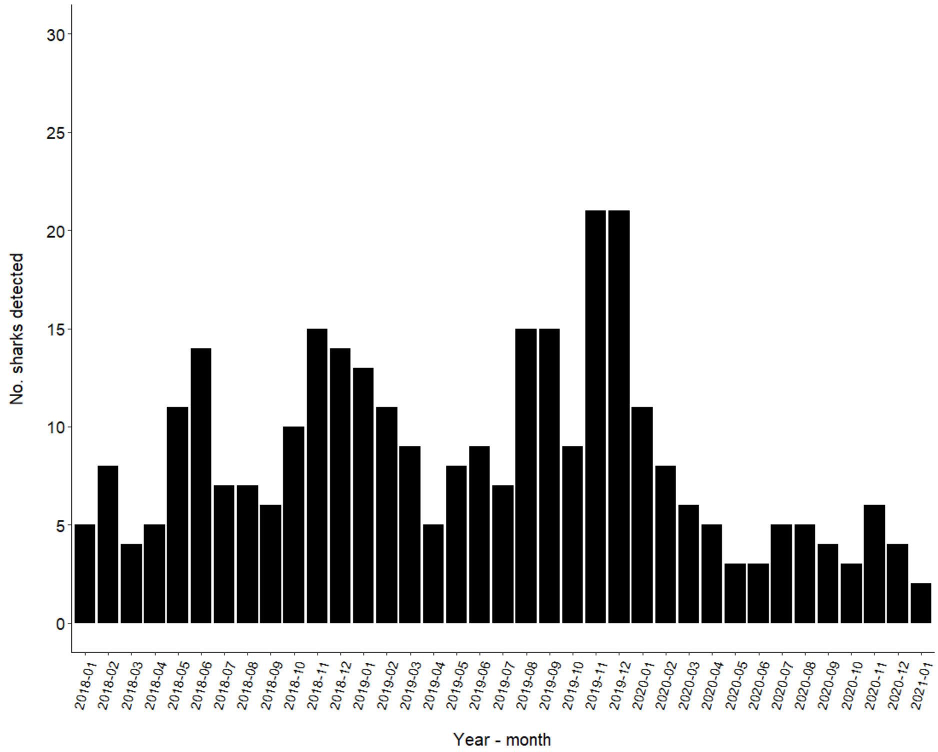


Figure 8. Number of tagged Galapagos sharks detected per month, from January 2018 to January 2021.

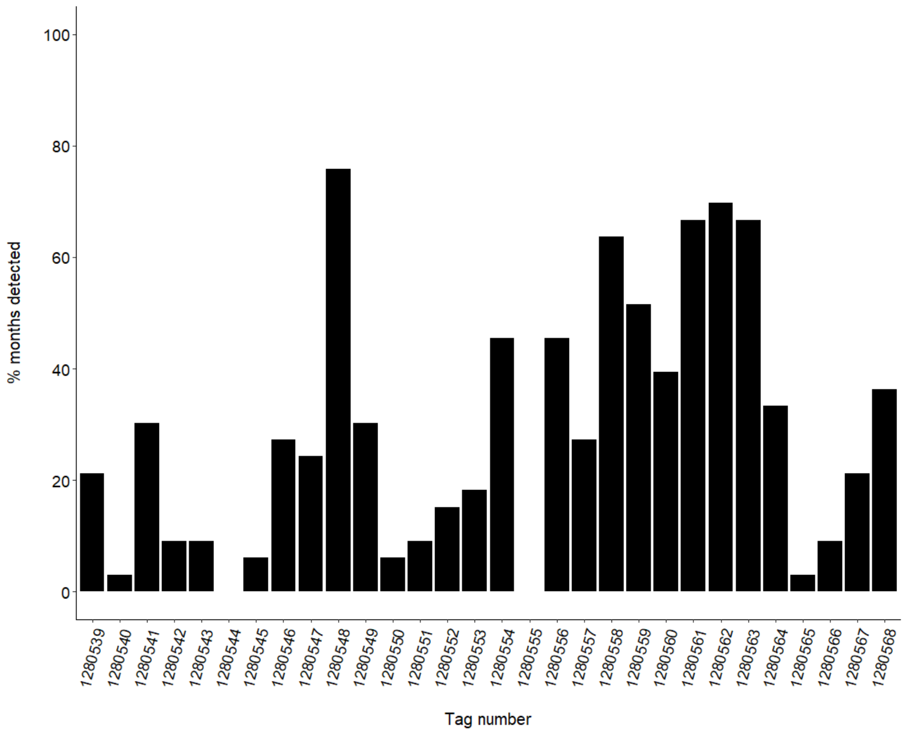


Figure 9. Percentage of months detected in for 30 tagged Galapagos sharks, from January 2018 to January 2021.

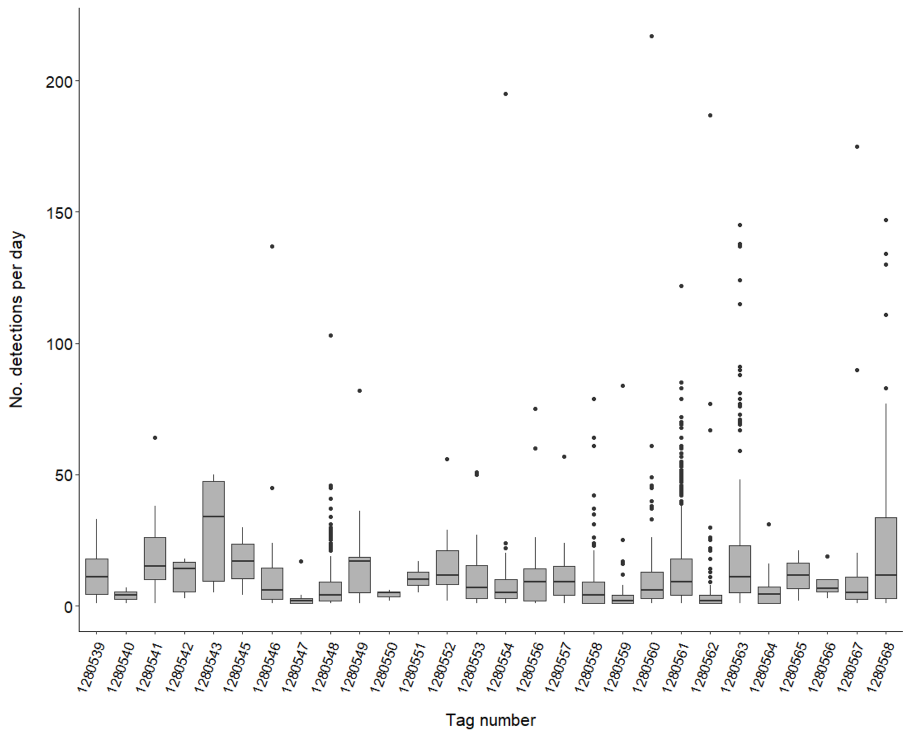


Figure 10. Number of detections per day for 28 tagged Galapagos sharks. Black lines inside boxplots indicate median number of detections per day, with outer box lines showing upper and lower quartiles. Black points show outliers >1.5 times the interquartile range.

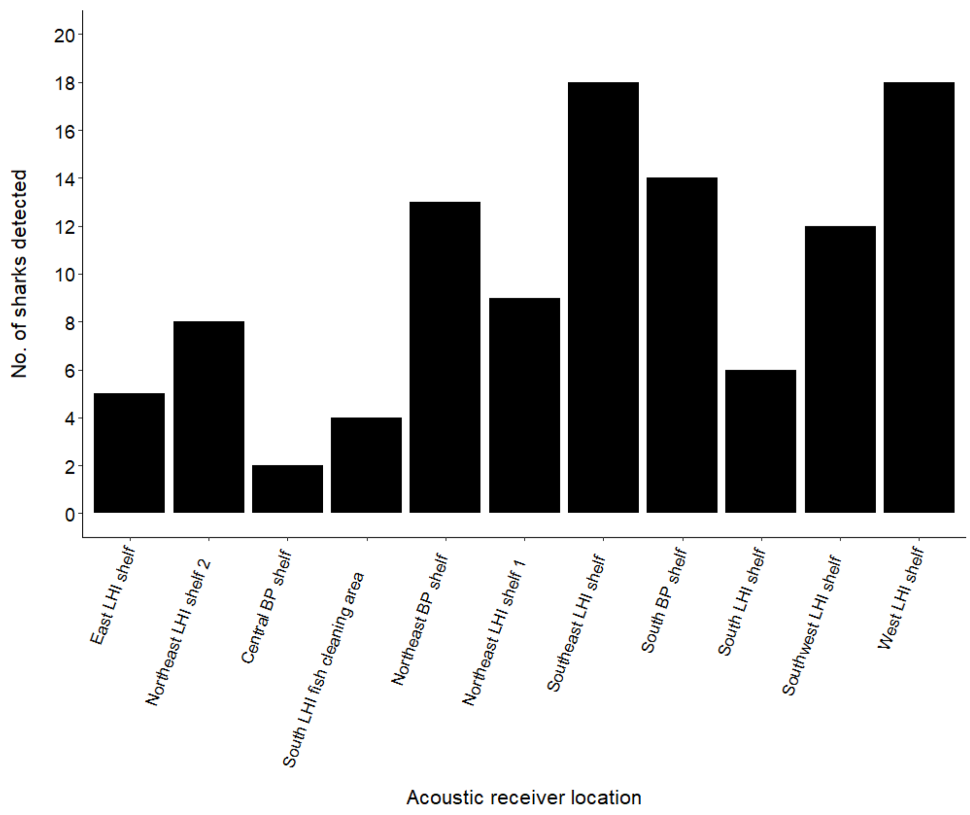


Figure 11. Total number of tagged Galapagos sharks detected at each of the acoustic receiver locations, from January 2018 to January 2021.

5.2 Dispersal distances of Galapagos sharks

The maximum distance that Galapagos sharks moved from their original tagging location (based on acoustic receiver detections) ranged from 0.4 – 36.3 km (mean of 12.2 km) in the marine parks surrounding LHI. Of the sharks that were recorded dispersing greater distances from their tagging location, some sharks displayed movements of between 4.9 and 12.2 km per day (mean of 6.8 km per day). However, one shark (tag number 1280549) was detected three times on 03/02/2021 at an acoustic receiver outside the LHI array, which was at a FAD at 32.78278°S, 152.41171°E, close to the Hunter Marine Park (Commonwealth) and Port Stephens – Great Lakes Marine Park (NSW) and approximately 30km offshore from Port Stephens in NSW, mainland Australia (Figure 12). This FAD This was 654 km from where it was originally tagged at the North BP shelf and 637 km from the acoustic receiver at the West LHI shelf, where it was last detected on 30/11/2019. Alternatively, there is a possibility that these detections resulted from the tagged Galapagos shark being predated upon by a white shark or tiger shark, which co-occur at LHI (see section 5.10), with this larger shark then retaining the tag in its digestive system for a period of time.

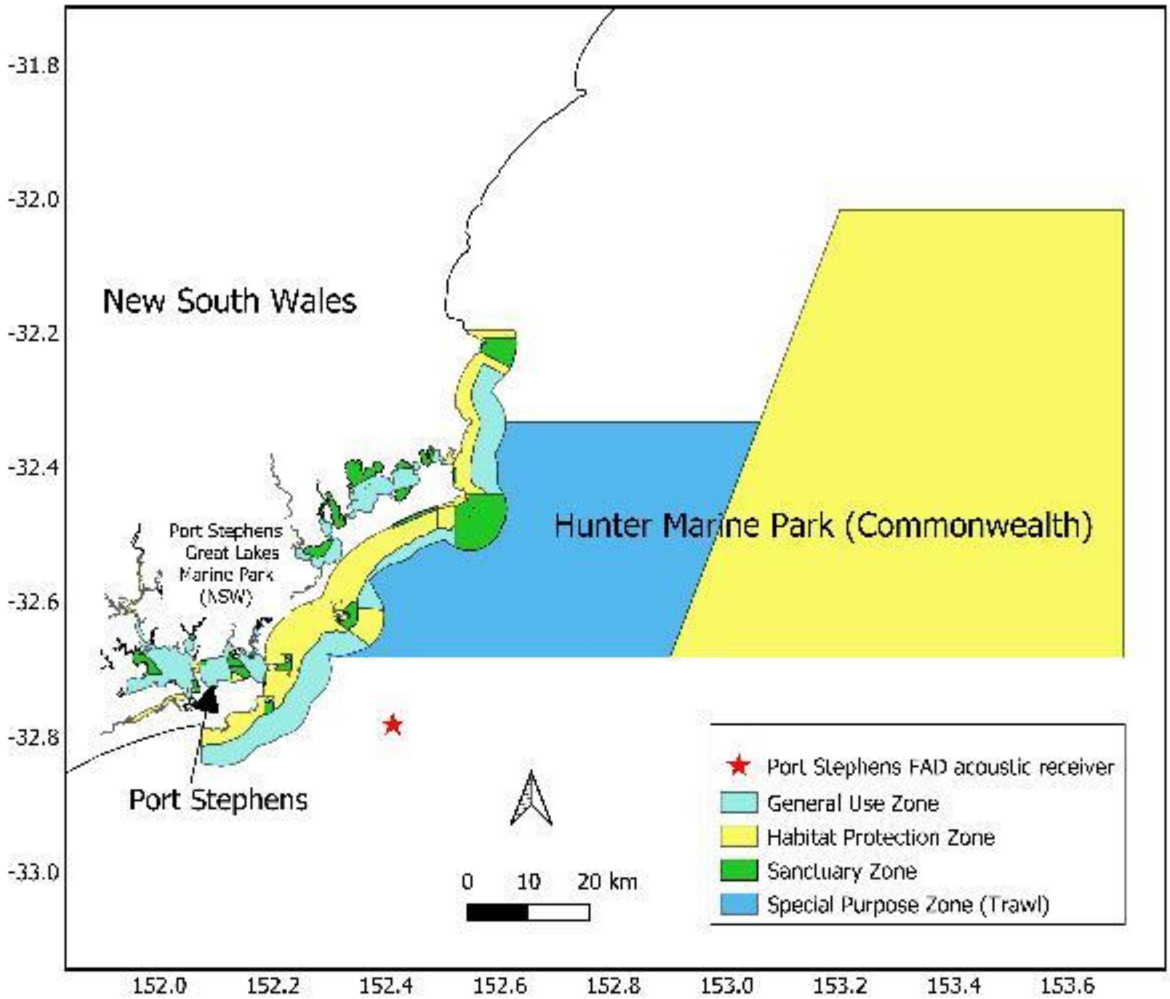


Figure 12. Map of the Port Stephens – Great Lakes Marine Park (NSW) and Hunter Marine Park (Commonwealth) and the location of the acoustic receiver (red star) where Galapagos shark 1280549 was detected on 03/02/2021.

5.3 Residency index

The residency index of Galapagos sharks was highly variable across the study period, with residency index values ranging from <0.01 – 0.57 (mean ± SE = 0.07 ± 0.02) (Figure 13). The majority of sharks (22 out of 28) had low residency index values <0.1, with the remaining six all >0.15 (Figure 13). Total length, sex and tagging location had no significant effect on the residency index of Galapagos sharks, although three of the four sharks tagged at the south LHI fish cleaning area location had higher residency index values of 0.19 (shark 1280562), 0.21 (shark 1280560) and 0.57 (shark 1280561).

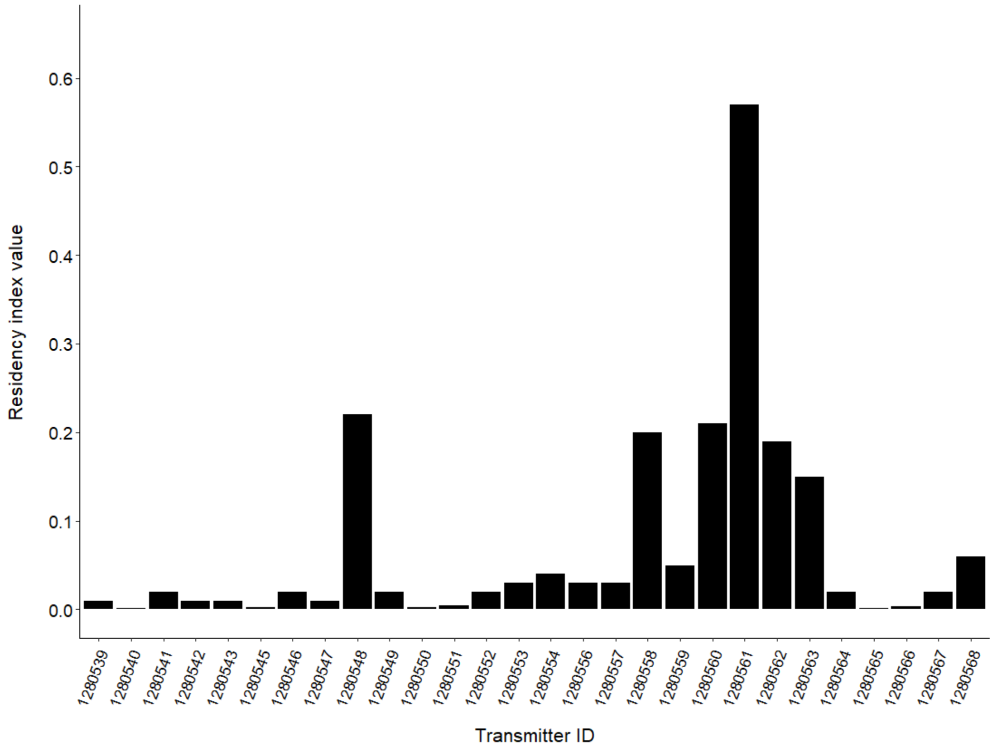


Figure 13. Residency index (number of days detected/total number of days in study period) values for 28 Galapagos sharks detected between January 2018 and January 2021.

5.4 Space use

In addition to acoustic receiver detection patterns, Kernel Utilisation Distribution (KUD) analyses identified the space use of nine (those detected at ≥5 different acoustic receiver locations) of the 30 tagged sharks across the marine parks surrounding LHI. Core (50%) KUD areas ranged from 0.28 km^2 – 217.65 km^2 (mean = 75 km^2), with most sharks (six out of nine) having core areas <55 km^2 (Table 6, Figure 14). Extent (95%) KUD areas were markedly larger than core areas for all nine sharks, especially for shark 1280549 (50% KUD area = 182.23 km^2 and 95% KUD area = 1328.81 km^2) and shark 1280567 (50% KUD area = 217.65 km^2 and 95% KUD area = 1342.63 km^2) (Table 6, Figure 14). The overall range in 95% KUD areas was 1.59 km^2 – 1342.63 km^2, with a mean of 496 km^2. KUD areas could not be calculated for the other 19 tagged Galapagos sharks, as they were detected at <5 acoustic receiver locations.

Table 6. Core (50%) and extent (95%) Kernel Utilisation Distribution (KUD) areas in km^2 for nine tagged Galapagos sharks that were detected at ≥5 acoustic receiver locations.

	Galapagos shark tag number								
	1280546	**1280549**	**1280557**	**1280560**	**1280561**	**1280562**	**1280564**	**1280567**	**1280568**
50% KUD area	40.60	182.23	55.91	7.83	0.28	45.64	103.02	217.65	22.75
95% KUD area	311.37	1328.81	475.29	65.06	1.59	287.62	473.21	1342.63	173.94
Sex	M	M	M	F	F	F	M	F	M
Total length	115	152	129	155	146	136	121	136	141

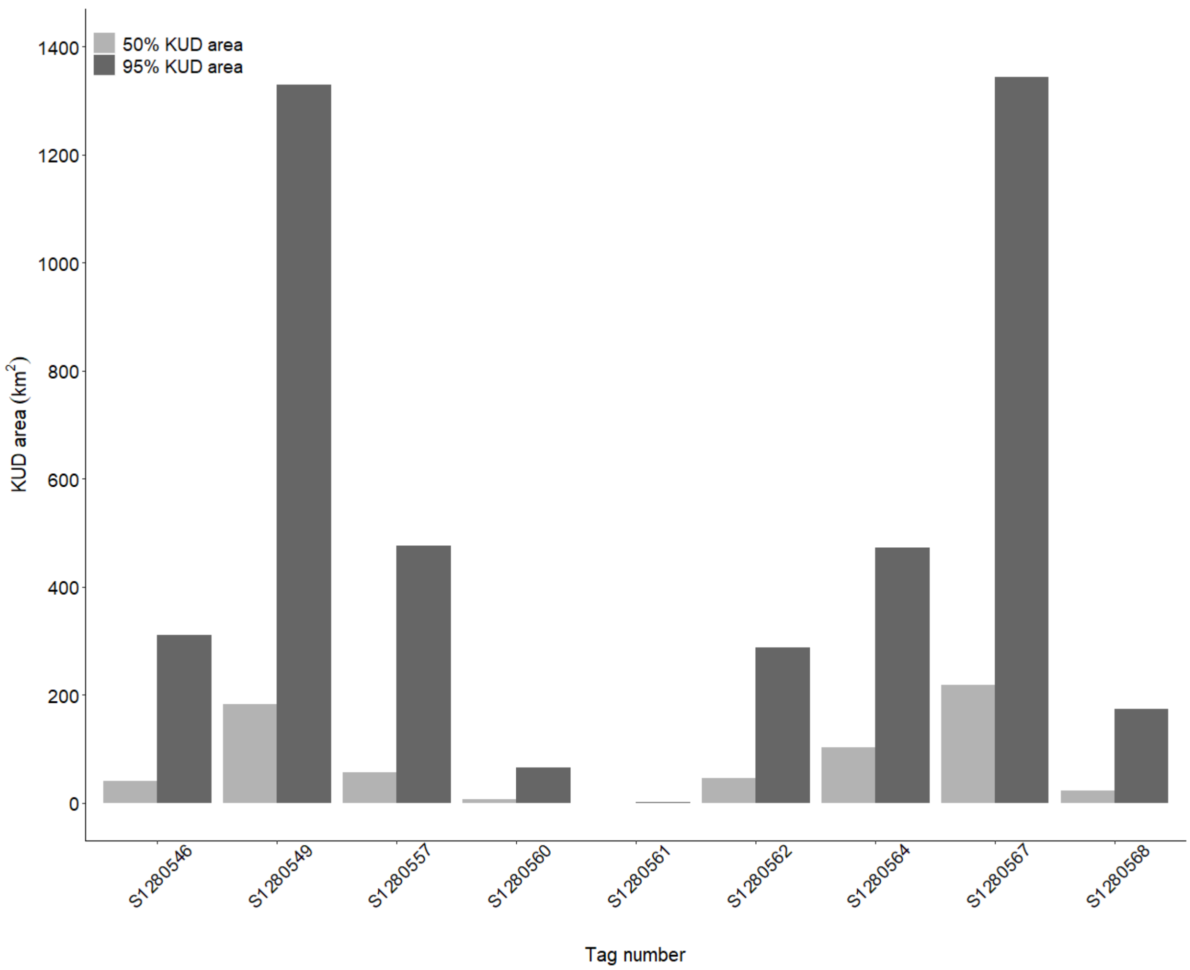
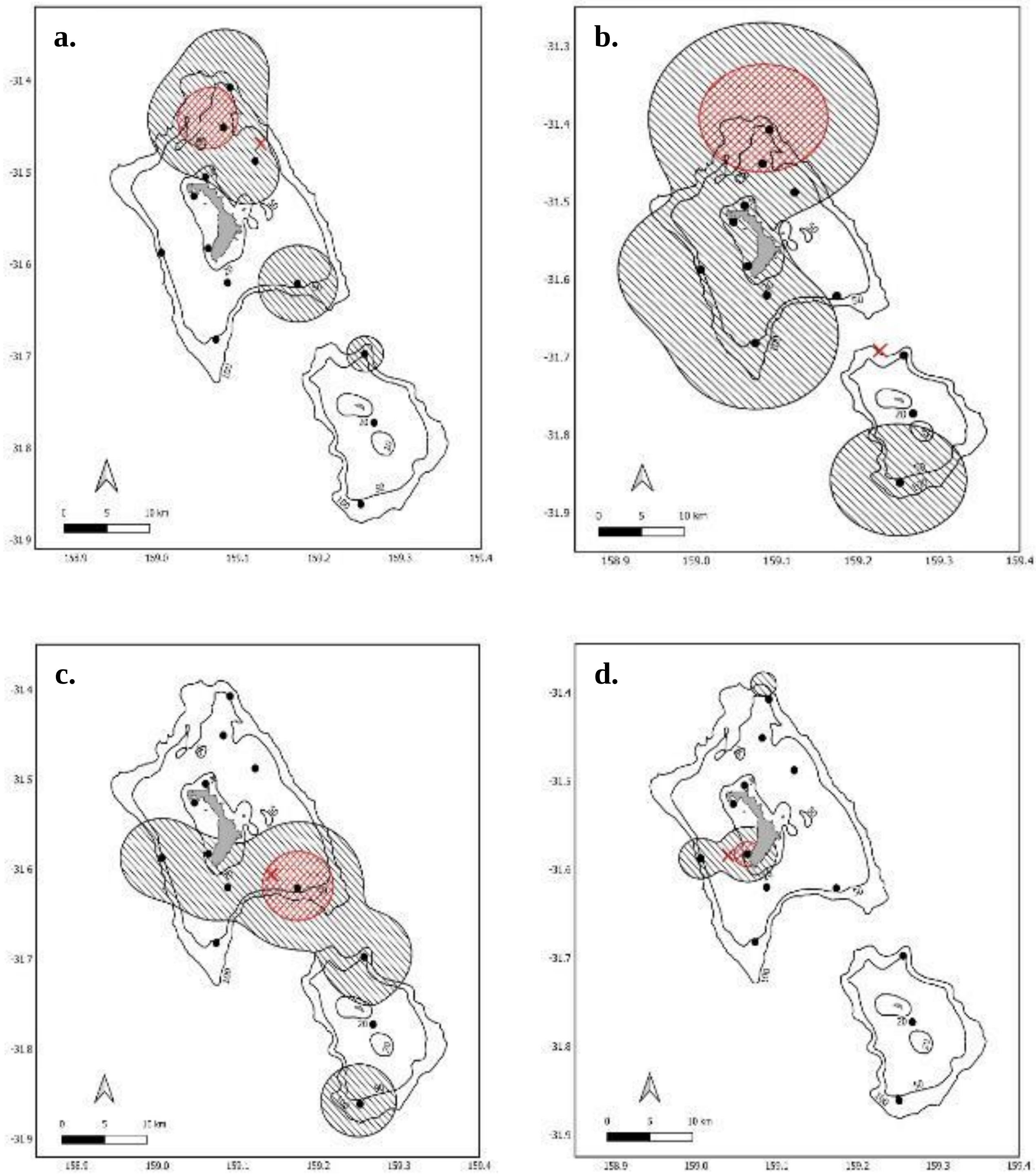
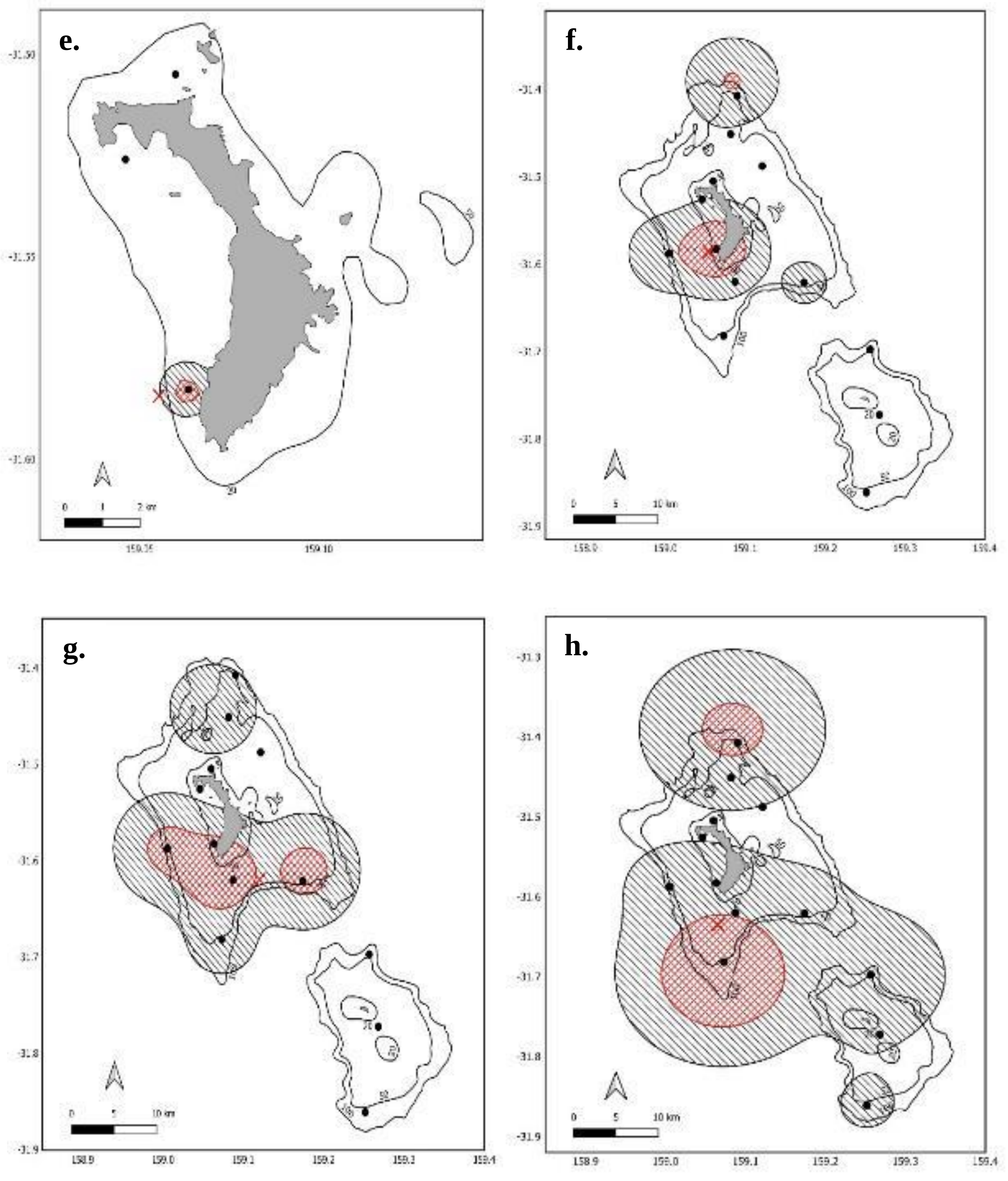


Figure 14. Core (50%) and extent (95%) Kernel Utilisation Distribution (KUD) areas in km^2 for nine tagged Galapagos sharks that were detected at ≥5 acoustic receiver locations. Lighter grey bars indicate 50% KUD areas and dark grey bars show 95% KUD areas.

The spatial coverage of the 50% and 95% KUD areas of the nine Galapagos sharks showed some similarities between individuals, for example sharks 1280546, 1280549 and 1280568 all had core KUD areas centred around the acoustic receiver location in the farthest northeast location in the marine parks surrounding LHI, although there were differences in the spread of their 95% KUD areas, with that of 1280549 covering a much larger area across the northern, western and southwestern sections of the LHI shelf and the southern portion of the Ball's Pyramid shelf (Figs. 15a, b, i). The 50% KUD areas of sharks 1280560, 1280561, 1280562 and 1280564 showed similar spatial patterns, with a concentration centred around the receiver at the south LHI fish cleaning location, especially shark 1280561 which had very small 50% and 95% KUD areas in this location (Figure 15d, e, f, g). However, sharks 1280562 and 1280564 had much broader 95% KUD areas, covering the western, southwestern and northern parts of the LHI shelf. The 50% KUD area of shark 1280557 was centred around the acoustic receiver at the southeast LHI shelf location, although its 95% KUD covered a much broader area encompassing receivers in both the west and south of LHI shelf and the north and south of the BP shelf (Figure 15c). Lastly, shark 1280567 had the largest 95% KUD areas, covering almost the entirety of both the LHI and BP shelves, with 50% core KUD areas centred around the southwest and northeast LHI receivers (Figure 15h).


a.
b.
c.
d.


e.
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10 km

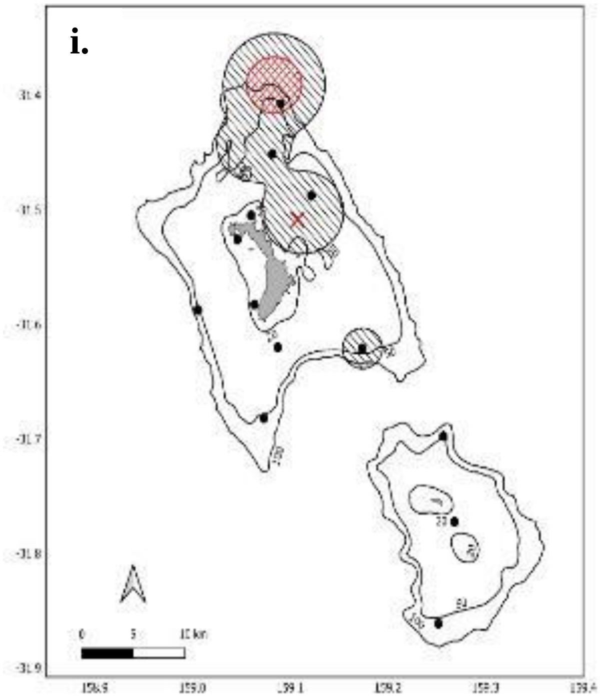


Figure 15. Kernel Utilisation Distribution (KUD) plots for nine tagged Galapagos sharks. (**a**) shark 1280546; (**b**) 1280549; (**c**) 1280557; (**d**) 1280560; (**e**) 1280561; (**f**) 1280562; (**g**) 1280564; (**h**) 1280567; (**i**) 1280568. Black hashed areas represent 95% extent KUD, red crossed areas represent 50% core KUD. Black points indicate acoustic receiver locations. Red crosses represent tagging locations for each shark. Solid black lines show depth contours in metres.

The majority of the tagged Galapagos sharks displayed larger 50% KUD areas in austral winter compared to summer, especially shark 1280549 which had an area of 453.82 km^2 in winter compared to 22.62 km^2 in summer (Figure 16a). Conversely, other Galapagos sharks had larger 50% KUD areas in summer, particularly shark 1280546, which was 230.58 km^2 in summer versus 2.93 km^2 in winter (Figure 16a). A very similar pattern occurred for the summer and winter 95% KUD areas for eight of the nine Galapagos sharks, although notably for shark 1280567 the summer 95% KUD area was larger (1198.56 km^2) than that in winter (388.20 km^2) (Figure 16b), opposite to the pattern in the summer and winter 50% KUD areas for this shark. Shark 1280561 had very small KUD areas in both summer and winter for 50% and 95% KUD (Figure 16a, b).

For all nine Galapagos sharks combined, the mean 50% KUD area was larger in winter than in summer, with values of 121.88 km^2 (+/- 35.38 S.E.) and 91.18 km^2 (+/- 72.86), respectively (Figure 17). Conversely, the mean 95% KUD area was marginally larger in summer (mean of 416.14 km^2 +/- 134.53) than in winter (mean = 400.43 km^2 +/- 182.50).

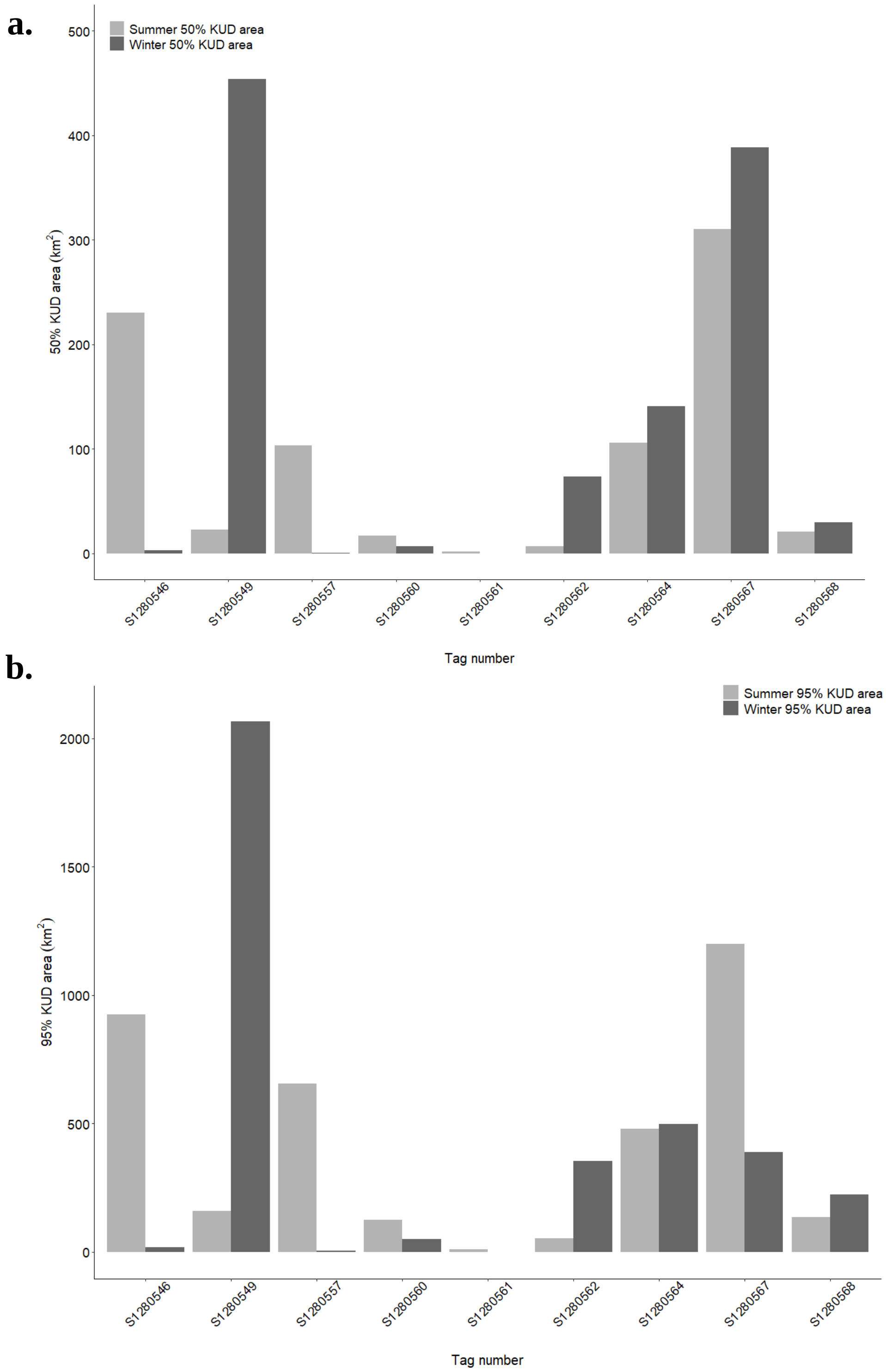


Figure 16. Kernel Utilisation Distribution (KUD) areas for nine Galapagos sharks tagged in the marine parks surrounding Lord Howe Island, by season. (**a**) 50% KUD areas; (**b**) 95% KUD areas. Lighter grey bars indicate austral summer KUD areas and darker grey bars show austral winter KUD areas.

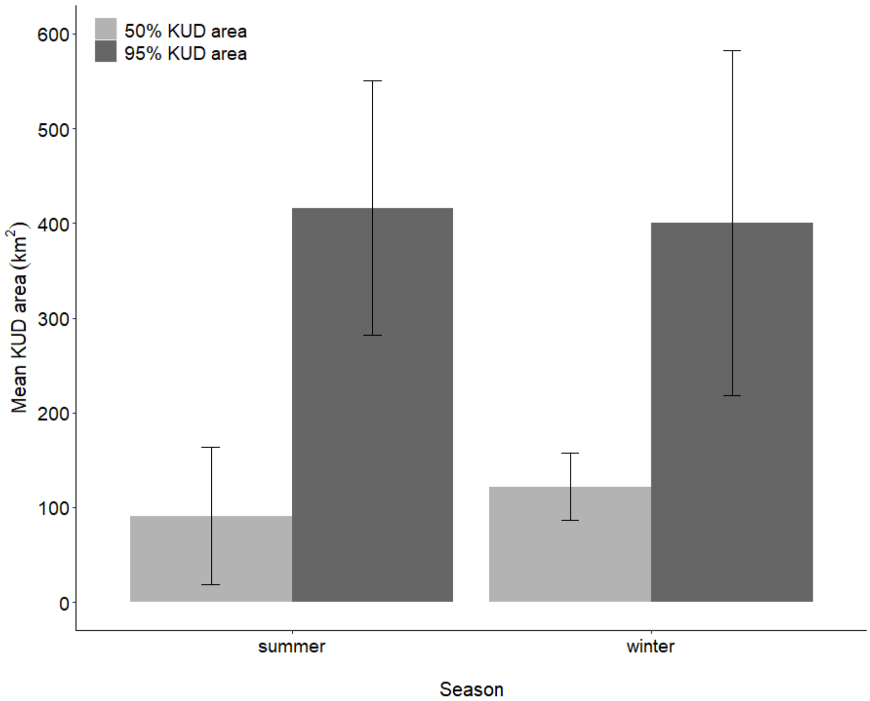


Figure 17. Mean Kernel Utilisation Distribution (KUD) areas for nine tagged Galapagos sharks in the marine parks surrounding LHI, during austral summer and winter months. Lighter grey bars represent 50% KUD areas and darker bars show 95% KUD areas. Error bars represent standard error of the mean.

The mean 50% KUD areas for female and male Galapagos sharks were very similar, with values of 67.85 +/- 58.79 km^2 and 80.90 +/- 33.05 km^2, respectively (Figure 18). However, the 95% KUD areas were somewhat larger for males (mean of 552.52 km^2 +/- 233.29) than females (mean of 424.23 km^2 +/- 360.52) (Figure 18).

Total length of the nine tagged Galapagos sharks had no clear relationship with either 50% or 95% KUD area (Figure 19). The largest 95% KUD area of 1342.63 km^2 was recorded for a Galapagos shark that was in the middle of the total length range of the sharks tagged, at 136 cm, whereas the smallest 50% KUD area of 0.28 km^2 was for a 146 cm Galapagos shark (Figure 19). Sharks at the smallest (115 cm) and largest (155 cm) end of the total length range also had relatively similar 50% KUD areas, of 40.60 km^2 and 7.83 km^2, respectively (Figure 19).

GLMMs run on both 50% and 95% KUD areas showed that season, sex and total length did not have a significant effect (all p-values >0.05) and these variables only explained 5.4% and 10.3% of the deviance in the response variable in these models, respectively.

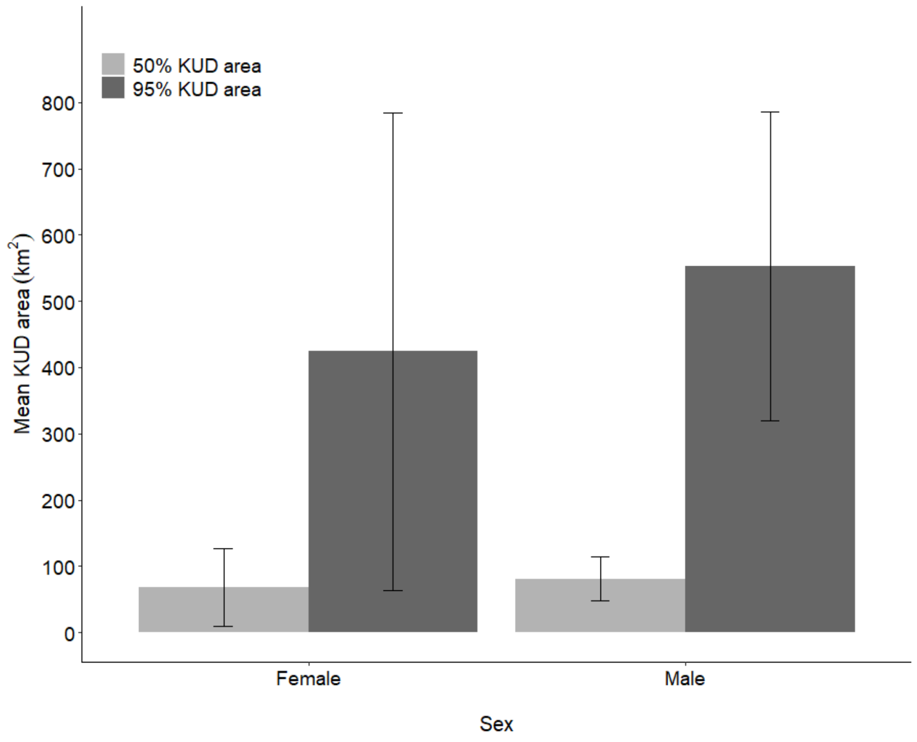


Figure 18. Mean Kernel Utilisation Distribution (KUD) areas for female (*n* = 4) and male (*n* = 5) Galapagos sharks. Lighter grey bars represent 50% KUD areas and darker bars show 95% KUD areas. Error bars represent standard error of the mean.

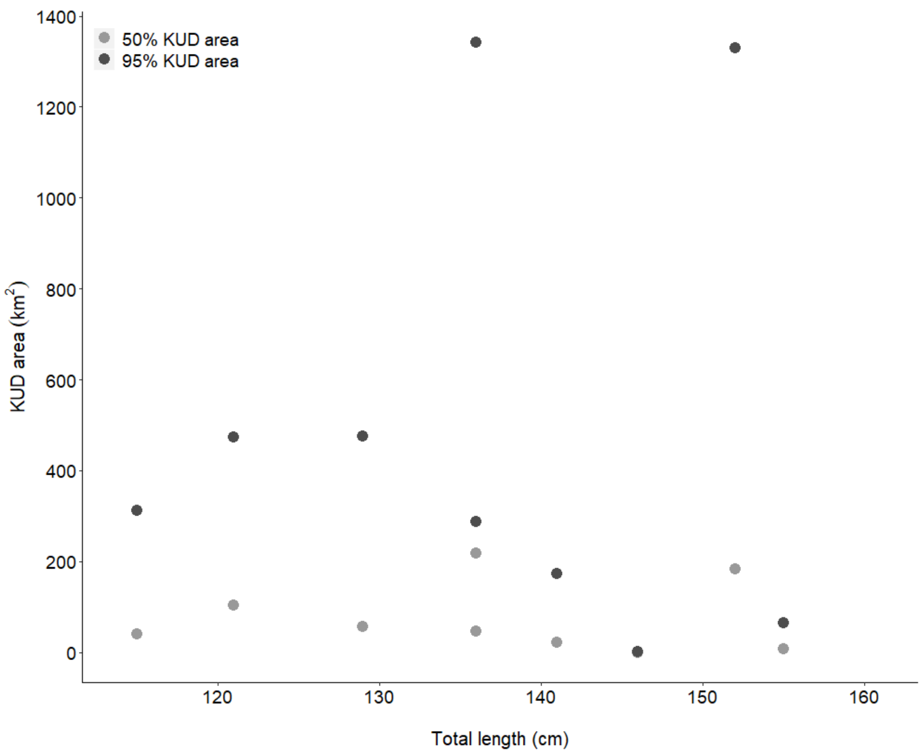


Figure 19. Kernel Utilisation Distribution (KUD) areas for nine tagged Galapagos sharks versus their total length. Lighter grey points represent 50% KUD areas and darker points show 95% KUD areas

5.5 Spatial patterns of fishing activity

Charter fishing vessel activity occurred throughout all times of year over the study period, with vessels fishing on 451 out of 1060 days (42.5%). Overall, fishing occurred across a large spatial area on both the LHI and BP shelves, with most areas having relatively low levels of fishing activity (values <50 VMS points per 1 km radius; Figure 20a). Some fishing also occurred beyond the shelf waters in depths >100 m, especially beyond the northwest and northeast corners of the LHI shelf and in the deep-water trench between the LHI and BP shelves. Locations with higher fishing activity (>300 VMS points per 1 km radius; Figure 20a) were close to the edge of the LHI and BP shelves, from 40 – 150 m depth, especially along the northeast and southwest corners of the LHI shelf and the northern portion of the BP shelf. However, some locations of higher fishing activity did occur in shallow waters from 20 - 30 m deep, particularly at the north end of LHI and around BP (Figure 20a). Close to the southern end of LHI there was a location which received high levels of visitation (~290 VMS points per km) from charter fishing vessels, which regularly clean fish and dispose of waste at this sheltered site. Raw VMS data also showed that this site was visited by at least one vessel on 20% of days where fishing occurred. No fishing activity occurred in the southern half of the BP shelf because this is an NTZ (Figure 20a). It is important to acknowledge that a low proportion of the vessel activity that was represented in Figure 20 may have been where the vessels were engaged in activities other than fishing, such as sightseeing, birdwatching or SCUBA diving, because these activities would be indistinguishable from fishing if they were also passively drifting at a speed <3 $km.hr^{-1}$. Additionally, the VMS data was generated from six vessels from January 2018 to November 2019, but only two vessels from December 2019 to January 2021. Furthermore, due to the COVID-19 pandemic, substantially lower levels of charter fishing occurred between March 2020 and October 2020, when LHI was closed to tourists.

Levels of fishing activity were higher overall in summer compared to winter, with maximum values of 330 and 200 VMS points per 1 km radius, respectively (Figure 20b, c). Additionally, the spatial coverage of fishing activity was much greater and occurred further offshore in summer months, especially in the northwest of the Lord Howe Island shelf and at the northern portion of Ball's Pyramid (Figure 20b, c). Although, there were some similarities between summer and winter, with notably higher levels of fishing activity just north of LHI, in the southwest corner of the LHI shelf and close to Ball's Pyramid. Hotspots of fishing activity (with values >200 VMS points per 1 km radius) occurred in the northeast and southeast of the LHI shelf in summer; whereas, levels of fishing activity were much lower in these areas in winter (<70 VMS points per 1 km radius; Figure 20b, c).

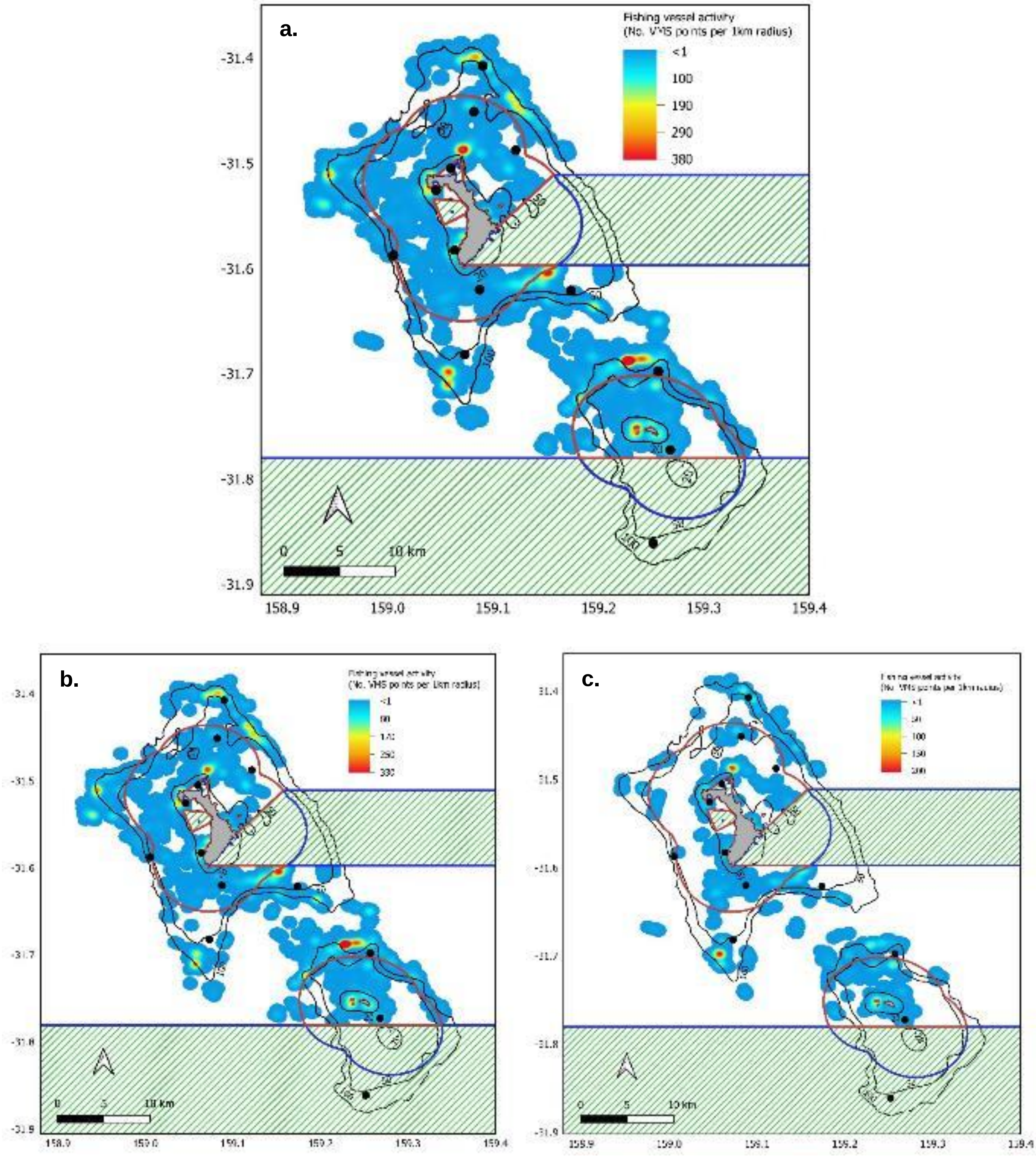


Figure 20. Heat maps of fishing activity during (**a**) all seasons from January 2018 – January 2021; (**b**) austral summer months (October to March); (**c**) austral winter months (April – September) generated using kernel density estimation for Vessel Monitoring System (VMS) data from six vessels. Blue = low fishing activity, red = high fishing activity, white background = no fishing. Solid dark red lines show the boundaries of the NSW State Marine Park and blue lines indicate the Commonwealth Marine Park. No-take zones are marked with hashed green

lines. Solid black lines with numbers show the 20 m, 50 m and 100 m depth contours. Black points indicate acoustic receiver locations.

Fishing occurred across a large depth range in the marine parks surrounding LHI; from 5 – 680 m, although the vast majority of VMS points (~85%) were at <100 m (Figure 21). In particular, the depth range from 20 – 60 m was the most frequently fished. Mean depth of fishing was 81.8 m.

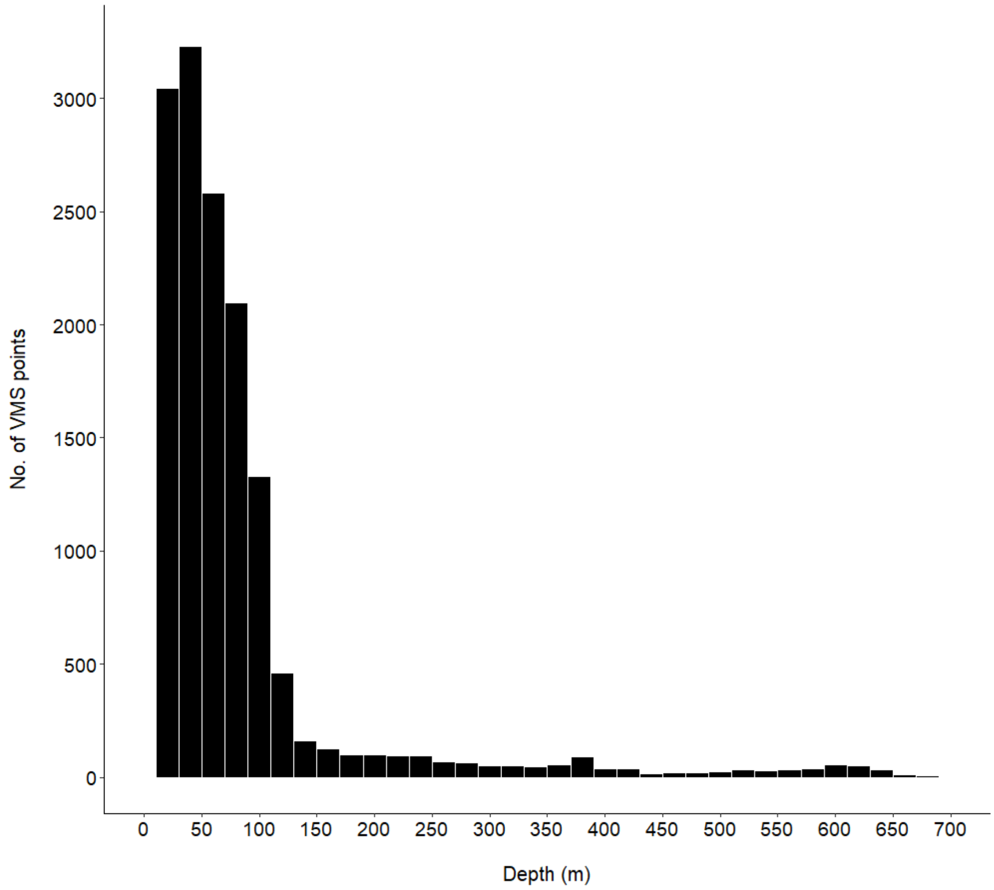


Figure 21. Frequency histogram for the depth of fishing in the marine parks surrounding LHI, based on number of Vessel Monitoring System (VMS) points recorded for charter fishing vessels.

The acoustic receiver deployment locations covered areas ranging from high fishing activity (>300 VMS points per 1km radius), for example the receivers deployed at the northeast of the LHI shelf and the southern LHI fish cleaning area, to medium fishing activity (approx. 100 – 150 VMS points per 1 km radius), such as the western LHI shelf and south of BP, to no fishing activity (0 VMS points per 1 km radius) in the southern BP shelf NTZ (Figure 22). Greater numbers of Galapagos shark detections were recorded in high fishing activity receiver locations, especially the northeast (2390 detections) and southeast (5497) LHI shelf and northeast BP shelf (2824), as well as at the location close to the southern tip of LHI (10895) where fish waste was regularly disposed of (Figure 22). Conversely, acoustic receivers located in areas of medium or lower fishing activity (south (87 detections) and east (223 detections) LHI shelf and central BP shelf (2 detections)) recorded much lower numbers of detections.

The very low number of detections recorded at the two sties close to the northern coast of LHI likely resulted from high levels of ambient noise from wave action on the reef and cliffs, which may have blocked the detection of acoustic signals from tagged sharks. The acoustic receiver located in the southern BP shelf NTZ recorded an intermediate level of detections (845) (Figure 22).

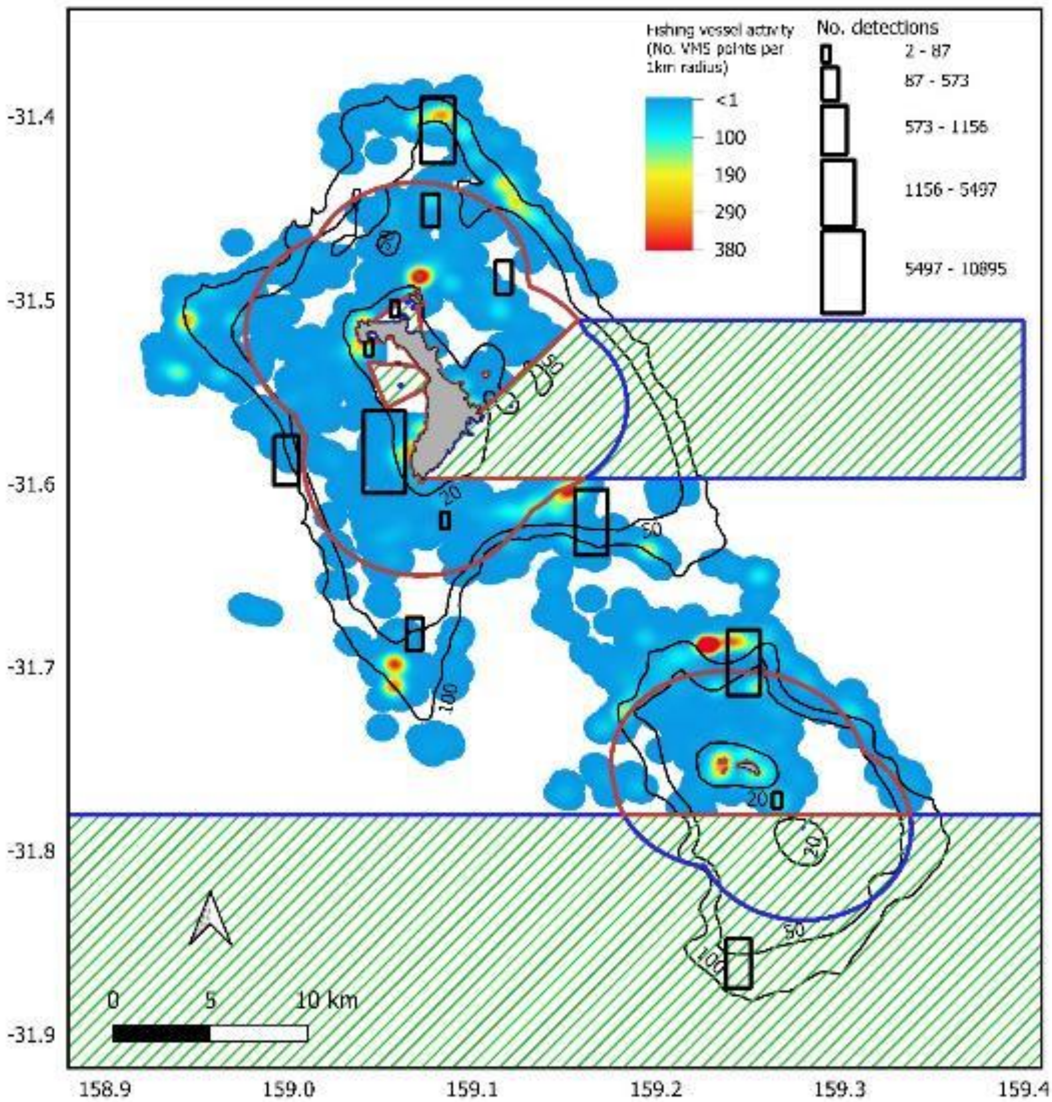
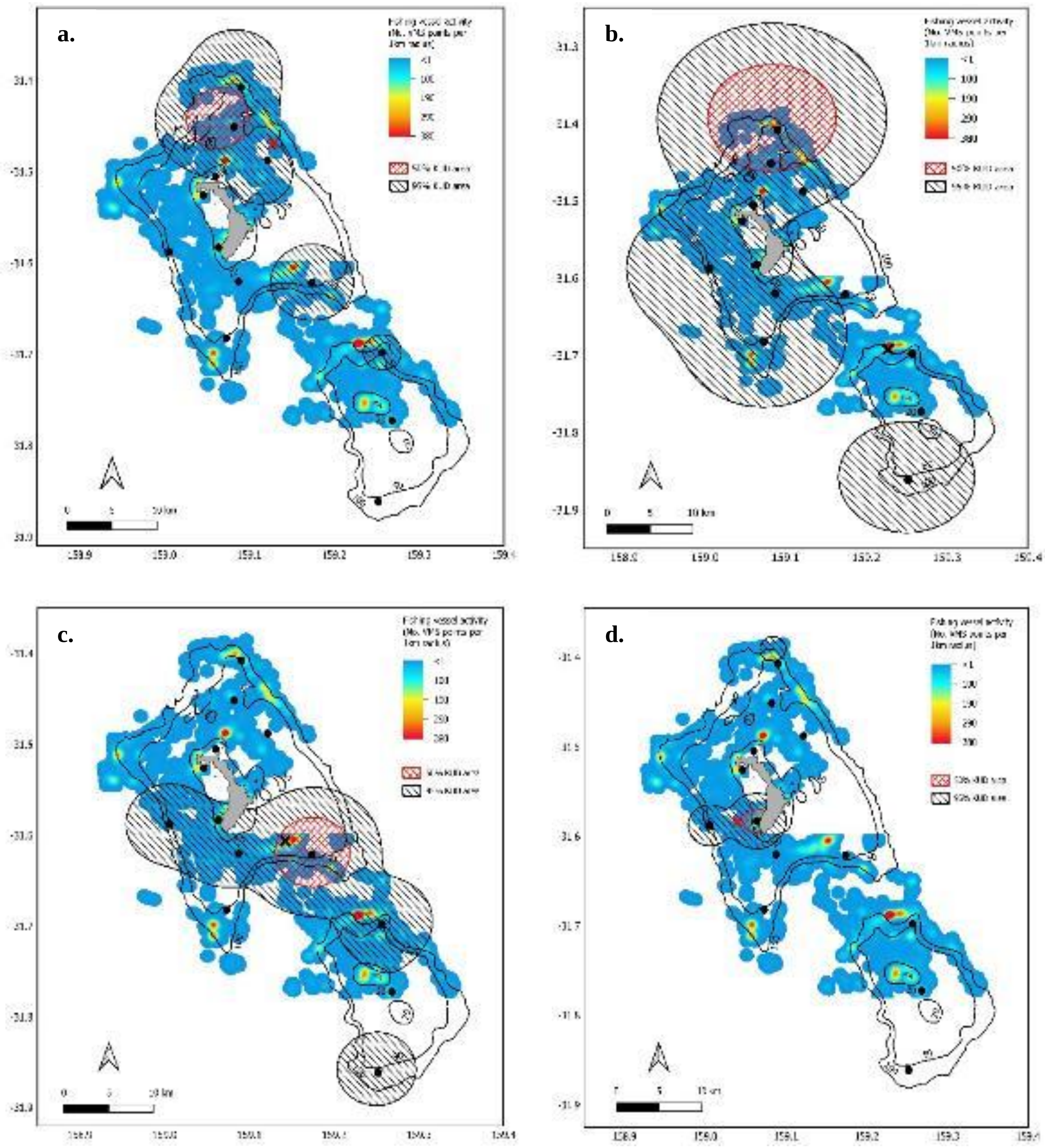


Figure 22. Map of total fishing activity (heatmap; low fishing activity = blue, high = red) and total number of Galapagos shark tag detections (size of black rectangles; larger = greater number of detections) in the marine parks surrounding Lord Howe Island. Solid dark red lines show the boundaries of the NSW State Marine Park and blue lines indicate the Commonwealth Marine Park. No-take zones are marked with hashed green lines. Solid black lines with numbers indicate depth contours in metres.

5.6 Spatial overlap between fishing activity and shark movements

The KUD areas of the nine Galapagos sharks showed a relatively high level of overlap with the locations of higher fishing activity determined from VMS data (Figure 23). The 50% KUD areas of some individuals showed high rates of overlap within specific areas where fishing activity was high, including the area where fish waste is disposed of close to the southern point of LHI (shark 1280560 and shark 1280561; Figure 23d, e), the southeast LHI shelf (shark 1280557; Figure 23c) and the northeast LHI shelf (sharks 1280546, 1280549 and 1280568; Figure 23a, b, i). The 95% KUD areas of the nine sharks were much larger, especially for sharks 1280549, 1280557 and 1280567, which covered a substantial portion of the LHI and BP shelves (Figure 23b, c, h). Despite the larger coverage of the 95% KUD areas, they generally still overlapped with areas where fishing activity was occurring, apart from parts of the large 95% KUD areas of sharks 1280549 and 1280567, which covered areas of deeper water (>100 m) and NTZs east of LHI and south of BP (Figure 23b, h).



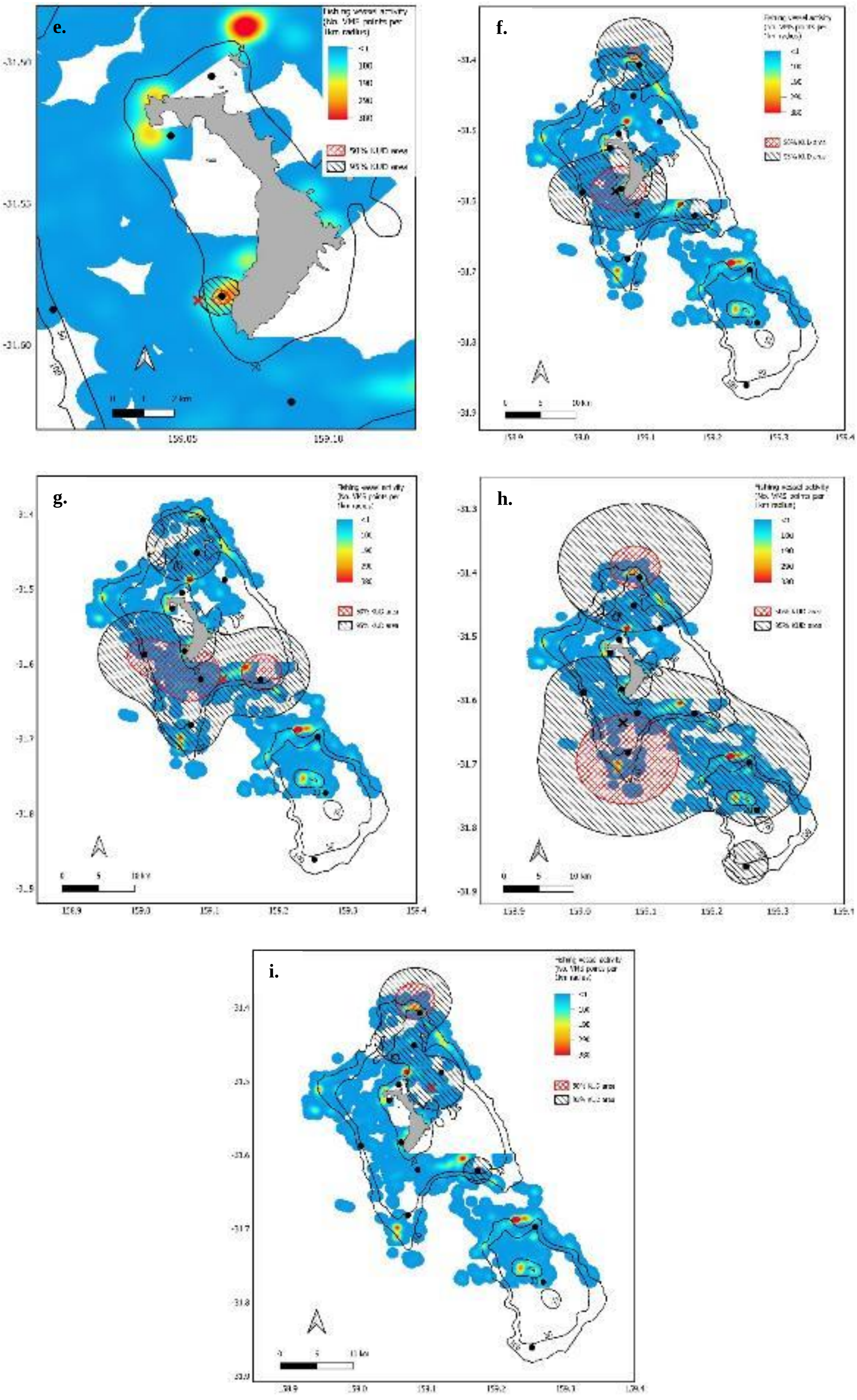

e.
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Figure 23. Overlap between fishing vessel activity (Vessel Monitoring System data; VMS) and individual Galapagos shark space use (Kernel Utilisation Distribution; KUD). (**a**) shark 1280546; (**b**) 1280549; (**c**) 1280557; (**d**) 1280560; (**e**) 1280561; (**f**) 1280562; (**g**) 1280564; (**h**) 1280567; (**i**) 1280568. Heatmap scale indicates blue for low fishing activity to red for high fishing activity. Areas marked by black hashed lines represent 95% 'extent' KUD areas and red crossed lines indicate 50% 'core' KUD areas. Small black points = acoustic receiver locations, red/black crosses = shark tagging locations. Solid black lines with numbers indicate depth contours.

5.7 Influence of fishing activity and environmental variables on shark detection rates

The full-subsets GAMM determined that the best model (i.e. with the lowest AIC and highest percentage deviance explained) included the predictor variables bathymetric variation, fishing activity (mean kernel density) and season. This model explained 29% of the deviance in the response variable. The predictor variables in this model had higher relative importance values than the other predictor variables, with values of 0.45, 0.32 and 0.97, respectively (Figure 24). Whilst depth had a slightly higher relative importance value (0.35) than bathymetric variation, these variables were correlated so were prevented from being included in the same model. Also, the GAMM containing bathymetric variation had a higher percentage deviance explained overall.

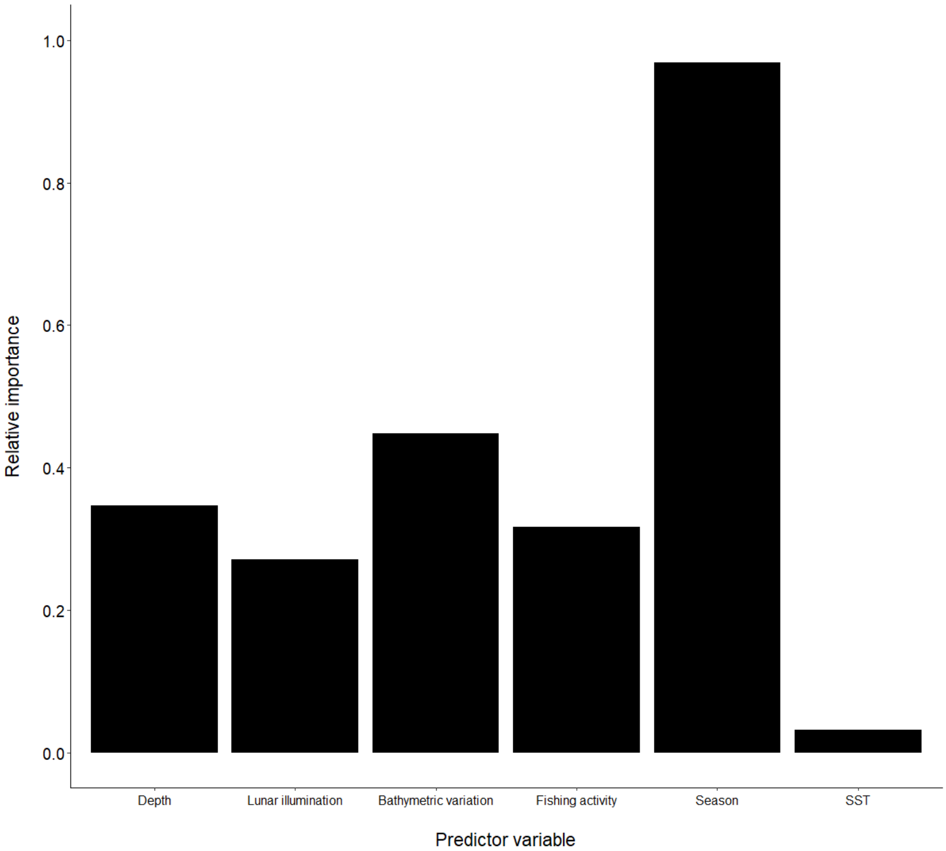


Figure 24. Relative importance values of all predictor variables tested in the full-subsets Generalised Additive Mixed Model (GAMM) quantifying number of Galapagos shark detections per day. SST = Sea Surface Temperature.

Bathymetric variation displayed an increasing positive relationship with the number of Galapagos shark detections per day, peaking at maximum values of bathymetric variation, although the 95% confidence interval bounds were substantially larger above 2.5 for this variable (Figure 25a). Fishing activity also had a linear and increasingly positive influence on the number of detections per day, peaking at the highest values of fishing activity (Figure 25b). Season had a marked influence on Galapagos shark detections, with summer displaying the highest number of detections and autumn the lowest, closely followed by winter (Figure 25c).

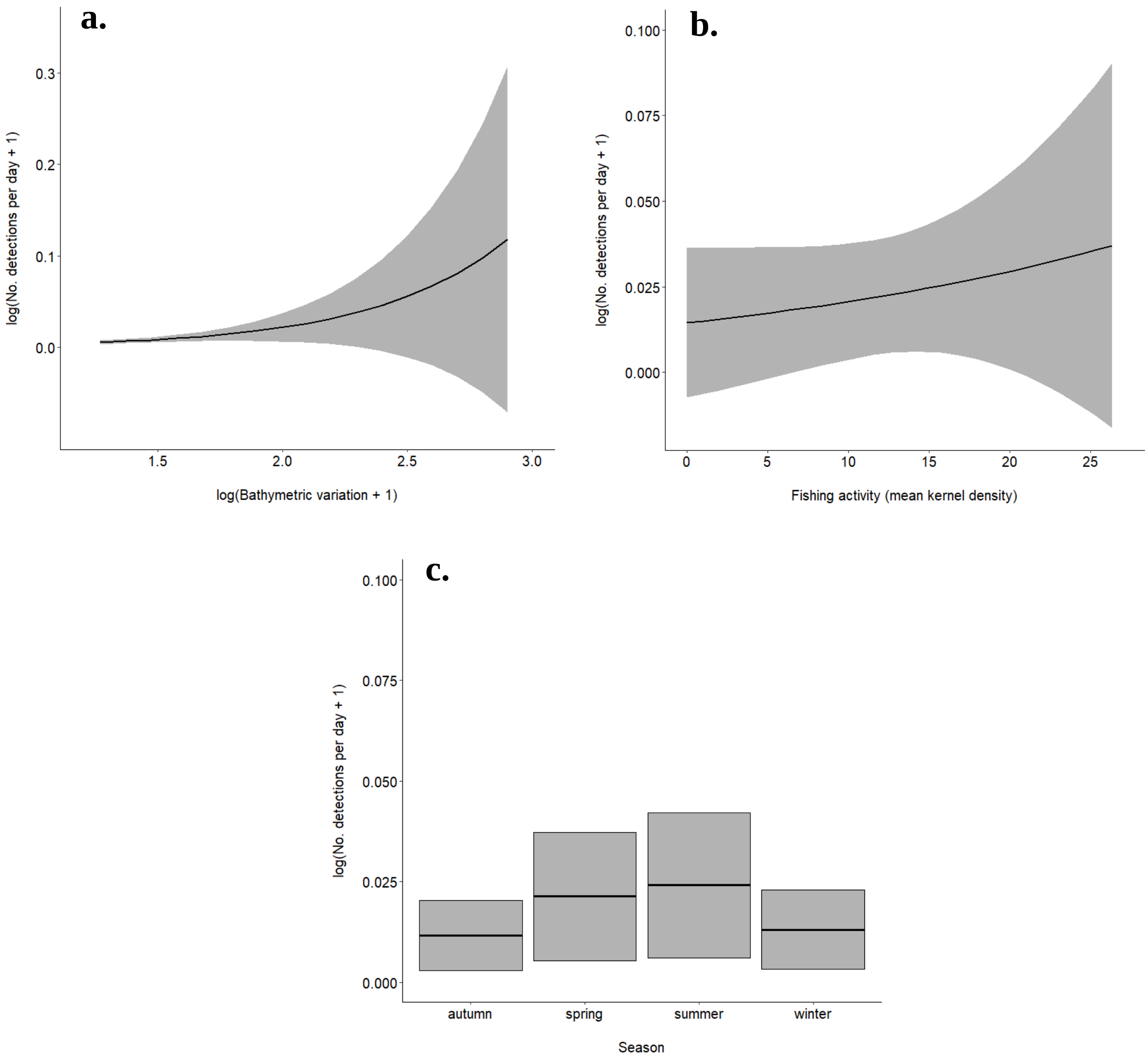


Figure 25. Predictor plots showing the influence of the predictor variables in the best Generalised Additive Mixed Model (GAMM) on the response variable - number of Galapagos shark detections per day. (**a**) Bathymetric variation (log + 1 transformed); (**b**) fishing activity (mean kernel density); (**c**) season. Solid black lines indicated the model predicted values and shaded grey areas show the 95% confidence intervals.

5.8 Depth patterns

Depth distributions for the 10 Galapagos sharks tagged with depth sensors ranged from 0 – 94 m, with a mean depth of 25.2 m (Figure 26). Five out of the 10 sharks had a total depth range between ≤5 m and 80 m, with the others having a smaller overall depth range. A high proportion of detections for sharks 1280560 and 1280561, which were predominantly detected at the shallow south LHI fish cleaning area, were in a narrow depth range between 10 m and 20 m (Figure 26). Conversely, sharks 1280559 and 1280562 had much broader depth distributions as shown by the relatively larger grey boxplots for these individuals in Figure 26. Six out of 10 sharks had a mean depth between 34 m and 48 m, whereas the remaining four sharks displayed a much shallower mean depth <26 m (Figure 26).

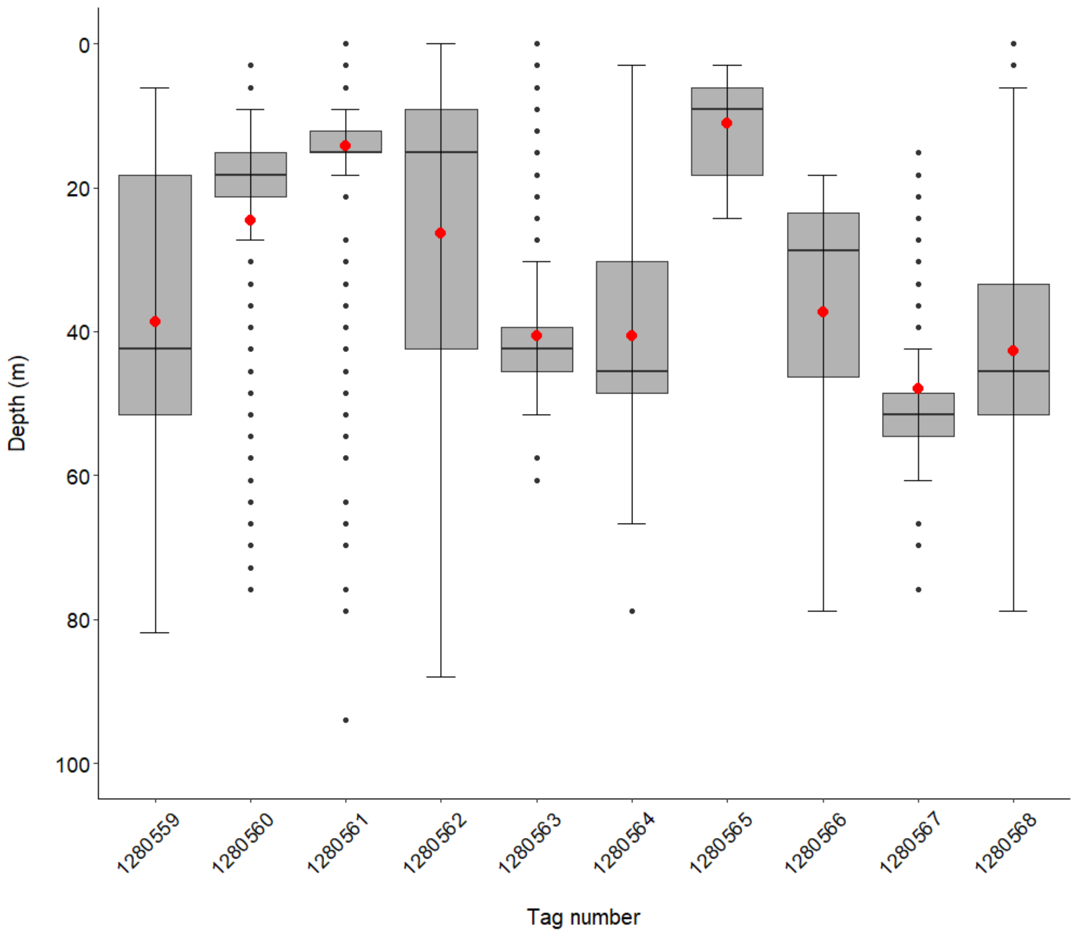


Figure 26. Depth distribution of 10 Galapagos sharks fitted with depth sensors, from January 2018 to January 2021. Black lines inside boxplots indicate median depth, with outer box lines showing upper and lower quartiles. Black points show outliers >1.5 times the interquartile range. Red points indicate mean depth.

The depth categories where sharks spent most time were 15m and 10m, with generally higher numbers of detections from 10 – 20m and 40 – 50m (Figure 27). Depth patterns were substantially different across the different acoustic receiver locations, partly influenced by the bottom depth at each site (Figure 28). At the south LHI fish cleaning area, two sharks (1280560 and 1280561) predominantly remained in the lower half of the water column, between 10m and 20 m depth (Figure 28a), with high residency at this location. However, shark 1280560 was not detected after 19/01/2020. At other receiver locations including the northeast and western LHI shelf, there was a marked pattern of regular vertical movements from a number of different sharks (Figure 28b, d). At the southeast LHI receiver location vertical movements were also observed, however shark 1280563 spent a large portion of its time closer to the seabed, between 35 and 45 m (Figure 28c).

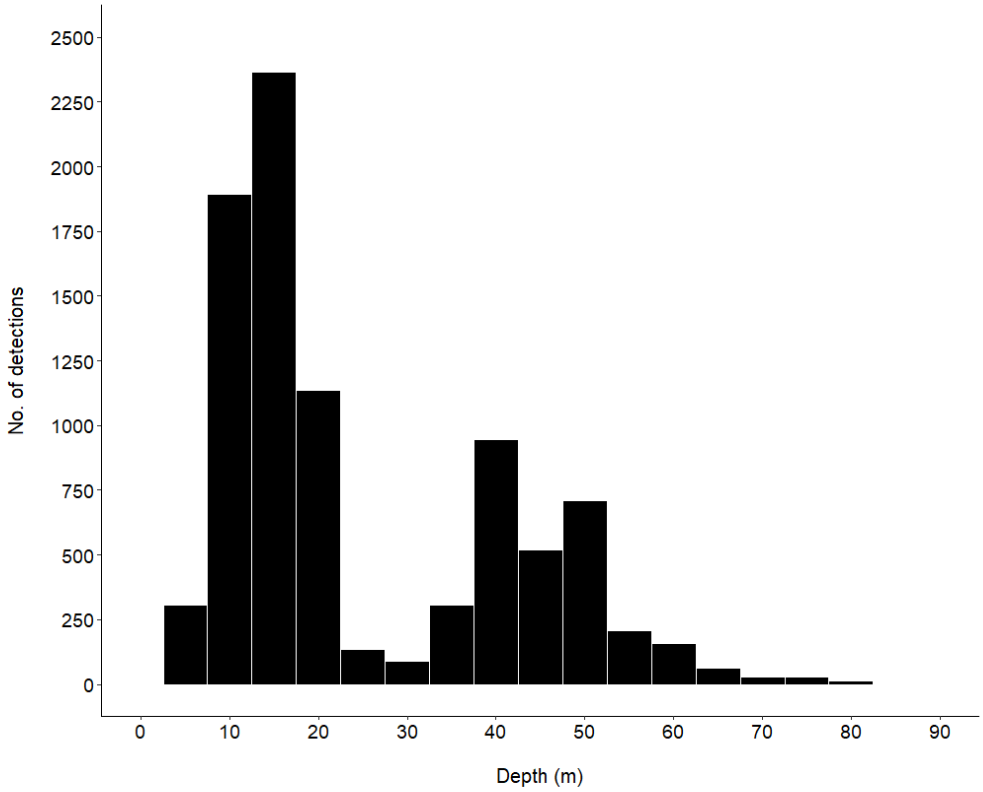
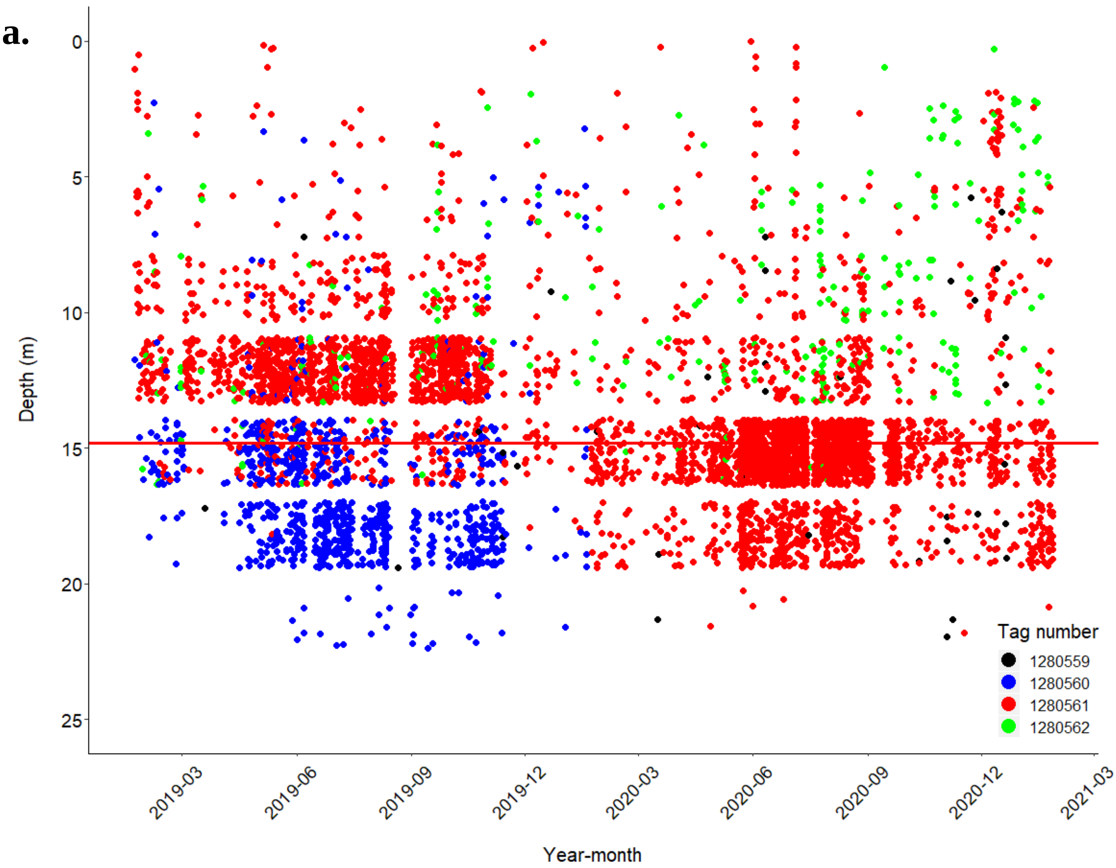
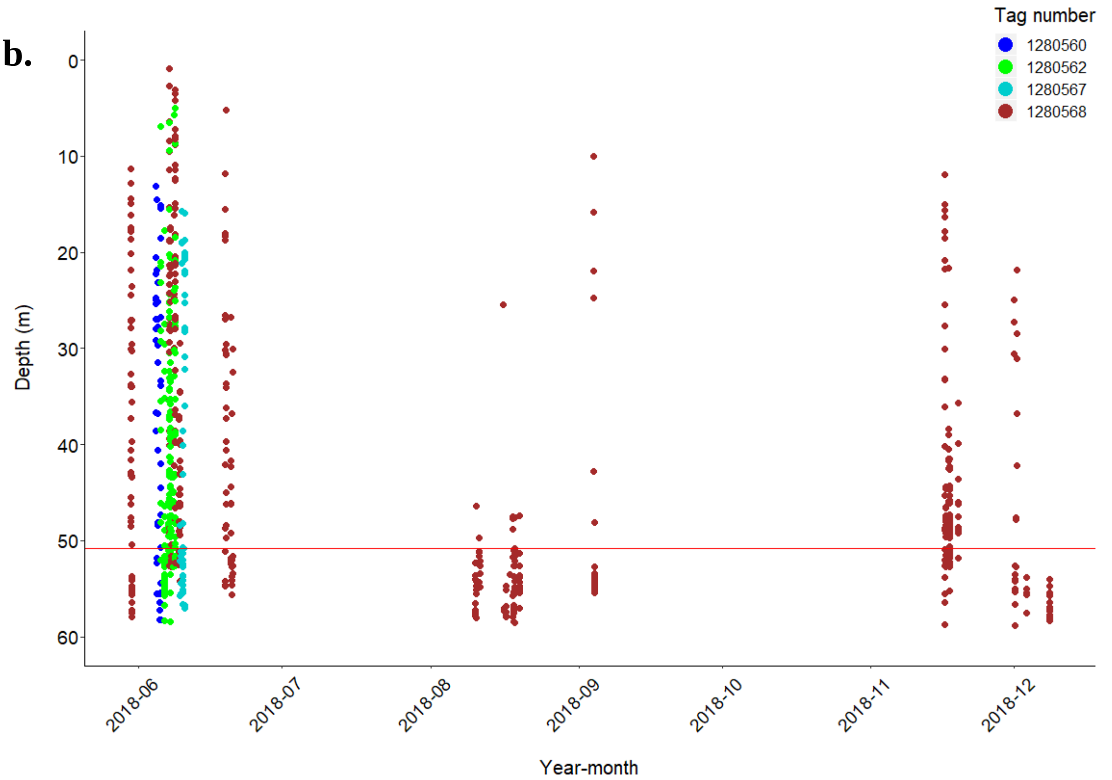


Figure 27. Number of Galapagos shark detections at different depth categories.

a.


Depth (m)
0
5
10
15
20
25
Year-month
2019-03
2019-06
2019-09
2019-12
2020-03
2020-06
2020-09
2020-12
2021-03
Tag number
1280559
1280560
1280561
1280562

b.


Depth (m)
0
10
20
30
40
50
60
Year-month
2018-06
2018-07
2018-08
2018-09
2018-10
2018-11
2018-12
Tag number
1280560
1280562
1280567
1280568

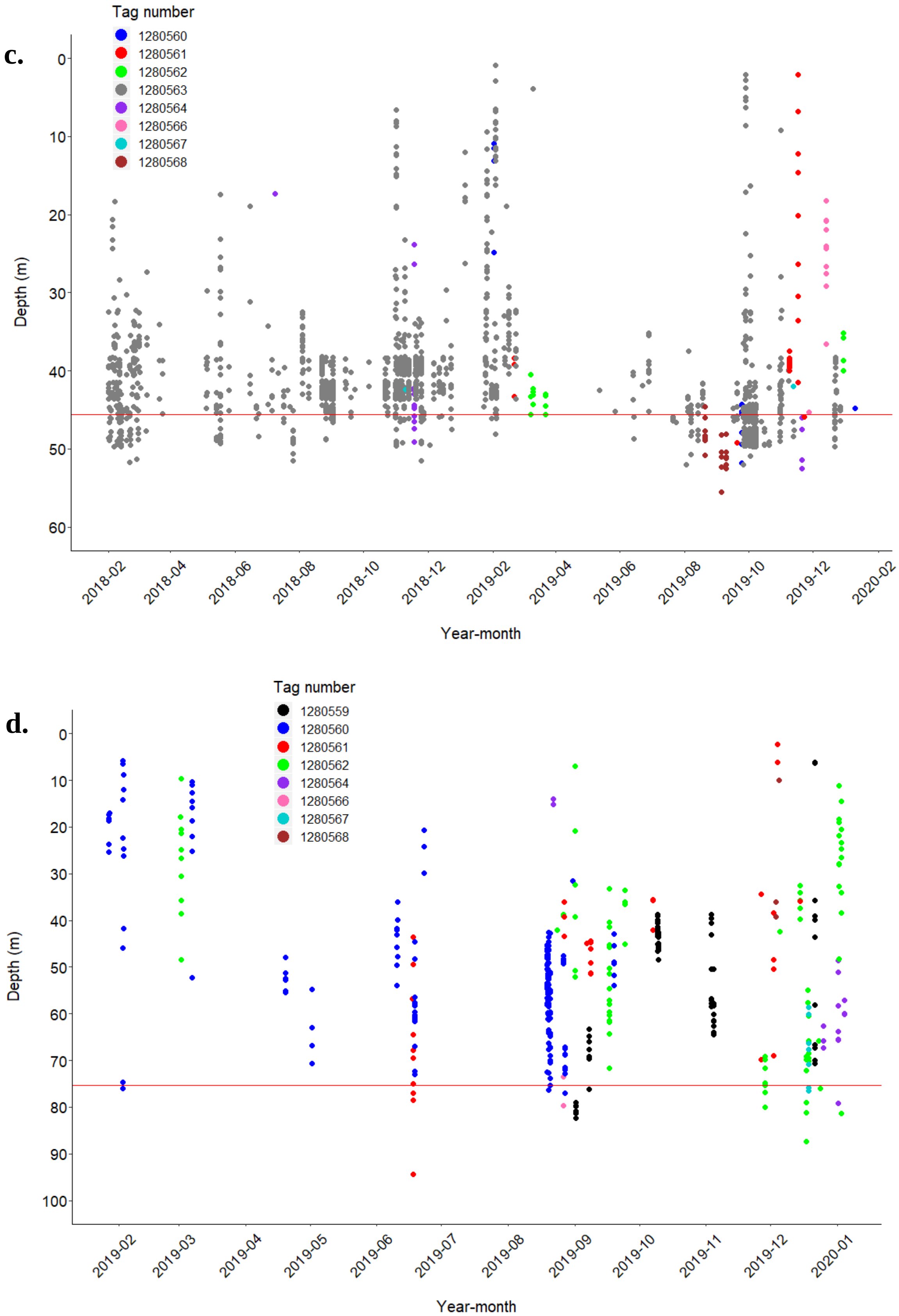
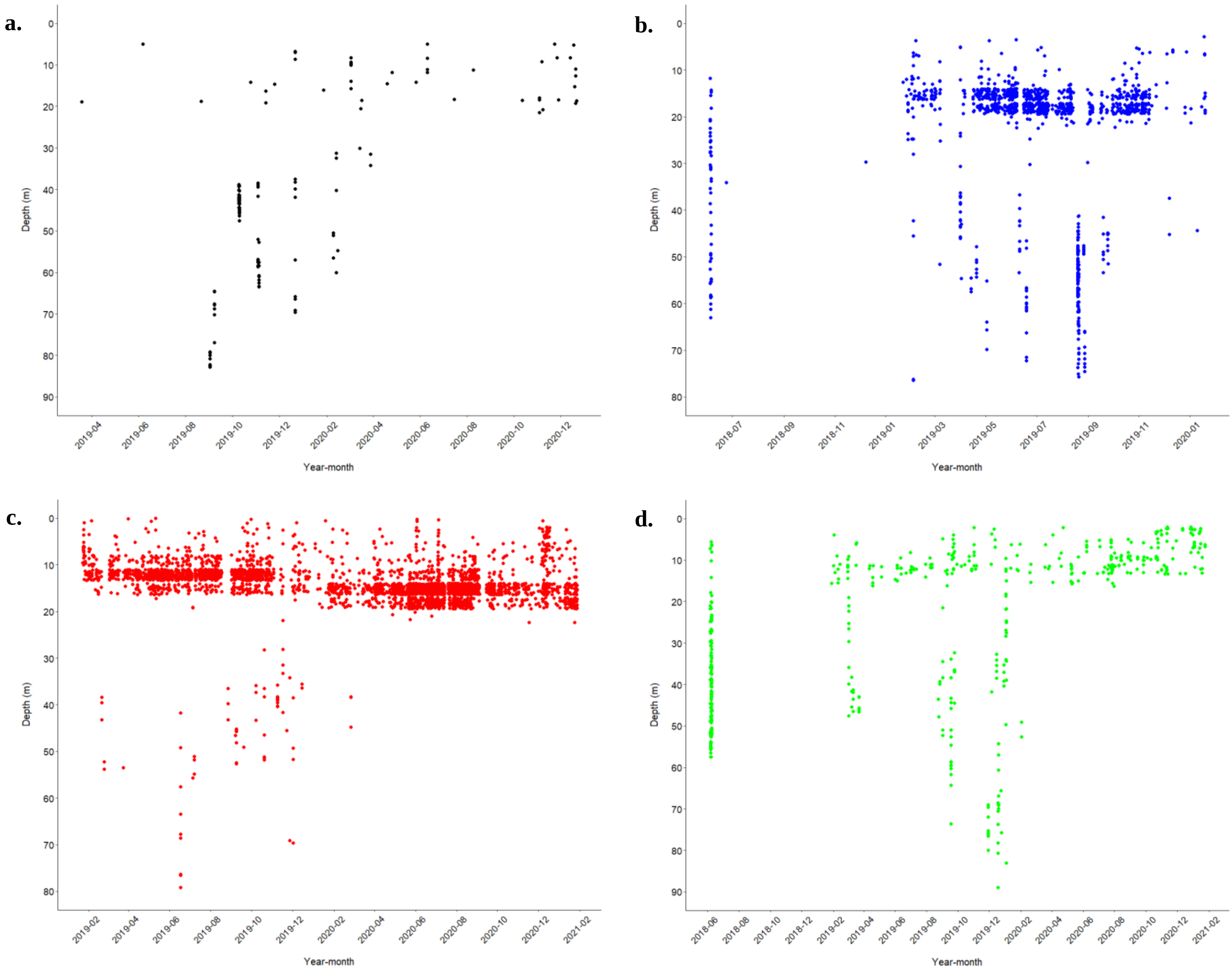


Figure 28. Depth points for Galapagos sharks at four acoustic receiver locations. (**a**) south Lord Howe Island (LHI) fish cleaning area; (**b**) northeast LHI shelf; (**c**) southeast LHI shelf; (**d**) western LHI shelf. Coloured points represent individual sharks as denoted in the legend. Red lines indicate the depth of the acoustic receiver at each location.

The depth distribution of the 10 Galapagos sharks varied substantially across time, with some sharks spending considerable proportions of time at similar depths when they were close to the seabed, for example sharks 1280560 (Figure 29b), 1280561 (Figure 29c), 1280562 (Figure 29d) and 1280563 (Figure 29e), whereas others made more frequent vertical movements up and down in the water column, across greater depth ranges, especially sharks 1280567 (Figure 29i) and 1280568 (Figure 29j). Although the vast majority of detections for sharks 1280560, 1280561 and 1280562 were between 10 – 20 m depth, which was at the south LHI fish cleaning area, these sharks did make occasional movements into deeper water, where they dived to >40 m depth and as deep as 90 m (Figure 29b,c,d). Shark 1280568 displayed particularly interesting vertical depth distribution, as it moved up and down in the water column over short timescales, sometimes moving from >60 m depth up to the surface (Figure 29j). Depth distribution data was more sparse for sharks 1280559 (Figure 29a), 1280565 (Figure 29g) and 1280566 (Figure 29h), although these sharks did also make vertical movements from <10 m to approximately 80 m.



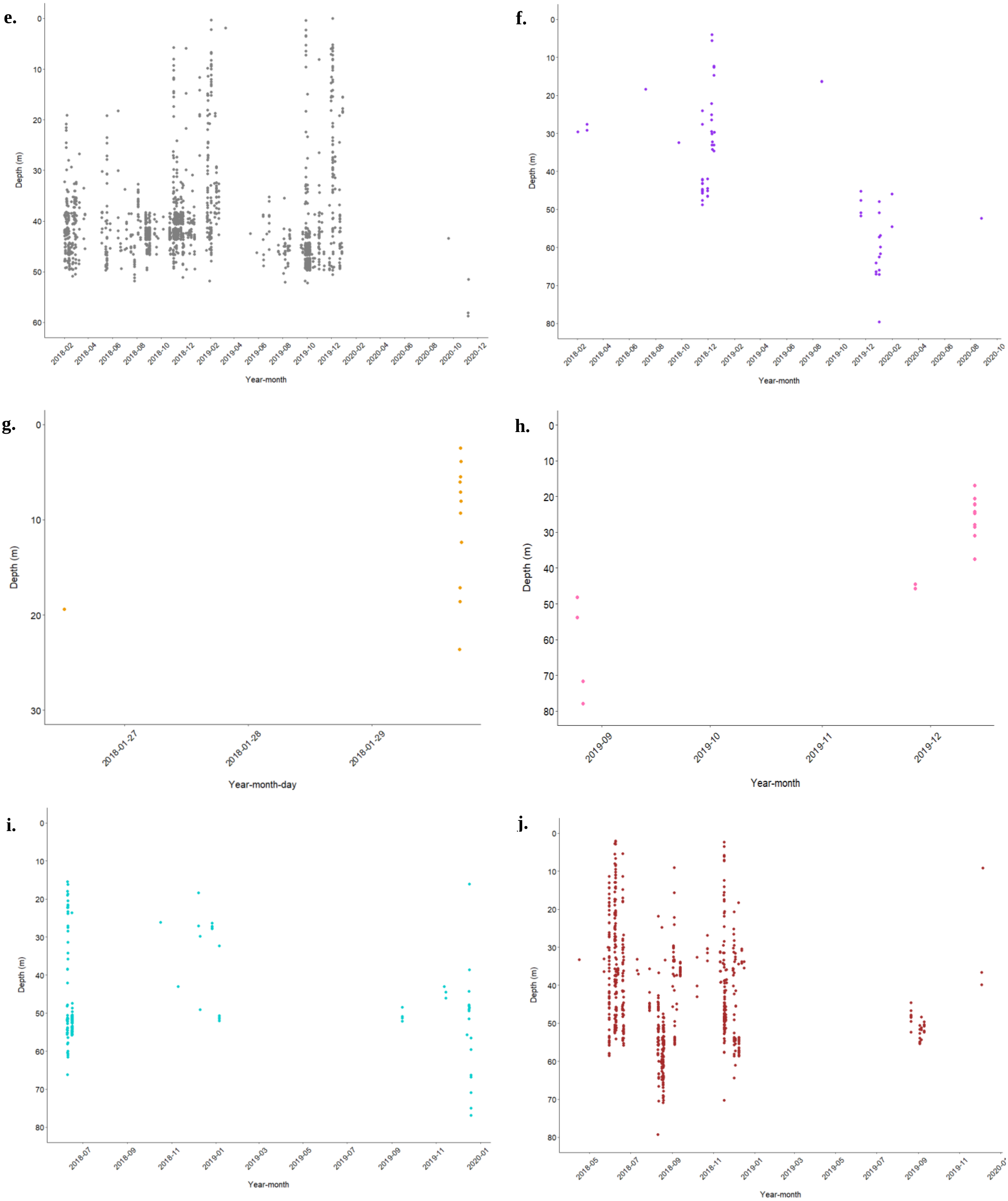


Figure 29. Depth distribution of 10 tagged Galapagos sharks from January 2018 to January 2021. (**a**) shark 1280559; (**b**) 1280560; (**c**) 1280561; (**d**) 1280562; (**e**) 1280563; (**f**) 1280564; (**g**) 1280565; (**h**) 1280566; (**i**) 1280567; (**j**) 1280568. Colours of points are the same as those in Figure 28.

There was a marked difference in the depth distribution of the 10 tagged Galapagos sharks between day and night, with sharks spending a greater proportion of time in shallower waters at night (mean depth of 18.8 m) compared to during the day (mean = 38.9 m) (Figure 30a). The majority of detections also occurred in <20 m depth at night, whereas they were mostly between 30 m and 50 m during the day (Figure 30a). There was only a small difference in the depth distribution of Galapagos sharks across seasons, with the shallowest mean depth of 18.1 m occurring in autumn and the deepest of 30.2 m occurring in spring (Figure 30b). The majority of depth values recorded in autumn were between 10 m and 20 m, whereas for other seasons they were predominantly from 20 – 40 m (Figure 30b).

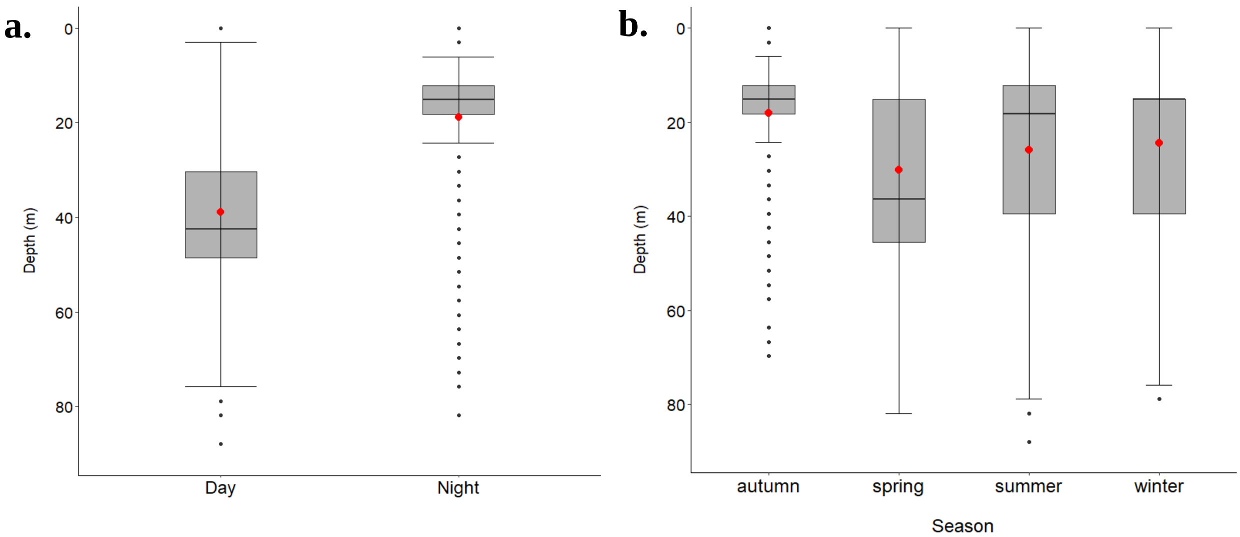


Figure 30. Depth distribution of sharks during (**a**) day and night periods; (**b**) seasons. Black lines inside boxplots indicate median depth, with outer box lines showing upper and lower quartiles. Black points show outliers >1.5 times the interquartile range. Red points indicate mean depth.

On an individual basis, there was a substantial amount of variation in the depth of detections during day versus night. Some sharks had a markedly different depth distribution at night compared to day time, such as shark 1280559 which had a median depth of 42.5 m during the day compared to 18.2 m at night (Figure 31). Similarly, sharks 1280560 and 1280562 had a marked difference in their median depths in day versus night, with 48.5 m and 18.2 m, and 36.4 m and 12.1 m, respectively (Figure 31). However, other sharks had very similar depth distributions during day and night, such as sharks 1280561 and 1280563, which had median depths of 12.1 m (day) vs 15.2 m (night) and 42.5 m (day) vs 42.5 m (night), respectively (Figure 31). Interestingly, shark 1280565 was solely detected during the day, although this shark was only detected 12 times in total.

There was a marked difference in the depth distribution of male and female sharks, with females having a much shallower mean depth (18.4 m), compared to males (41.0 m) (Figure 32). Additionally, the majority of detections for females were concentrated at depths between 10 m and 20 m, whereas for males they were predominantly between 40 m and 50 m (Figure 32).

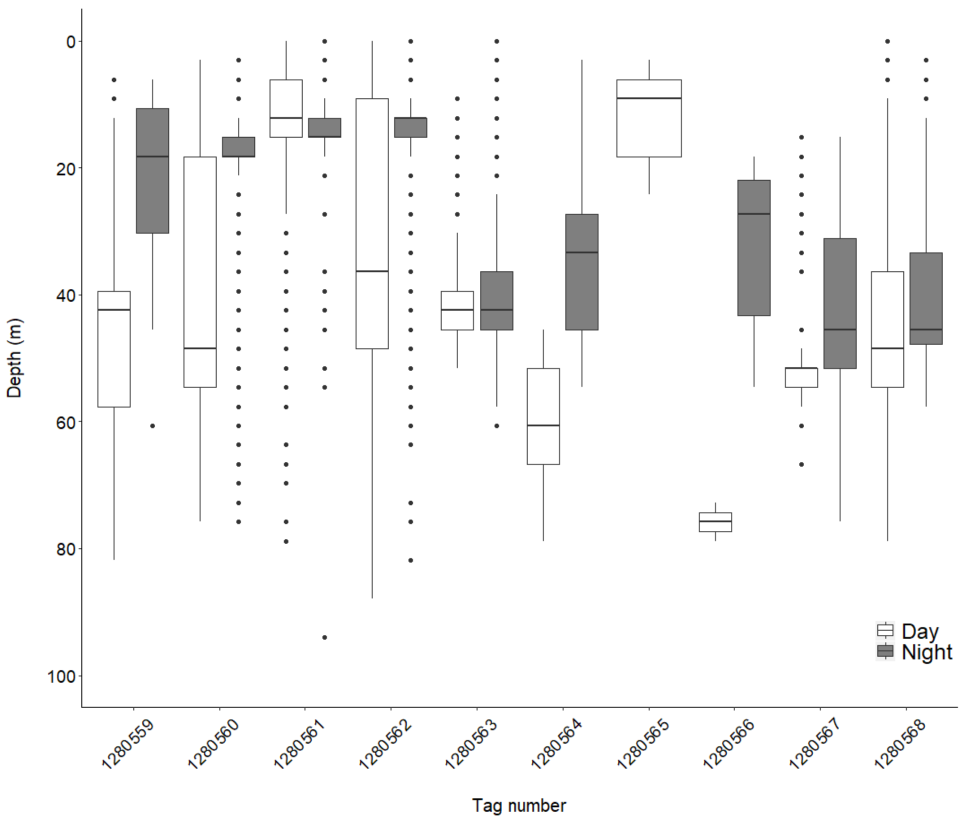


Figure 31. Depth distribution of 10 Galapagos sharks during day (white bars) and night (grey bars). Black lines inside boxplots indicate median depth, with outer box lines showing upper and lower quartiles. Black points show outliers >1.5 times the interquartile range.

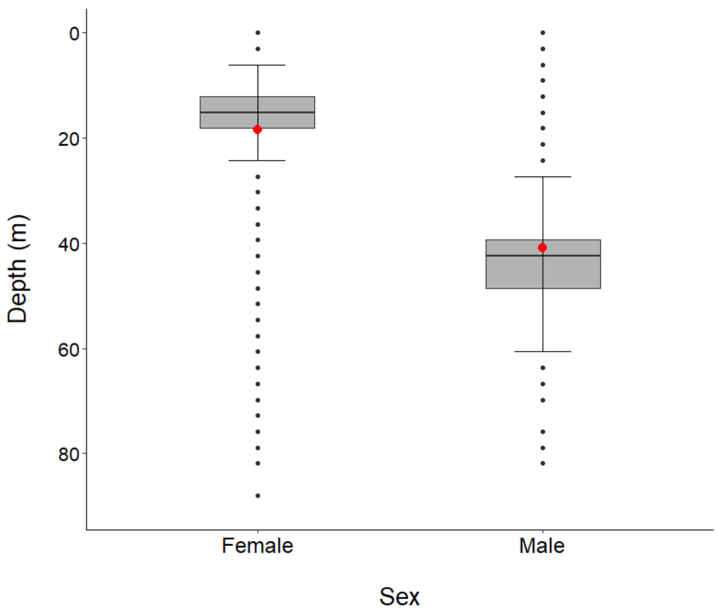


Figure 32. Depth distribution for female (n=5) and male (n=5) Galapagos sharks between January 2018 and January 2021. Black lines inside boxplots indicate median depth, with outer box lines showing upper and lower quartiles. Black points show outliers >1.5 times the interquartile range. Red points indicate mean depth.

There was no clear pattern between the mean depth of the 10 tagged Galapagos sharks and their total length, which ranged from 116 – 155 cm, although the shallowest mean depth of 11.1 m was recorded for the smallest shark (1280565) (Figure 33). The largest shark, 1280560, had an intermediate mean depth of 24.6 m, whereas the deepest mean depth of 48.0 m was recorded for shark 1280567, which was 136 cm in total length (Figure 33).

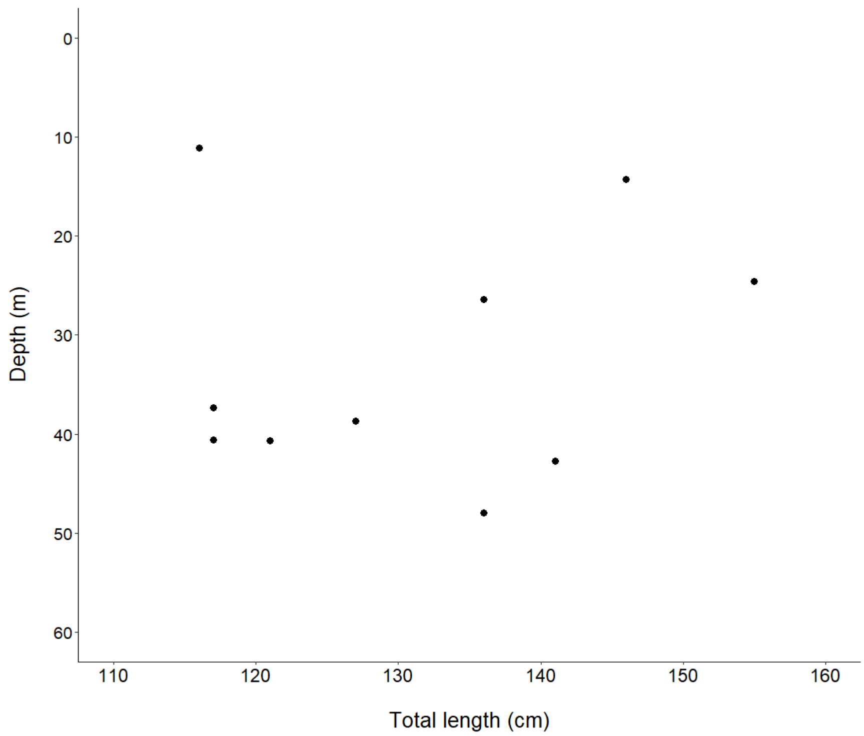


Figure 33. Mean depth and total length of 10 tagged Galapagos sharks in the marine parks surrounding Lord Howe Island.

Using the stepwise GLMM approach, the best model contained the predictor variables diel period and season. These variables had a significant influence on the depth of Galapagos sharks (diel period: Chisquared value = 51.57, Degrees of Freedom (DF) = 1, p-value = <0.001; season: Chisq = 158.80, DF = 3, p-value = <0.001). This model explained 65% of the deviance in the response, with the random effect variables station and tag number accounting for 64% of this and the fixed effect variables only 1%.

Depth sensors also indicated some periods of rapid vertical movement of sharks. Galapagos sharks 1280562 and 1280568 displayed vertical movements from 50 m to <5 m at the receiver location in the northeast LHI shelf, across a two-hour period on 08/06/2018 (Figure 34a). This included one instance where both sharks moved upwards at the same time, from approximately 40 m depth to <5 m over a 15-minute period (Figure 34a). At the western LHI shelf acoustic receiver location, shark 1280560 moved upwards from 75 m to 6 m over a 20-minute period on 03/02/2019 (Figure 34b). At this location, shark 1280562 undertook a 'V' shaped dive over a 10-minute period, moving from 12 m to 48 m and then back to 12 m, on 01/01/2020 (Figure 34c).

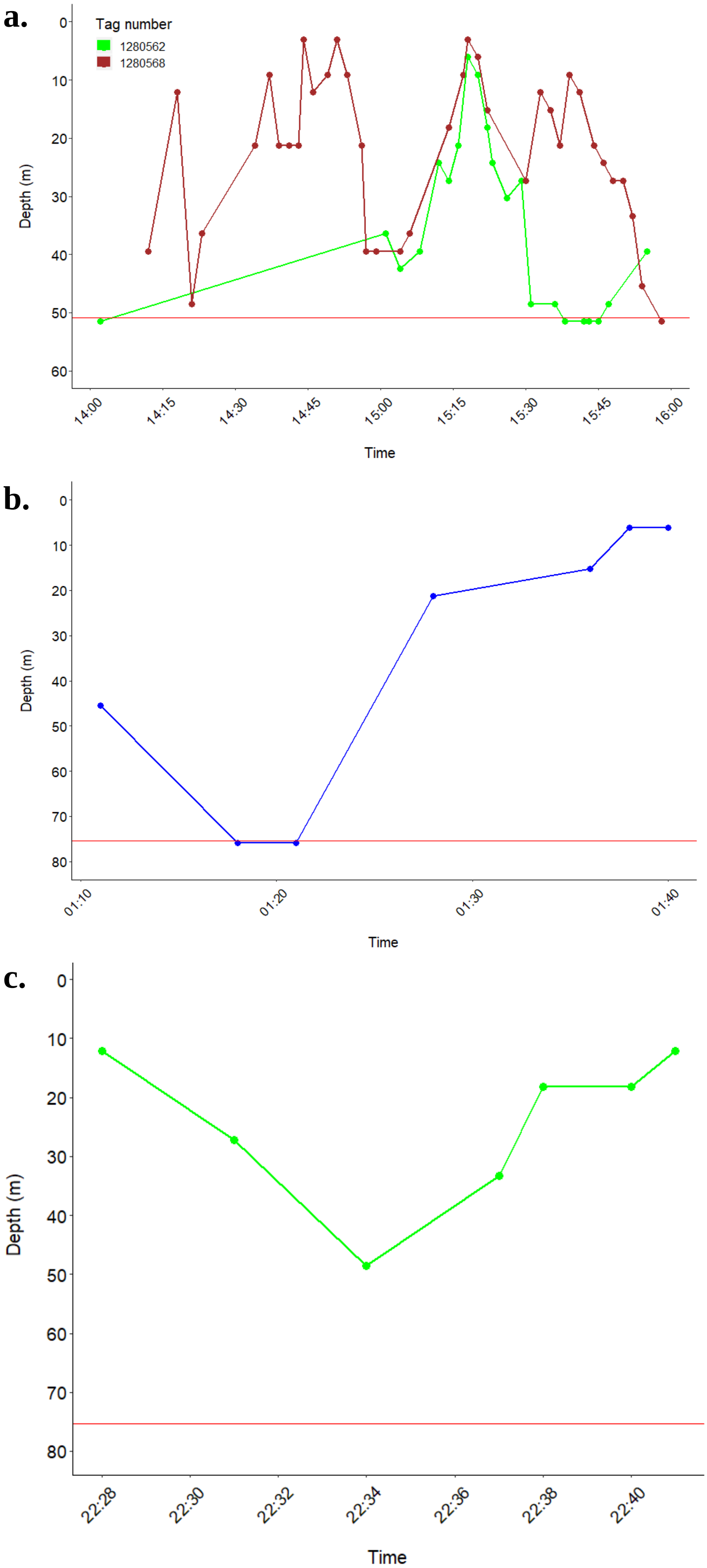

a.
Tag number
1280562
1280568
Depth (m)
0
10
20
30
40
50
60
14:00
14:15
14:30
14:45
15:00
15:15
15:30
15:45
16:00
Time
b.
Depth (m)
0
10
20
30
40
50
60
70
80
01:10
01:20
01:30
01:40
Time
c.
Depth (m)
0
10
20
30
40
50
60
70
80
22:28
22:30
22:32
22:34
22:36
22:38
22:40
Time

Figure 34. Vertical movement patterns of Galapagos sharks over short timescales. (**a**) northeast Lord Howe Island (LHI) shelf (sharks 1280562 and 1280568); (**b**) western LHI shelf (shark 1280560); (**c**) western LHI shelf (1280562). Red lines indicate the depth of acoustic receivers on the seabed at these locations. Brown, green and blue lines indicate individual sharks' vertical movements.

5.9 Temperature data

Data from the 10 Galapagos sharks fitted with temperature sensors showed a cyclical seasonal pattern, where temperatures peaked in January - March and reached a minimum between June and September in all three years of the study (Figure 35). The minimum temperature of 17.4 °C occurred in August 2018 and the maximum of 26.1 °C in February 2020. The majority (>60%) of temperature datapoints were between 19 and 21 °C, with low numbers occurring at the high (26 °C) and low (18 °C) ends of the temperature range (Figure 36). The drop in number of detections between 22 °C and 26 °C was relatively gradual, however there was a rapid increase in number of detections between 18 °C and 19 °C, from <300 detections at 18 °C to >1700 at 19 °C (Figure 36).

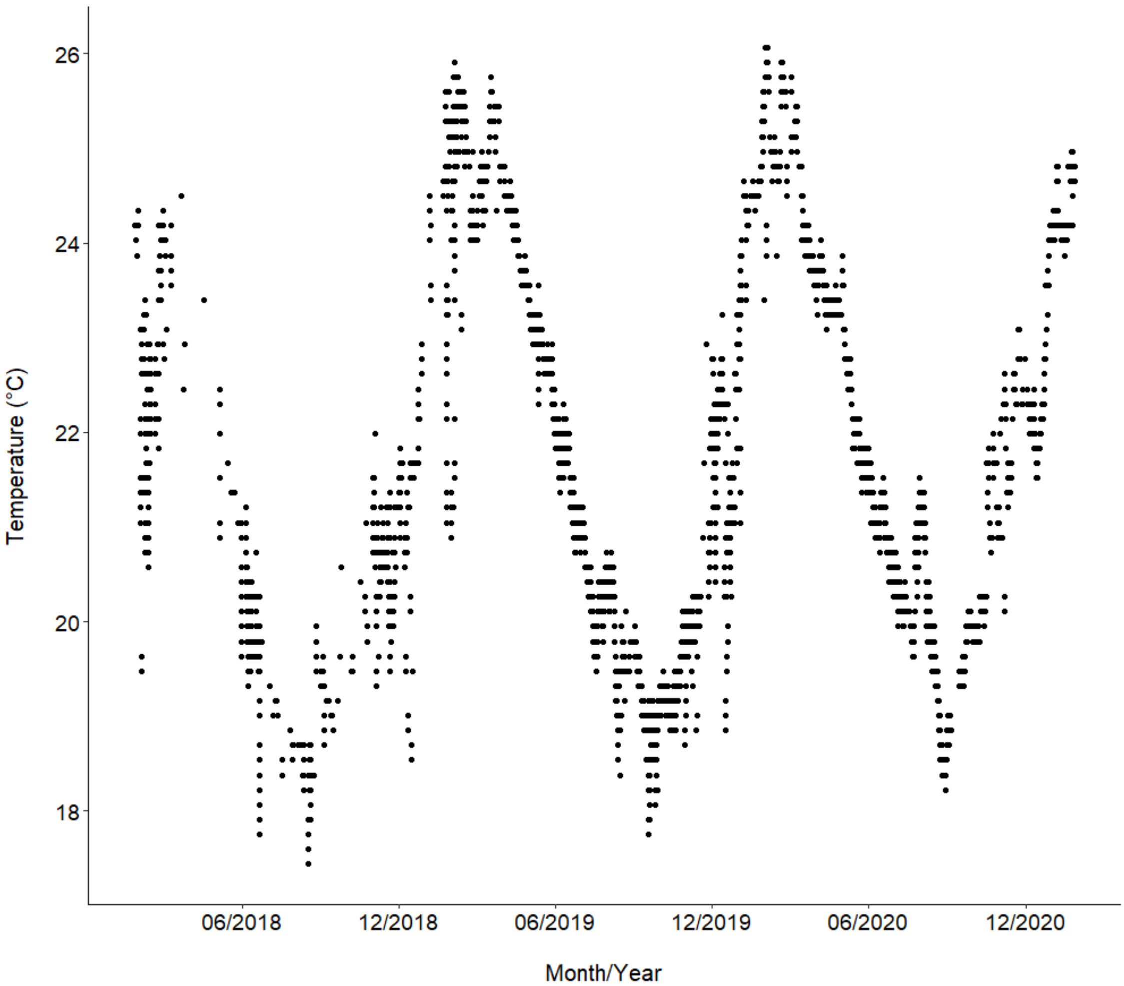


Figure 35. Temperature values from 10 tagged Galapagos sharks between January 2018 and January 2021.

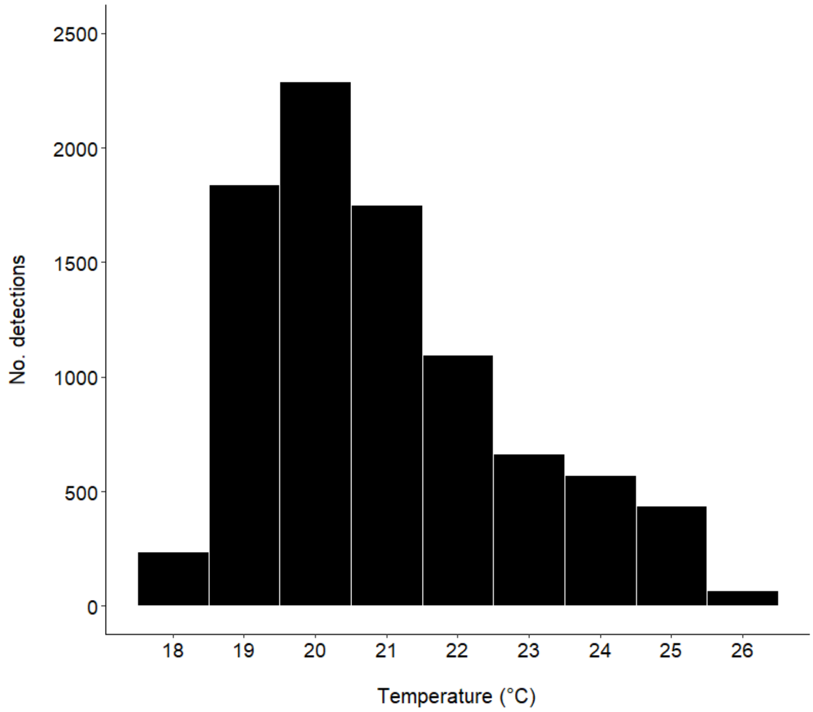


Figure 36. Number of detections at each degree of temperature for 10 Galapagos sharks fitted with temperature sensors.

5.10 Movements of other sharks detected in the marine parks surrounding LHI

In addition to Galapagos sharks tagged as part of this research, two other tagged sharks were detected within the acoustic receiver array. Between 15/05/2019 and 02/07/2019 a white shark (which was originally tagged in South Australia in 2016 and was ~3 m in total length; C. Huveneers, pers. comm.) was detected 93 times across six different acoustic receivers. The western LHI shelf acoustic receiver recorded the greatest number of detections (35) for this shark, followed by the southeast LHI shelf and southwest LHI shelf locations (both 19) (Figure 37). Fewer detections (<10) were recorded at each of the northeast BP shelf, south BP shelf and south LHI fish cleaning areas (Figure 37). This shark was detected at the acoustic receivers located on the western LHI shelf, southwest LHI shelf and southeast LHI shelf from 15/05/2019 until 18/06/2019, after which it crossed the deep channel to the Ball's Pyramid shelf, being detected by the acoustic receiver on the northeast BP shelf and then the south BP shelf on consecutive days. It then crossed back to the LHI shelf and was detected on three receivers (southeast LHI shelf, western LHI shelf and south LHI fish cleaning area) on the same day (21/06/2019). The shark was then detected again at the southwest LHI shelf and southeast LHI shelf receivers on 29/06/2019 and 02/07/2019, respectively. A 2.46 m female tiger shark originally tagged off Ballina, NSW in March 2020 (P. Butcher, pers. comm.) was also detected 24 times on acoustic receivers in the marine parks surrounding LHI, between 14/12/2020 and 16/12/2020. This shark moved from the southwest LHI shelf acoustic receiver location to the south BP shelf in two days.

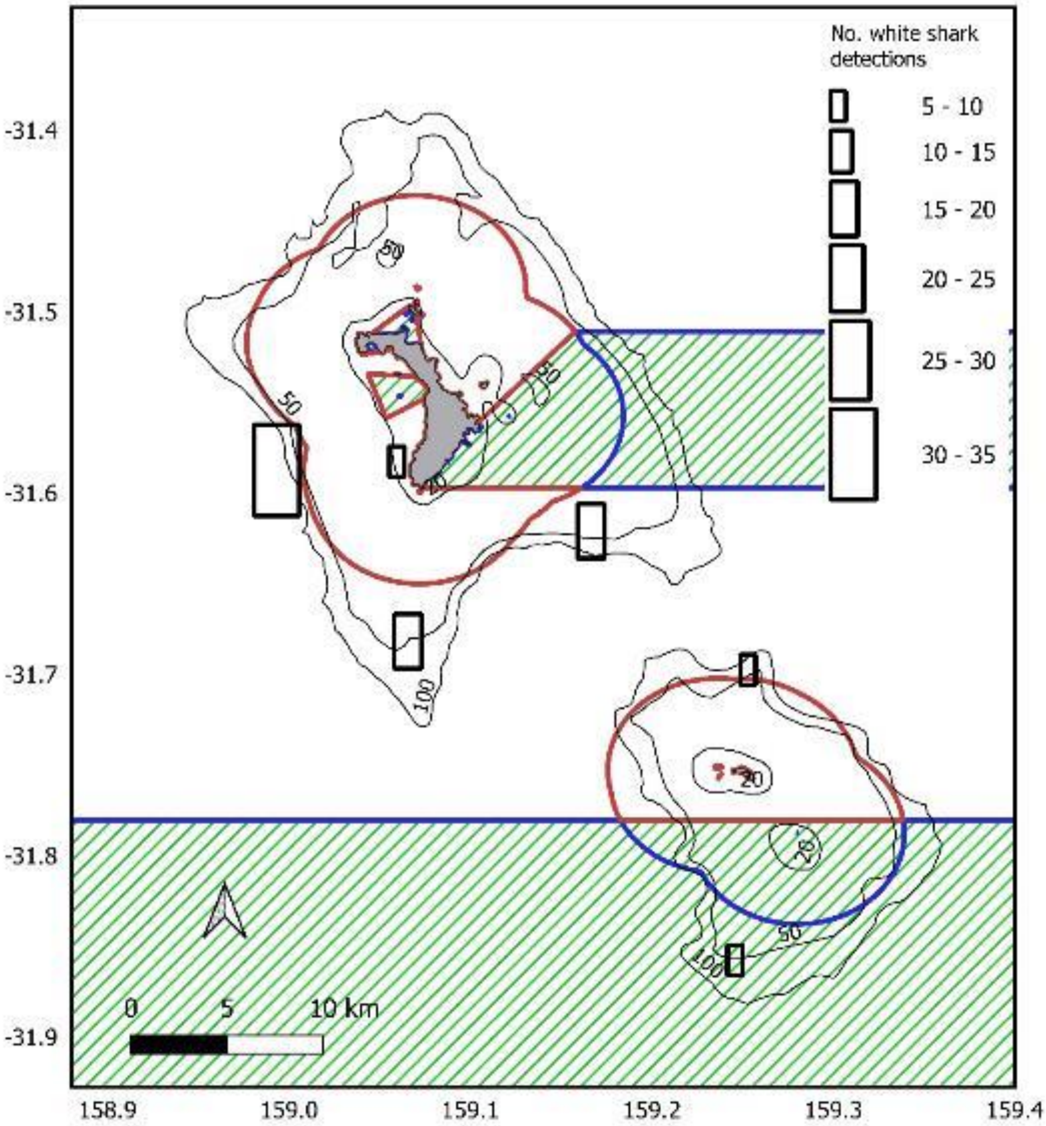


Figure 37. Number of white shark detections at acoustic receiver locations in the marine parks surrounding Lord Howe Island. Size of black rectangles denotes the number of detections. Solid dark red lines show the boundaries of the NSW State Marine Park and blue lines indicate the Commonwealth Marine Park. No-take zones are marked with hashed green lines. Solid black lines with numbers show the 20 m, 50 m and 100 m depth contours.

5.11 Survey of LHI charter and recreational fishers

Currently, the 10 main local fishers interviewed spend similar amounts of their time fishing as part of the artisanal fishery (including charters) and recreationally throughout the year, with slightly more effort spent fishing recreationally (59.5 ± 31.5 SD%) than as part of the fishery (40.5 ± 31.5%), despite high individual variations. There are minor differences in the type of fishing activity between summer and winter seasons, with slightly more time spent recreational fishing in winter than in summer. It is important to note that there are substantial individual variations in activity type within and between seasons. Fishing vessels vary considerably in size (5 – 11.5 m) and tonnage, and take from 1 to 5 people on board during fishing activities (1.4 ± 0.5 SD – 4.6 ± 4.1), i.e. on average, 3 people per trip (including crew). On average, fishers reported a fishing frequency of 2 ± 1.1 SD days a week throughout the year, with 2.4 ± 1.0 days a week in summer months (October – March) versus 1.6 ± 1.2 SD days a week in winter months (April – September).

In terms of shark depredation, the fishers surveyed reported an average of 50.6 ± 26% fish lost to sharks per trip throughout the year. Of the depredated catch, fishers reported retrieving, on average, the head only a third of the time, and nothing the rest of the time, across trips (27.7 ± 22.8% versus 72.2 ± 22.8% of occurrence across trips). Bait loss was also reported to occur, on average, 8.7 ± 3.9 times per trip. Fishing gear loss was also reported and is estimated to cost the fishers $96.9 ± 3.9 per trip.

The area where depredation is reported to occur the most is identified as the LHI shelf (by n = 9 out of 10 fishers), followed closely by the BP shelf (n = 8), then both shelves' edges (n = 7). Locations identified as having low levels of depredation (n = 2) are the near shore and lagoon. The only locations considered depredation-free by all fishers (n = 10) are beyond the 150m depth mark. Thus, near shore and beyond 150 m appear to be locations with limited shark-fisher interactions. All fishers reported that Galapagos sharks are found almost everywhere, although one fisher mentioned that some less fished locations around the LHI shelf might be better for fishing within 100 – 200m. The majority of fishers (n = 9) state that there are considerably less interactions with Galapagos shark at depths beyond 100m and close to none beyond 200 – 250m, i.e. when deep fishing for kingfish or other fish species (e.g. cod, snapper, and blue-eyed trevalla, *Hyperoglyphe antarctica*, respectively). A few fishers (n = 4) reported the presence of Galapagos sharks beyond 200m depths, at 400m and up to 600m, but only occasionally (n = 2) or rarely (n = 2) did they report catching them at such depths. Those that were caught at these depths were larger individuals >2 m. Half of fishers (n = 5) reported bycatching other shark species at depths greater than 200m, such as silky and shortfin mako sharks, or green-eyed spurdogs (*Squalus chloroculus*; unconfirmed species identification – ongoing collaboration with the Australian Museum in Sydney).

All fishers report cleaning fish while in transit, with none cleaning at their fishing locations. Some fishers (n = 2) acknowledged cleaning at specific locations if the weather is rough, such as outside the north or south passages of the lagoon. One fisher acknowledged observing a significant difference between past cleaning practices at certain designated locations and the associated heavy presence of Galapagos sharks in the past. The area close to the base of Mt Gower remains one of these specific cleaning areas, sheltered from the weather, where highly residential sharks are found, even today. As pointed out by some fishers, it indicates this cleaning spot is still in use.

Seventy percent of fishers reported a clear seasonal pattern in Galapagos shark depredation, where it peaked during summer months; although, the level of fishing activity is not constant throughout the year. The remaining thirty percent acknowledged barely fishing in winter months, or not having specific comments about it. Some (30%) also mentioned that depredation is lower April. Half of fishers reported having noticeably less depredation events when targeting pelagic species using trolling and diving lures, whereas 20% reported having more depredation issues whilst pelagic fishing. Another 20% had more issues when fishing for demersal species using rod and line. Only one fisher (10%) reported having more shark bycatch when trolling with lures. Sixty percent of fishers stated that depredation also depended on the fish species hooked, while 30% think that Galapagos sharks depredate regardless of the fish species hooked. Amongst the species reported (for the six fishers who noticed a preference), the kingfish is the preferred species (n = 8), followed by the silver trevally (*Pseudocaranx dentex*) and tuna species (n = 5). Interestingly, these fishers also noted that Galapagos sharks avoid cod species, and other large, bottom-dwelling and spiny species (e.g. bass groper, *Polyprion moeone*). Some fishers suggested that this preference may be a matter, not only of size and spines, but also fish behaviour (large-schooling, mid-water, pelagic species being preferred over non-schooling, deep-water, demersal species).

For shark catch, all fishers estimated catching 7.7 ± 4.2 Galapagos sharks per trip. Seventy percent of fishers declared releasing all the sharks they bycaught, while 30% keep some for local restaurants (on-demand) or for bird photography trips (where only the livers are used, and the remaining meat discarded). Targeted catch of sharks is reported to occur only occasionally during the year. Some fishers (20%) acknowledged having kept all shark bycatch in the past, when the commercial shark fishery was still active. Only one fisher (10%) reported removing hooks from all sharks being released. In terms of reporting, only one fisher (10%) stated that they report all shark interactions, including bycatch, depredation (with notes on the fish proportions retrieved on-board), and the proportion of sharks kept or released – it should be noted at this point only the charter fishers are required to report on catch as a requirement of their State permit and Commonwealth tourism licence. Another (10%) reports only shark bycatch (either kept or released); but not interactions when the sharks snap off the lines or depredate hooked fish. Two fishers (20%) acknowledge reporting as many sharks as they can remember at the end of a trip, but not being able to report exact numbers if there were numerous encounters/interactions across trips.

Fishers reported using a range of methods to try to reduce shark bycatch and depredation. Seven fishers (70%) have adapted their fishing practices and made some change either in the fishing gear or the technique they use to reduce shark depredation. The specific changes made include; using jigs and/or lures instead of bait (n = 4), using an electric winch (n = 1) to reduce fish retrieval times (acknowledging that this is only good for the smaller scale recreational operators in the artisanal fishery, and not the charter vessels due their customers desire to catch fish by rod and line), using electric reels with less hooks on (n = 1) to reduce fish retrieval times and increase likelihood of getting it on-board, limiting the number of lines and/or hooks in the water at any one time (n = 1), using handlines when possible (n = 1), which is not always the safer practice during charter fishing with many people on-board, and driving the boat forward while retrieving hooked fish (n = 1). Three of them (30%) have not implemented any changes and continue to fish with rods and reels, both for their recreational fishing (as they noticed not much benefit from trying other techniques or gear) and their charter fishing activities (as tourists prefer this form of fishing experience). Fishers stated that certain fishing gear was more effective at retrieving fish successfully compared to rod and line. For instance, two fishers (20%) used electric reels for recreational fishing and one of them (10%) targeted kingfish with trolled lures when they are close to the surface. Another more popular technique is to use handlines (60%), but most acknowledged that they only used handlines occasionally, and not when charter fishing, if the kingfish were close to the surface (20%). In the past, some fishers reported using handlines for commercial fishing when the size limit allowed the catch of smaller kingfish <65 cm TL. Interestingly, 20% think that the change in size limit pushed fishers to fish deeper with rod and line, which increased the fight times of fish and gave sharks greater opportunity to depredate them. Half of the fishers surveyed acknowledged using rods and lines in depths lower than 80m for charter fishing, mainly to please their customers, i.e. by giving them the fighting experience they are after, without tiring them with deeper lines to reel. Fishers stated that customers do not like the use of electric reels and winches to experience fishing, nor the use of handlines for large fish they aim to catch because of the risk of heavy line burns. All the respondents believed that the use of rod and line instead of other gear exacerbated the shark depredation issue at LHI.

Overall, the majority of local fishers have already changed some of their fishing approaches to try and reduce the shark interactions. The main methods now adopted in their daily fishing practices include one or a combination of the following techniques; changing locations / moving regularly (70%), using jigs and/or lures (70%), turning off their engine and/or echo sounder (50%), trolling (30%), fishing shallower (<30 m) or near the surface (<10 m) (30%), using electric reels or winches (20%), making a big move or very fast small moves away from depredation incidences (20%), deep fishing (>250 m) (10%), using handlines (10%), using poppers (10%), using bait other than pilchards (10%), driving the boat forward during retrieval to drag hooked fish away from sharks while retrieving it (10%), avoiding feeding sharks by keeping depredated fish in a tub to bring back or dispose in deep water or while in transit (10%), stopping prior to arriving at the fishing spot to gear up and thus maximise fishing time at specific fishing spots before sharks arrive (10%), not visiting the same fishing spots regularly and trying to micro-manage the fishing effort at each location (10%), and using birds as indicators of the presence of targeted fish (10%). The whole cohort of fishers observed that each technique can be effective for a certain amount of time per trip or on a certain number of trips in a year, but they are not universally effective enough to largely reduce depredation rates.

As a result, the fishers stated that they would be willing to try new techniques to reduce depredation, with 50% of them being open and willing to trial new electrical shark deterrent technologies and assist researchers in trialling them at specific sites around LHI. The other half were either non-responsive (30%), thought they would not work or were unsure of the effect on other fish, including targeted species. The lack of education on fish sensory biology could be easily remediated if presented alongside the role and functioning of electrical deterrent technologies in this regard.

All fishers acknowledged encountering predominantly Galapagos sharks during fishing. Although, 80% reported catching mako sharks occasionally, tiger (60%) and silky sharks (50%) seasonally (mainly during summer months), bottom-dwelling and deep-sea shark species (50%) when deep or demersal fishing (Squalus spp., unconfirmed species – likely dogfish and spurdog given the descriptions and preliminary identification with the Australian Museum). Bronze whaler sharks (*Carcharhinus brachyurus*) (or other unidentified whaler species; *Carcharhinus spp.*) (30%) were also commonly caught throughout the year, with white sharks (30%) very occasionally caught (once or twice a year), and thresher sharks (*Alopias spp.*) rarely. Forty percent of fishers declared seeing hammerhead shark species cruising by past their vessels, but not interacting with their fishing activity.

5.12 Lord Howe Island shark catch data 2015 – 2018

Sharks are commonly caught in the marine parks surrounding LHI during charter fishing, as indicated by previous data showing that shark catch represented 25% of the total annual catch between 2004 and 2015 (Figueira & Hunt, 2017). Although Galapagos sharks constitute most of the shark catch, this total catch figure includes other species than Galapagos shark (e.g. *Squalus spp*., and other *Carcharhinus spp.*), as reported by local charter operators (see section 5.11). This bycatch of sharks results from the animals interacting with the bait or live hooked fish (depredation), while operators target kingfish or other species.

Between 2015 and 2018, the total shark catch was reported to be 4441 individuals, with an average of 1114 ± 500 sharks caught each year (Table 7), which remained similar to 10,994 individuals and an average of 916 ± 223 sharks caught each year between 2004 and 2015 (Figueira & Hunt, 2017). However, approximately 98% of sharks were released with only 2% retained each year (Table 7), compared to an average of 3% individuals retained between 2004 and 2015 (Figueira & Hunt, 2017). As previously observed by Figueira & Hunt (2017) between 2004 and 2015, the annual shark catch also varied considerably from year to year between 2015 and 2018, with number doubling in some years (Table 7).

Table 7. Total annual number of sharks caught (Galapagos and other species pooled), with numbers and percentages of shark retained and released, in the Lord Howe Island charter fishery between 2015 and 2018.

Year	Total catch	Retained	Released	% Retained	% Released
2015	1230	52	1178	4.23	95.77
2016	1600	1	1599	0.06	99.40
2017	795	23	772	2.89	97.11
2018	816	7	809	0.86	99.14
TOTAL	**4441**	**83**	**4358**	**1.87**	**98.13**

The sharks caught between 2015 and 2018 had a mean total length of 92.86 ± 61.08 cm (Table 8). Galapagos sharks are typically born at 50-70 cm in size (total length) and mature between 180 – 220 cm (for males and females, respectively) (Wetherbee et al., 1996). Any size range category smaller than 50cm in these data is therefore likely to represent other shark species, such as *Squalus spp.* or other deep-sea species that are smaller in size at birth (<25 cm). As reported in section 5.11, deep-sea *Squalus spp*. are commonly bycaught in deeper waters (>300 m) on the outside shelves of Lord Howe Island and Ball's Pyramid. Some small length values being reported in the data may however be erroneous; e.g. for the n = 153 reported numbers below 20 cm. The numbers represented in Table 8 also suggest, although indirectly, that most of the Galapagos sharks bycaught by the local charter fishery would be immature (<200 cm), with only n = 108 individuals greater than 2 m in total length or more were caught. These larger individuals could also be from other shark species, e.g. silky or mako sharks, as reported in section 5.11.

Table 8. Size range (total length, cm) of the shark catch (Galapagos sharks and other species pooled) between 2015 and 2018.

Count per size range (in cm)				
<50	**50-100**	**100-150**	**150-200**	**200-250**
1541	400	1733	677	108

Between 2015 and 2018, 1516 fishing trips were logged, while 664 of them i.e. 43.8% reported a shark catch. On average 2.93 ± 6.53 sharks were bycaught per trip when including the n = 852 trips with no reported shark catch; whereas, 6.68 ± 8.51 sharks were bycaught per trip, on average, for trips where shark catches were recorded. This could suggest a potential underreporting of shark catches, given that shark bycatch rates estimated during the survey of fishers were 7.7 ± 4.2 Galapagos sharks caught per trip (section 5.11). Furthermore, only one individual was reported to be retained in 2016, which is likely a misrepresentation of the retained shark catch that year. The current missing information on the local population size, structure and connectivity of Galapagos sharks (which ongoing genetic research aims to address – see section 7) further highlights the need to collect more accurate catch estimates of shark catch, possibly down to the species level, if not the genus at least.

5.13 Galapagos shark necropsies

Necropsies were performed on two juvenile Galapagos sharks that were found deceased, respectively at Ned's beach in November 2019 and Old Settlement beach in September 2020. This gave the opportunity to collect important information on the biology of this species, which has received very little research in Australian waters to date. Detailed morphometric measurements were recorded on a NSW DPI Fisheries shark necropsy form (Figure 38a, b) for both sharks. The first shark was a female 83 cm in total length and the second was a female of 73 cm total length. The first individual had a recently consumed mullet in its stomach (Figure 38d) and the second had remains of unidentifiable small fish. The cause of death for the first shark was unknown, whereas the second shark appeared to have died from its stomach lining and an adjacent artery being pierced by a fish spine in the stomach, which may have caused internal haemorrhaging. Both sharks showed no signs of injury from fishing gear (Figure 38c) so this was ruled out as a cause of death. Genetic samples were taken to contribute to an ongoing collaboration with Macquarie University to investigate the population genetics of this species. Samples of stomach contents, muscle tissue and liver were also taken for potential future collaborative studies on diet of Galapagos sharks. Vertebrae were retained for ageing of the sharks. The electrosensory system of the sharks were mapped to provide new information on the sensory biology of the species. The jaw of the shark was donated to the LHI Museum for display.

Figure 38. Necropsy of a juvenile Galapagos shark: (**a**) recording detailed morphometric measurements of the shark on a NSW DPI Fisheries necropsy form; (**b**) checking the mouth for any signs of injury or fishing gear; (**c**) stomach of the shark with protruding piece of fish bone (red circle) which may have caused death; (**d**) stomach contents including a recently consumed mullet in three pieces. Image credits: Justin Gilligan, NSW DPI Marine Parks.

6. Discussion

6.1 Detection patterns

The acoustic receiver array in the marine parks surrounding LHI produced a three-year dataset of Galapagos shark detection data for 28 of the 30 tagged sharks. Tagged Galapagos sharks were present in every month of the three-year research period, and five individuals showed regular and consistent detection patterns for >12 months, providing preliminary evidence that at least some of the Galapagos shark population in the marine parks surrounding LHI is resident year-round. This supports findings from Hawaii, where acoustic telemetry and satellite tracking showed residency of Galapagos sharks around French Frigate Shoals (Meyer et al., 2010) and from Bermuda, where conventional tagging and recapture data indicated high site fidelity (Kohler et al., 1998). Similarly, in the eastern tropical Pacific, Lizardi et al. (2020) found high levels of site fidelity to tagging sites, with >80% of movements being <50 km.

Seasonal variation occurred for the number of detections recorded in the marine parks surrounding LHI, with higher numbers of detections and a greater number of tagged sharks detected in spring and summer months. Fishers surveyed as part of the current research also reported more frequent shark interactions (both bycatch and depredation) in summer. This reflects patterns of catch-per-unit-effort (CPUE) recorded in Hawaii, where CPUE for all size classes was highest in summer (Wetherbee et al., 1996). This may be related to seasonal changes in current patterns and/or greater productivity and prey density during spring and summer. Lizardi et al. (2020) also recorded substantial differences in the detection patterns and movements of Galapagos sharks during wet versus dry seasons in the eastern tropical Pacific.

There was a notable variation in the detection patterns of individual sharks, with some having consistent and very high numbers of detections at the same acoustic receiver location, whereas others displayed much more sporadic detection patterns across multiple acoustic receiver locations. This high level of variation in movement and behaviour has been documented in other shark species, where some individuals show resident behaviour and others can be more transient (Holmes et al., 2014; Bonnin et al., 2019; McMillan et al., 2019). Due to the relatively low coverage of acoustic receivers across the entire area of the marine parks surrounding LHI in the current study (distances between receivers were between 5 and 15 km), as well as their small detection range (400 – 600 m), we are unable to determine whether gaps in detection patterns for some individuals represent migration away from the marine parks surrounding LHI for periods of time, or that they were simply outside of the detection range but still within the marine parks. The loss of some acoustic receivers and data due to acoustic release malfunctions also limits the conclusions we can draw, especially for year three of the study (January 2020 – January 2021) where only three acoustic receivers were retrieved. Two out of the thirty Galapagos sharks originally tagged in January 2018 were never detected, which could be due to either the sharks leaving the marine parks surrounding LHI altogether, residing in deeper water or being caught and killed by predators or fishers. These sharks were released in good condition after tagging, so it is unlikely that they died as a result of the capture and tagging process, however it is a possibility.

6.2 Dispersal distances of Galapagos sharks

The small dispersal distances (up to 36.3 km) for all but one of the Galapagos sharks from their tagging locations in the current study were relatively similar to other studies that have investigated Galapagos shark movement patterns, for example in the eastern tropical Pacific where sharks typically moved less than 50 km from the original location (Lizardi et al., 2020), and in the North Atlantic near Bermuda, where Galapagos sharks displayed movements <100 km (Kohler et al., 1998). However, one shark in the current study did move substantially further, from the North BP Shelf where it was tagged, to near Port Stephens in mainland NSW, a distance of 654 km. Records of Galapagos sharks in mainland Australian waters are rare (Last & Stevens, 2009) and this would be the first documented movement of a Galapagos shark from LHI to mainland Australia. Yet, there is a chance that these detections resulted instead from the shark being predated upon by a larger shark (e.g. a white shark or a tiger shark, which co-occur at LHI and are known to feed on smaller sharks (Ebert et al., 2021)) at another location, which then carried the tag in its digestive system for a period of time. Past research which involved feeding acoustic tags to bull sharks *Carcharhinus leucas* found that they remained in the digestive system for 24 hours to 34 days (mean 6.8 days) (Brunnschweiler, 2009). Long-distance movements have only rarely been reported in the literature for Galapagos sharks, including one shark which travelled 2958 km from the

Revillagigedo Islands to the Galapagos Islands in the eastern tropical Pacific (Lizardi et al., 2020) and one which moved 2859 km south-east from Bermuda (Kohler et al., 1998). Although, the spatial coverage of the acoustic receiver array deployed at multiple island groups in the eastern tropical Pacific and the scope for shark recaptures in the North Atlantic was much greater than the current study, which only deployed a low number of acoustic receivers across a small area. It is therefore possible that more of the tagged Galapagos sharks in the current study did move much further, but this was not detected. There may be a small percentage of the Galapagos shark population at LHI that travels longer distances, which is seen in other shark species and is known as 'partial migration' (Chapman et al., 2011; 2012; Papastamatiou et al., 2013; Espinoza et al., 2016). Yet, previous genetic research does not support this, because the LHI population was found to be genetically distinct from the population at Elizabeth and Middleton Reefs (van Herwerden et al., 2008), which are ~170 km and ~230 km away from LHI, respectively. Deploying additional acoustic receivers at other island groups across the Tasman Sea, such as at Elizabeth and Middleton Reef and Norfolk Island, would provide an opportunity to detect these larger scale movements, as would satellite tagging of a small number of Galapagos sharks. The distance travelled per day by tagged Galapagos sharks in the marine parks surrounding LHI (4.9 – 12.2 km) was less than that recorded for this species around Salas y Gómez in the South Pacific Ocean, which ranged from 17.5 – 45 km per day (Morales et al., 2021). However, the latter study used satellite tracking as opposed to acoustic telemetry. Deploying satellite tags on Galapagos sharks in the marine parks surrounding LHI would provide a unique opportunity to collect more detailed information about the horizontal and vertical movements and behaviour of this species.

6.3 Residency index of sharks

The residency index of the tagged Galapagos sharks in the marine parks surrounding LHI acoustic receiver array was relatively low (<0.1) for most individuals, apart from six sharks which were resident at the south LHI fish cleaning area and north Ball's Pyramid acoustic receiver locations. The low residency values for most sharks likely resulted in part from the small number of acoustic receivers that were deployed at distances of 5 – 15 km apart, and the fact that a declining number of receivers were recovered throughout the three years of the study due to equipment malfunctions. Additionally, the Galapagos sharks with lower residency index values may have been moving to different areas of the marine parks surrounding LHI outside the detection range of the acoustic receivers, when they were following shifting current patterns and the distribution of their prey species. Current patterns and prey density have been shown to exert a strong influence on the movement patterns of sharks at other oceanic islands, including hammerheads and Galapagos sharks at the Galapagos islands (Hearn et al., 2010; Ketchum et al., 2014). The Galapagos sharks with higher residency index values may have been responding to favourable environmental conditions and prey abundance in these locations. Alternatively, the presence of consistent food in the form of hooked fish and/or fish waste discarded from fishing vessels, may have led to the higher residency of sharks in these locations, especially for the four tagged sharks which all had higher residency at the south LHI fish cleaning area. A number of fishers use this sheltered location to clean fish and dispose of waste, especially during rougher weather, as reported in section 5.11. This is confirmed by the high kernel density values for this location and the fact that raw VMS data showed this site was visited by at least one vessel on 20% of days where fishing occurred.

6.4 Space use of Galapagos sharks and overlap with fishing activity

Similar to the results for detection patterns and residency index, the space use areas of the tagged Galapagos sharks in the marine parks surrounding LHI were highly variable, with some sharks showing small KUD areas centred around 1 – 2 acoustic receivers whereas others had much larger KUD areas covering extensive portions of the LHI and BP shelves. However, the fact that KUD areas could only be calculated for nine of the 28 tagged sharks suggests that the rest may have had relatively smaller home ranges or that they spent larger portions of time in areas where there was either no acoustic receivers present or where the receivers were not able to be retrieved, for example in the northwest LHI shelf location. Yet, the range in KUD areas recorded for the nine Galapagos sharks in this study was still relatively similar to that of grey reef (*Carcharhinus amblyrhynchos*) and silvertip sharks (*Carcharhinus albimarginatus*) in the British Indian Ocean Territory (Carlisle et al., 2019) and tiger sharks in the Galapagos islands (Acuña-Marrero et al., 2017). There was no influence of season, sex or total length on the space use of Galapagos sharks in the present study, another similarity to tiger sharks in the Galapagos islands (Acuña-Marrero et al., 2017). Galapagos shark core KUD areas overlapped with areas of higher fishing activity in specific locations around the marine parks surrounding LHI, especially near shelf edges and where fish waste was disposed, although it is important to acknowledge that the VMS data availability from December 2019 to January 2021 was limited to only two vessels and that the COVID-19 pandemic resulted in substantially lower levels of fishing activity from March – October 2020. Nonetheless, this spatial overlap of shark activity and fishing, combined with a higher number of detections at acoustic receiver locations where greater fishing activity occurred and the previously discussed higher residency of sharks at a site where fish waste was disposed, suggests that sharks may be attracted to areas where fishing occurs regularly in the marine parks surrounding LHI, due to the availability of a food source. The presence of bait, injured fish struggling on a hook, and released fish, all represent a comparatively energy-efficient food source for sharks compared to pursuing prey naturally (Mitchell et al., 2018b). The regular occurrence of fishing and fish waste disposal in specific 'hotspots' (such as the south LHI fish cleaning area which vessels visited on 20% of days) may therefore be leading to the formation of behavioural associations in the Galapagos sharks, where they associate a particular sensory cue (likely either the boat engine noise and/or fish oil and blood, as this would propagate the furthest in the pelagic environment) with the availability of an energetically efficient food source (Lieberman, 1990). Such associations have been recorded in multiple species in captive settings (Clark, 1959; Guttridge & Brown, 2014; Vila Pouca & Brown, 2018) and research on wild lemon sharks recorded short-term changes in movement and activity patterns and the development of anticipatory behaviour prior to feeding, in just 11 days (Heinrich et al., 2021). Ecotourism provisioning of bull sharks in Fiji and whitetip reef sharks *Triaenodon obesus* in the Coral Sea has also been observed to alter movement patterns and behaviour (Fitzpatrick et al., 2011; Brunnschweiler & Barnett, 2013). Furthermore, a recent study in the Ningaloo Marine Park recorded decreasing arrival and feeding times of sharks over a six-day period when bait was provided in the same location, (Mitchell et al., 2020), with this behavioural mechanism thought to be driving higher shark depredation rates at sites of concentrated fishing activity (Mitchell et al., 2018a).

The overlap between fishing activity and Galapagos shark movements at shelf edges also likely occurred because fishers in the marine parks surrounding LHI mainly target yellowtail kingfish in waters 50-100 m depth (mean depth from VMS data was 81.8 m), which is similar to the preferred depth range of Galapagos sharks observed in this study (Figure 26) and in previous research (Wetherbee et al., 1996; Meyer et al., 2010; Madigan et al., 2020). Additionally, Galapagos sharks and yellowtail kingfish can co-occur in some locations where they feed on the same baitfish prey species (LHI charter fishers, pers. comm.; Mitchell & Camilieri-Asch, pers. obs.) and Galapagos sharks may also prey on kingfish directly. In this case, there is a direct competition for resources between the Galapagos sharks and fishers, as is also seen for other pelagic species, such as where silky sharks and oceanic whitetip sharks (*Carcharhinus longimanus*) co-occur with and prey on tuna species, which are simultaneously targeted by commercial fishers (Tolotti et al., 2020; Young & Carlson, 2020). Larger scale studies have recently documented a high degree of overlap between longline fishing activity and a range of pelagic shark species (Queiroz et al., 2019), further demonstrating this overlap and potential competition for resources. The shelf edges where we recorded highest overlap in the marine parks surrounding LHI may support higher productivity due to current patterns bringing nutrient rich water from depth via upwelling (Coelho & Santos, 2003). Seamount upwelling is a phenomenon known to occur at other isolated seamounts (Genin & Dower, 2007; White et al., 2007), so it may be a key factor driving productivity in the waters surrounding LHI. Indeed, high chlorophyll-*a* concentrations have been recorded at Lord Howe Island and other seamounts and islands in the Tasman Sea (Bradford & Roberts, 1978). Similar overlaps between fishing activity and shark habitat use have been documented near other oceanographic features, including frontal systems and eddies (Queiroz et al., 2012; Gaube et al., 2018) and seamounts are known to be hotspots of pelagic shark abundance (Litvinov, 2007; Stevenson et al., 2007; Morato et al., 2010). Fishers and Galapagos sharks are therefore both likely to favour these areas of higher current strength and productivity along the shelf edges in the marine parks surrounding LHI, bringing them into contact with each other and causing this high level of overlap. The fact that shark KUD areas did not overlap with some of the fishing activity hotspots at the northern tip of LHI and close to BP is likely because they are shallower areas <20 m, which are less favourable habitat for Galapagos sharks.

6.5 Influence of fishing activity and environmental variables on shark detection rates

The level of fishing activity was also an important driver of the number of shark detections, as quantified by GAMMs. The positive linear relationship between fishing activity and number of shark detections further reinforces the possibility that Galapagos sharks were associating fishing vessels with a food source in the marine parks surrounding LHI. Mitchell et al. (2018a) found a similar relationship, where shark depredation rates were higher in areas where greater fishing activity occurred, and where vessels were fishing in close proximity. Bathymetric complexity also exerted an important influence on shark detections, with higher detections occurring over more complex seabed. Limbaugh (1963) also reported that Galapagos sharks were more abundant over rugged seabeds, and topographic features have been identified as an important driver of pelagic shark abundance at a range of locations around the world (Worm et al., 2013; Bouchet, 2015; Bouchet et al., 2020). Structural complexity of the seabed was also found to support greater abundances of yellowtail kingfish in the marine parks surrounding LHI (Rees et al., 2018), possibly because these areas support greater prey assemblages, which may attract Galapagos sharks as they are known to feed on the same prey as the yellowtail kingfish (LHI charter fishers, pers. comm.; Mitchell & Camilieri-Asch, pers. obs.) and the sharks may also prey on yellowtail kingfish directly. Baited camera surveys have found higher shark abundance in reef habitats with greater benthic relief (Sherman et al., 2020). Season also exerted an important influence on Galapagos shark detection rates, with the highest number of detections in summer and spring, similar to trends recorded in Hawaii from both cage diving sightings logs (Meyer et al., 2009) and longline fishing surveys (Wetherbee et al., 1996). Higher number of detections may have occurred in summer in the marine parks surrounding LHI due to greater levels of fishing activity attracting sharks to those acoustic receiver locations which had higher levels of fishing nearby. Indeed, fishers interviewed in the survey as part of this project reported higher numbers of shark interactions in summer months. Additionally, changes in current patterns, productivity and water temperature may have created more favourable environmental conditions for Galapagos sharks at the acoustic receiver locations, compared to other seasons where the sharks may have had to travel further to find prey, perhaps in deeper water or further offshore. Considering that all the sharks tagged in this study were juvenile, these seasonal differences were not linked to migratory behaviour driven by reproductive cycles, corroborating the reported movements off Hawaii (Wetherbee et al., 1996; Meyer et al., 2009).

6.6 Depth patterns

Depth distributions of Galapagos sharks in the current study were relatively similar, although shallower, to those recorded from satellite tags around Ascension Island in the South Atlantic Ocean and Salas y Gomez in the southeast Pacific Ocean, where mean depth was 53 m (Madigan et al., 2020) and 60 m (Morales et al., 2021), respectively, compared to 25.2 m in the current study. Madigan et al. (2020) also reported that Galapagos sharks spent 85% of their time at depths <85 m, and in Hawaii, satellite tagged Galapagos sharks predominantly occupied depths <100 m, although they did make occasional dives >200 m and up to 680 m (Meyer et al., 2010). Catch data from the Hawaii Cooperative Shark Research and Control Program indicates similar vertical habitat use patterns, with the majority of sharks being caught between 30 and 50 m (Wetherbee et al., 1996; Papastamatiou et al., 2006). The overall depth distribution data for Galapagos sharks in the marine parks surrounding LHI was, however, skewed by the high number of detections for the three individuals which had high residency at the south LHI fish cleaning area, where the depth was only 10-20 m. Also, the maximum depth of acoustic receivers was 75 m, so it was not possible to detect deeper dives of Galapagos sharks beyond the shelf, which may occur.

Diel period had a significant effect on the depth distribution of Galapagos sharks in the marine parks surrounding LHI, with shallower depths occupied at night compared to during the day. This indicates that the Galapagos sharks undertook diel vertical migration. This vertical movement behaviour has also been documented for Galapagos sharks in the South Atlantic (Madigan et al., 2020), blue sharks (*Prionace glauca*) off eastern Australia (Stevens et al., 2010), bigeye thresher sharks (*Alopias superciliosus*) in the Southern California Bight (Aalbers et al., 2021), and tiger sharks off northeast Brazil (Afonso & Hazin, 2015). Diel vertical movement may be driven by the movement of prey assemblages including small pelagic fish and squid into shallower depths at night (Watanabe et al., 2006; Musyl et al., 2011; Madigan et al., 2020). However, diel vertical movements were more variable for Galapagos sharks tagged in the southeast Pacific, where some occupied deeper water during the day vs night and others the opposite (Morales et al., 2021), and oceanic whitetip sharks and silky sharks displayed reverse diel vertical migration in the South Atlantic (Madigan et al., 2020). Localised differences in prey species movements and environmental conditions may therefore be important for driving variation in Galapagos shark diel vertical movements between locations. Lunar illumination could also have an influence, because the higher level of light intensity and deeper penetration of light around the full moon could facilitate visual hunting at greater depths. Indeed, Vianna et al. (2013) found that grey reef sharks moved into deeper water during the full moon, with school sharks (*Galeorhinus galeus*) and porbeagle sharks (*Lamna nasus*) also displaying a similar pattern (West & Stevens, 2001; Saunders et al., 2011).

Season also had a significant effect on the depth of Galapagos sharks in the present study, with shallowest mean depth occurring in austral autumn and the deepest mean depth in spring. This seasonal change in depth distribution may reflect differences in foraging driven by changes in productivity and the associated movement of prey species (Bessudo et al., 2011), as well as behavioural thermoregulation (Campana et al., 2011; Andrzejaczek et al., 2018), because the Galapagos sharks may have moved into deeper water in spring as surface waters warmed. Changes to the thermocline depth may also have an influence on these observed seasonal changes in depth distribution, as has been recorded for other pelagic shark species (Madigan et al., 2020). The sex of the Galapagos sharks in the marine parks surrounding LHI had no significant effect on their depth distribution, unlike in Hawaii where mature males and females were segregated by depth, with a mean capture depth of 60.2 m for males and 34.2 m for females (Wetherbee et al., 1996; Papastamatiou et al., 2006). The fact that all Galapagos sharks tagged in the marine parks surrounding LHI were juveniles may therefore explain this lack of sexual segregation, as one theorised role of sexual segregation in sharks is to reduce the injury and harassment of mature females by males during aggressive courtship and attempted mating behaviour (Sims, 2005). There was no evidence of differences in depth being driven by total length in the present study, potentially also because all sharks tagged were juveniles within a relatively small size range (116 – 155 cm). Size segregation has been reported for Galapagos sharks in Hawaii, with juveniles being caught at greater depths than adults (Wetherbee et al., 1996). At Clipperton Island and the Revillagigedo Islands in the eastern tropical Pacific, juveniles have been documented to be restricted to very shallow areas (Limbaugh, 1963; Kato & Carvallo, 1967). Hammerschlag and Fallows (2005) also noted high abundance of juveniles in a shallow (<20 m) lagoon at Bassas da India atoll in the southwest Indian Ocean, suggesting it may be a nursery area. Some small juvenile Galapagos sharks occur in the lagoon at LHI, however, it does not appear to be a key nursery area with high juvenile density like Bassas da India and the Revillagigedo Islands. Some Galapagos sharks smaller than 1 m total length were observed during fishing in offshore waters of the marine parks surrounding LHI ranging from 30 – 100 m deep, including one neonate shark <70 cm with a still visible umbilical scar (Mitchell & Camilieri-Asch, pers. obs.). Larger adult sharks >2 m in length were not encountered, however, and they are only occasionally reported by local fishers, raising the question as to whether they spend a greater proportion of their time in deeper (>100 m) offshore waters, leave the marine parks surrounding LHI to migrate to other areas, or are not attracted to baited fishing gear.

The Galapagos sharks tagged in the present study made occasional rapid vertical movements, which may be related to feeding events or when they were trying to evade predators. Rapid vertical movements may also indicate Galapagos sharks following hooked fish upwards as they are retrieved to a fishing vessel. ‘V’ shaped or ‘yo-yo’ dives shown in Figure 34 have also been documented in Galapagos sharks in the South Atlantic (Madigan et al., 2020), as well as a range of other pelagic shark species and are hypothesised to represent foraging behaviour or possible behavioural thermoregulation (Nakamura et al., 2011; Coffey et al., 2017; Andrzejaczek et al., 2018). Deploying satellite tags on a small subset of Galapagos sharks in the marine parks surrounding LHI could provide further insights into their vertical movements and behaviour, as these tags would provide complementary movement data including high-resolution sea temperature, depth and light level data.

6.7 Temperature data

There was a clear seasonal pattern in the water temperature values recorded from tagged Galapagos sharks, although temperature differences of up to 2 – 3 °C at the same time of year did occur, which were likely caused by the sharks changing depth, especially if they were moving through the thermocline. Varying current patterns could also influence these short-term changes in temperature. Overall, the majority of detections for Galapagos sharks in the marine parks surrounding LHI occurred at temperatures between 19 and 21 °C, which is notably lower than other locations, such as in the eastern tropical Pacific, where the peak number of detections was between 25 and 30 °C (Lizardi et al., 2020). Additionally, satellite tagging data from Hawaii indicated that Galapagos sharks spent the vast majority of time in temperatures >24 °C, although they did make occasional short dives into deeper water where temperatures reached as low as 7 °C (Meyer et al., 2010). These records indicate the large temperature range this species can tolerate. Galapagos sharks tagged at Ascension Island occupied a similar temperature range to those in the present study, ranging from 16 – 27.5 °C, although these sharks spent the majority of time at temperatures between 23 °C and 27 °C (Madigan et al., 2020). The waters of the marine parks surrounding LHI may therefore be close to the lower limit of the species' optimal temperature range, which may also explain the higher numbers of detections recorded in spring and summer months.

6.8 Mitigating negative shark-fisher interactions

The combination of shark movement and fishing vessel activity data, along with the broader contextual information collected from fishers through the survey, provides an holistic assessment of the negative shark-fisher interactions that are occurring in the marine parks surrounding LHI. It is clear that shark-fisher interactions are happening regularly and lead to negative consequences for fishers (lost bait, target fish and fishing gear, costing on average $97 per trip) and sharks (retained hooks and retaliatory killing by fishers) in the marine parks surrounding LHI. This conflict is reported to have increased in the last 5-10 years, with up to 50% of catch lost to depredation on some trips and high levels of bait loss (on average 8.7 baits lost per trip). Such continued loss of revenue and customer satisfaction will be detrimental to charter fishing businesses. The risk of increased mortality of Galapagos sharks due to continued high bycatch levels (~6 sharks caught per trip and 1114 sharks caught per year on average, between 2015 and 2018, although this is likely underestimated due to non-reporting of shark catch by some fishers) and deliberate killing by fishers represents a threat to this population, because it may be genetically isolated and thus at greater risk of decline from anthropogenic pressures. A separate study involving collaborators at Macquarie University is currently underway to use population genetics approaches to estimate the effective population size of Galapagos sharks in the marine parks surrounding LHI and the level of connectivity with other populations at Elizabeth and Middleton Reefs, Norfolk Island and New Zealand. This will help to identify how vulnerable the Galapagos shark population at LHI is to fishing, climate change and other threats, based on its current size and level of genetic isolation.

In light of the negative impacts caused by shark-fisher interactions in the marine parks surrounding LHI, there is a pressing need to identify potential methods for reducing these interactions. Spatial data on the movement patterns of sharks and how they overlap with fishing vessel activity can be applied using a fisher-driven approach, to reduce negative interactions with sharks. Our results demonstrate that there are a number of key hotspot areas where shark movements and fishing activity overlap, primarily at key shelf-edge locations throughout the marine parks surrounding LHI, as well as where fish waste is discarded. Additionally, we have identified certain depth ranges and times of year when shark presence and activity is higher. By identifying these areas and times at which shark interactions may be more likely to occur, it is now possible for fishers to make more informed decisions about where they fish, to avoid areas where the chance of shark interactions is higher. This approach could be further improved by satellite tagging a small number of Galapagos sharks in the marine parks surrounding LHI, to collect complementary data on shark movements, which could be coupled with VMS data to increase the spatial and temporal resolution of these hotspot locations. This could also be combined with improved data collection on the spatial occurrence of shark interactions by fishers, by building extra fields into their electronic catch reporting system.

Reducing the regularity at which these hotspot sites are fished may help to minimise the reinforcement of behavioural associations in Galapagos sharks. Spreading the fishing activity across a broader range of sites and reducing the spatial predictability, which is a key driver of depredation (Tixier et al., 2021) will therefore help to reduce the occurrence of depredation for fishers. Certain sensory cues, such as the noise of outboard engines, are likely to be important for the formation of behavioural associations in sharks (Mitchell et al., 2018b), therefore reducing the intensity and propagation of these cues may provide some reduction in shark interactions. This could involve turning off the engine and echosounder after arriving at a fishing spot. Some fishers in the marine parks surrounding LHI report already trying this with limited success, and fishers in the Marianas Islands noted much lower shark depredation rates when using smaller boats with different engine types (e.g. zodiacs) and kayaks (Iwane & Leong, 2020). The cleaning of fish and discarding of fish waste is likely to also be having an important influence on the behaviour of Galapagos sharks in the marine parks surrounding LHI by driving behavioural associations with vessels. This is evident from the higher residency and smaller KUD areas of sharks tagged at the south LHI fish cleaning area. One approach for mitigating this behaviour could be the recent installation of fish waste bins on Lord Howe Island, and a composting facility, which provide fishers with the option of retaining their fish waste for disposal on land, rather than at sea. Fish waste is being utilised as a premium compost in other parts of Australia (see examples: https://ocean2earth.com.au/no-fish-waste/; https://vfa.vic.gov.au/aquaculture/composting-fish-waste-from-the-aquaculture-industry), thus could be an option for LHI as well.

Behavioural avoidance strategies have been identified by Tixier et al. (2021) to be one of the most effective methods for reducing depredation to date, across many diverse fisheries. Gilman et al. (2007) also reported that many fishers actively avoid known environmental conditions that are likely to result in higher shark interaction rates, including certain temperature ranges and oceanographic features like fronts and currents. In the tuna and billfish longline fishery off eastern Australia, commercial fishers report lower shark bycatch when setting lines on the colder sides of fronts (Gilman et al., 2007). Increasing our understanding of the complex environmental conditions, current patterns, vertical water column structure and oceanographic features around the marine parks surrounding LHI, and how Galapagos sharks interact with them, which could be identified through satellite tagging, may therefore help fishers to make such informed choices in the future. A majority of fishers interviewed as part of the survey in the current study also identified moving between sites frequently to be one of the more effective approaches to minimise depredation, because it reduces the chances of sharks locating their vessel. This technique was also regularly used by fishers suffering depredation from pelagic sharks in the Marianas Islands (Iwane & Leong, 2020), and was reported to be partially successful (53% effectiveness) in reducing depredation across a diverse range of net and line fishers suffering depredation from both sharks and cetaceans, as long as the vessel moved a large enough distance to prevent the predators following (Tixier et al., 2021). Using a combination of strategies involving more targeted fishing in locations with environmental conditions less favourable to Galapagos sharks, frequent moving between sites and avoiding repetitive fishing in the same locations could therefore provide some immediate reduction in shark interaction rates in the marine parks surrounding LHI.

In addition to modifying spatial fishing patterns, the survey conducted as part of this project, along with other discussions with local recreational and charter fishers, have identified a range of other methods which could be adopted (and are already being used in some cases) to reduce negative shark interactions. Specifically, changing to electric reels or handlines was suggested by many fishers, to enable hooked fish to be brought to the boat more quickly, especially when targeting larger yellowtail kingfish. Historically, charter fishing operators used handlines to catch smaller kingfish, which were easy to haul up to the boat, but the introduction of the 65 cm minimum landing size led to the targeting of larger kingfish in deeper water using rod and reel, increasing fight times of the fish and giving Galapagos sharks greater opportunity to depredate them. However, whilst electric reels and handlines might reduce fight times, they are less favoured by charter fishing customers due to potential injury from line burn in the case of handlines and reduced fisher satisfaction when using electric reels. Nonetheless, having the option to use different gear types allows fishers to make a more informed choice. Fishing with lures and jigs instead of bait has been identified by some fishers to be an effective way of reducing shark bycatch through direct hooking, although depredation can still occur. If targeting yellowtail kingfish, the use of trolling as opposed to static bottom fishing can result in lower shark bycatch and depredation. Interestingly, some fishers in the Mariana Islands report using distraction as a method of reducing depredation, where they will throw fish scraps or other objects like rocks into the water to distract the shark whilst a fish is being reeled in to the boat (Iwane & Leong, 2020). Research by Gilman et al. (2007) across 12 different commercial longline fisheries, noted gear modifications that can have some benefit in reducing shark bycatch and depredation, including the use of fish bait instead of squid, switching to different hook sizes or types (circle vs 'J' hooks) and changes to set depths to avoid optimal depth ranges for certain shark species. In the marine parks surrounding LHI, anecdotal reports from fishers suggest that shark interactions occur most frequently in mid-shelf depths between 50-100 m, with sharks rarely occurring at depths beyond 150 m. Indeed, VMS indicated the mean depth of fishing was 81.8 m. Some fishing was <30m when weather was bad or when targeting reef species and some >200m when targeting deep-water species like bar cod (*Epinephelus ergastularius)* and blue eye trevalla (*Hyperoglyphe antarctica*). Also, whilst a number of VMS datapoints had depths >200 m (Figure 21), the fishers may have been targeting pelagic fish in midwater depths in these locations, so the actual depth of fishing would have been less than the bottom depth value. Some local fishers have changed their practices to only fish in deeper water where they know they will encounter fewer sharks. However, this approach may be limited for charter fishing operators whose customers prefer to target yellowtail kingfish in the 50-100m range. Indeed, the strong focus of the charter fishing operators on this one target species is likely to be an important factor driving the frequent occurrence of interactions with sharks, because the yellowtail kingfish are known to co-occur, likely because they both target pelagic baitfish prey and larger sharks will also prey on kingfish directly. Diversifying the fishing strategies to target more species at different depth ranges may thus be another approach that could reduce the frequency of shark interactions. Indeed, fishers surveyed in this project reported lower occurrence of depredation on spiny demersal fish species, such as cods, compared to pelagic species like yellowtail kingfish and trevally.

Another approach for reducing shark interactions in the marine parks surrounding LHI could be trialling of shark deterrents. Electrical deterrents which overstimulate the electrosensory system of sharks hold the most promise (Gilman et al., 2008; Mitchell et al., 2018b), as they will only effect sharks and not the target teleost species, which do not possess this sensory system (Hart & Collin, 2015). Small electrical deterrents have shown success in reducing the frequency with which sandbar sharks (*Carcharhinus plumbeus*) and spiny dogfish (*Squalus acanthias*) took bait in laboratory trials (Howard et al., 2018). Additionally, the recently developed OceanGuardian FISH01 (https://ocean-guardian.com/products/fish01) and the FishTek Marine SharkGuard (https://www.fishtekmarine.com/sharkguard/) are two electrical deterrents that have been specifically designed to reduce shark depredation and bycatch, respectively. The FISH01 creates a strong electrical field that is projected to cover an area of up to 15 m deep by 6 m wide under the vessel, to deter sharks from depredating hooked fish as they are retrieved to the vessel. The SharkGuard creates a small-scale electrical field (40 cm in diameter) around the hook to directly deter sharks from taking the bait and hooked fish and has shown promising results during initial trials in Mediterranean longline fisheries, reducing blue shark bycatch (https://www.youtube.com/watch?v=EhgoHnR605w). This deterrent is also cost effective and easier to mount on fishing gear, making it practical to use for fishers. These devices could both be trialled in the marine parks surrounding LHI to assess their effectiveness at reducing both shark bycatch and depredation and fishers surveyed as part of this project have indicated they would support such a trial.

7. Research contribution and project outputs

This research is the first to describe and characterise the movement patterns of Galapagos sharks within the marine parks surrounding LHI, to assess the level of interactions between these sharks and fishers, and thus the first to monitor their movements and habitat use with an acoustic telemetry array at this location. To build on the main objectives of this research, we developed further collaborations to make use of the samples we collected during fieldtrips, including;

- Genetic samples (fin clips): these samples were collected opportunistically during the tagging of Galapagos sharks at LHI, while others were sourced from new collaborators at the Auckland Museum (NZ), New Caledonia, Norfolk Island. This genetic research is allowing us to investigate other important research questions relating to the management of Galapagos sharks in the marine parks surrounding LHI, such as the local population size, its genetic structure and its level of connectivity to other populations across the Tasman Sea. For example, a Galapagos shark previously tagged by gamefishers at Elizabeth Reef (~160 km north of LHI) in 2018 was recaptured at LHI in the same year, suggesting that there may be connectivity between these two areas. Genetic techniques will enable us to investigate this possibility further. This research is being undertaken through a PhD project focusing on these genetic analyses, to fill current knowledge gaps (van Herwerden et al., 2008; Kyne et al., 2019). PhD candidate Ms. Emma Petrolo is co-supervised by lead investigators Drs. Mitchell and Camilieri-Asch, in collaboration with Prof Adam Stow, who hosts the research at Macquarie University

- Shark parasites: external parasites were opportunistically collected whilst tagging Galapagos sharks, as part of this project. These have been sent to experts at the Australian Museum in Sydney and the Queensland Museum in Brisbane, for identification and lodging into specimen collections. One species is a new record for LHI.

- Deep-sea shark species: anecdotal reports of deep-sea shark catch was discussed whilst working with local charter fishing operators. A whole specimen was donated to us and NSW DPI Marine Parks upon request. The specimen was sent to the Australian Museum in Sydney for formal identification, which is still ongoing. Formally identifying the species commonly bycaught by fishers is of outmost importance for local management, as some of these deep-sea *Squalus spp.* are listed as endangered by the IUCN (Walker & Rochowski, 2019).

The results of the research conducted to date, as part of the Galapagos shark telemetry research and these other opportunistic collaborations, have been/will be presented through a variety of formats, to communicate findings with different audiences and stakeholders. These include:

Two journal manuscripts, currently in preparation, submitted for publication in 2021:

1. Mitchell JD, Camilieri-Asch V, Gudge S, Gilligan J, Woods C, Jaine FRA, Peddemors V and Langlois T. Investigating Galapagos shark interactions with fishing vessels in the marine parks surrounding Lord Howe Island: an integrated approach using acoustic telemetry and vessel monitoring system data. *Nature Scientific Reports* (in preparation)

   This manuscript uses acoustic telemetry data from tagged Galapagos sharks alongside VMS data for fishing vessels to investigate the extent to which shark movements and fishing activity overlap, with a view to designing adaptive measures to help fishers reduce negative interactions with sharks (i.e. depredation).

2. Mitchell JD, Camilieri-Asch V, Gudge S, Gilligan J, Woods C, Jaine FRA, Peddemors

V and Langlois T. Movement ecology and behaviour of Galapagos sharks (*Carcharhinus galapagensis*) in the marine parks surrouding Lord Howe Island. *Marine Ecology Progress Series* (in preparation)

This manuscript describes the movement and behavioural ecology of Galapagos sharks in more detail, including their residency patterns, home range size, distribution across the marine parks and vertical movements.

Additional manuscripts are expected to be published in 2022-2023:

3. Camilieri-Asch V, Mitchell JD, Gudge S, Woods C and Cutmore S. Ectoderm parasites found on Galapagos sharks in the marine parks surrounding Lord Howe Island. *International Journal for Parasitology*

This manuscript describes the five species of parasites observed and commonly found on Galapagos shark specimens caught during tagging within the marine parks surrounding LHI. It particularly highlights the presence of one species, which was never documented in LHI waters before. The specimens of this species have already been sent to the Australian Museum in Sydney and the Queensland Museum in Brisbane, for their collection.

4. Mitchell JD, Camilieri-Asch V and Nogueira de Moraes L. Perceptions of Lord Howe Island residents towards Galapagos sharks. *Marine Policy*

This manuscript combines the results from; 1) the survey collecting information from LHI charter and recreational fishers, 2) the currently ongoing online survey of all local adult residents (including fishers) about the social perceptions towards Galapagos sharks at LHI, and 3) the regular meetings with fishers held during each fieldtrip between 2018 – 2022.

5. Petrolo E, Mitchell JD, Camilieri-Asch V, Boomer J, Brown C and Stow A. Assessing the genetic connectivity and population composition of Galapagos sharks in the Tasman Sea region. *Frontiers in Marine Science*

This manuscript aims to investigate population connectivity across the wider southwest Pacific region (including New Zealand, the Kermadec Islands, Norfolk Island, Elizabeth and Middleton Reefs, and New Caledonia) using single nucleotide polymorphisms (SNPs), to assess how genetically isolated the LHI population is.

6. Petrolo E, Mitchell JD, Camilieri-Asch V, Boomer J, Brown C and Stow A. Effective population size of Galapagos sharks in the marine parks surrounding Lord Howe Island: implications for management. *PloS One*

This manuscript aims to estimate the population size of Galapagos sharks at LHI using a type of analysis that calculates the level of kinship between pairs of samples from juvenile sharks, and thus extrapolates the subsequent adult population. It will also present modelling analyses based of these results, and the previous manuscript, to identify the vulnerability of the LHI population to current and future threats (e.g. fishing efforts, climate change etc.).

One oral presentation at the Oceania Chondrichthyan Society (OCS) virtual conference in November 2020:

- Mitchell JD, Camilieri-Asch V, Gilligan J, Gudge S, Woods C, Jaine FRA, Peddemors V and Langlois TJ. Galapagos shark movements, residency and interactions with fishing vessels in the marine parks surrounding Lord Howe Island, Australia.

Two presentations at the World Fisheries Congress in September 2021:

- A poster presentation:
  Mitchell JD, Camilieri-Asch V, Jaine FRA, Gilligan J, Gudge S, Woods C, Peddemors V and Langlois TJ. An integrative approach to understand and manage negative interactions between Galapagos sharks and charter fishers in the marine parks surrounding Lord Howe Island, a World Heritage site.

- An oral presentation:
  Mitchell JD, Camilieri-Asch V, Jaine FRA, Gilligan J, Gudge S, Woods C, Peddemors V and Langlois TJ. Galapagos shark movement ecology and interactions with fishing vessels in the Lord Howe Island Marine Parks

One-page communication articles published bi-annually in January 2018 – 2021, i.e. before and after each field work campaign:

- in the LHI local newspaper – 'The Signal' (1-4 issues per year)
- in the newsletter from the NSW DPI Lord Howe Island – 'Marine Parks News'

Annual oral presentations/lectures at the LHI Museum in January 2018 – 2021:

- delivered at the end of each field work campaign, attended both by locals and tourists
- to inform the local community and tourists about the research and latest results

Annual meetings with members of the LHI Board and community in 2018 – 2021:

- meetings with local community members, fishers and other stakeholders on LHI have been held to hear people's views on the Galapagos shark population at LHI and how it affects tourism activity

A mini-documentary produced by Andre Rerekura and Anoushka Freedman in 2018:

- focusing on the Lord Howe Island Galapagos shark research
- shared online in early 2021 on the NSW DPI SharkSmart social media page; https://www.instagram.com/tv/CLs7on4hrbx/?igshid=pchkp0xn6t67

Annual posts on social media to promote the research and all partners and collaborators, i.e. before each fieldtrip campaign

Regular communication of tagging and recapture data to the NSW Gamefish Tagging Program in 2018 – 2021

An ongoing online survey of the local adult community of LHI:

- to determine perceptions of local residents towards Galapagos sharks via online and paper-based survey forms
- So far, *n* = 20 forms have been completed out of 250 targeted residents.

Press releases for local, regional (NSW) and national media agencies in 2021-2022

Interim and final reports to IMOS Animal Tracking Facility (ATF) in 2021

Information leaflets distributed to charter operators and the LHI Tourism Association in 2022

Articles in recreational fishing magazines from 2022

Ongoing attempts to procure additional funding through various international funding bodies have been made since 2017, however these have been unsuccessful because the issue and research was seen as too localised.

8. Recommendations

This research has generated important insights into the movement patterns of Galapagos sharks in the marine parks surrounding LHI and how they overlap with fishing activity. This information is complemented by the detailed information collected from fishers through the survey, which identified specific measures being used to reduce shark interactions. Based on this combined data and information generated by the project, a set of best-practice guidelines have been created for fishers, with the goal of reducing negative shark-fisher interactions. These guidelines will be produced in a concise, eye-catching brochure (with supporting photos and diagrams), as well as a small explanatory video (that will be distributed via social media) and these education/interpretation tools will be promoted via the local Marine Park News, the LHI Signal, social media avenues (DPI, Parks Australia) and via direct distribution to local fishers and residents. These guidelines include:

Areas and times of overlap

- Avoid or reduce the time spent in hotspot areas where shark presence has been found to overlap with fishing activity, as identified in Figure 39. Sharks have learnt to associate the presence of vessels in these areas with the availability of food in the form of bait and hooked fish, therefore avoiding these areas will help to break this behaviour in the sharks and reduce the frequency of negative interactions occurring between fishers and sharks.

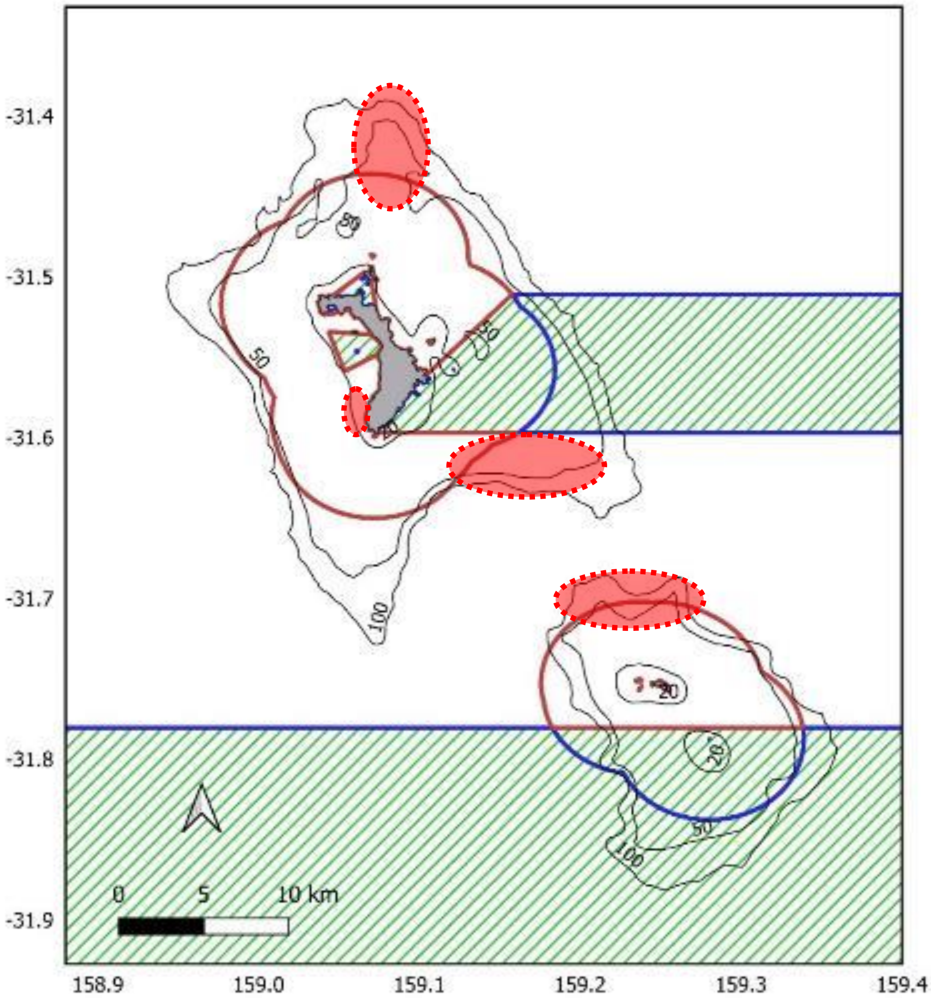


Figure 39: Hotspot areas of overlap between shark presence and fishing activity, as identified previously (Figure 23) by the combination of acoustic telemetry data for tagged Galapagos sharks and Vessel Monitoring System (VMS) data from charter fishing vessels. Ovals with light red dotted lines indicate hotspots areas which should be avoided by fishers if possible, to reduce the likelihood of encountering sharks. Solid dark red lines show the boundaries of the NSW State Marine Park and blue lines indicate the Commonwealth Marine Park. No-take zones are marked with hashed green lines. Solid black lines with numbers show the 20 m, 50 m and 100 m depth contours.

Choice of fishing locations

- Regularly move location when fishing (e.g. every 30 minutes)
- Prepare all fishing gear (e.g. get rods out and bait hooks) before arriving at your fishing location, to maximise fishing time before sharks arrive
- Fish in different areas on consecutive days to avoid attracting sharks to the same locations on consecutive days
- Move on to another location as soon as a shark takes a fish off your hook
- Consider fishing in either shallower (less than 30 metres) or deeper (greater than 100 metres) water, because Galapagos sharks occur most frequently between 50 metres and 100 metres

Cleaning fish

- Dispose of fish products (including bait and waste) on shore at the composting system at the waste management facility because any fish waste entering the water will encourage sharks to associate fish (food) with vessels
- If you must clean fish and dispose of fish waste at sea, do it only when moving / not stationary
- If you must clean fish at sea, do it at a different location on each trip
- If you need to clean fish at sea, do it well away from the island to avoid attracting sharks closer to areas where people swim/snorkel/dive/surf

Choice of fishing gear

- Use handlines if fishing in shallow water (less than 30 metres) or electric reels/hydraulic winches if fishing in deeper water (greater than 100 metres)
- Charter fishing operators can educate customers about the shark depredation issue and provide customers with the choice of using handlines, winches and/or electric reels to decrease the probability of depredation occurring
- Use jigs or lures instead of baited hooks
- Use trolling to target pelagic species as sharks will have less time to take hooked fish near the surface
- Turn off the echosounder when you arrive at a fishing location to reduce the likelihood of attracting sharks
- Consider purchasing shark deterrent devices, and keep up with new technologies as they are released

Target species

- If targeting kingfish, search for and target schools near the surface as they will be easier to bring up to the boat quickly, avoiding losses to sharks
- Consider targeting bottom dwelling species (e.g. snapper, cod) which are less likely to be taken by sharks than kingfish and other pelagic fish
- Diversify the species you target to spread fishing effort across a wider group of species

Data collection

- All participants in the artisanal fishery should report their catch, including shark interactions, using a logbook system. This will help to address current uncertainties in the level of catch of target species and the frequency of shark interactions
- Improvements should be made to existing reporting requirements associated with shark interactions (including both shark bycatch as well as loss of bait and hooked fish due to depredation), to enable temporal and spatial trends to be identified
- Onboard fisheries observers should be used to achieve regular coverage of charter fishing operators' trips, to ground truth data collected via the electronic logbook system

Island-wide response

- Residents and authorities may wish to explore the possibility of a commercially viable option to convert fish waste into compost e.g. Ocean2earth on south coast of NSW (ocean2earth.com.au)
- Authorities may wish to collaborate to install fish cleaning tables and fish waste bins near the boat ramp/jetty to reduce fish waste dumping at sea and increase the likelihood of residents using these facilities

9. Future research directions

To build on these guidelines, the authors recommend a range of approaches to further enhance data collection opportunities and develop more effective measures to reduce shark-fisher conflict at Lord Howe Island.

9.1 Continuing the deployment of acoustic receivers

To collect long-term data on the movement patterns of the tagged Galapagos sharks, which still have approximately six years of battery life left in the acoustic tags, we recommend continuing the deployment and maintenance of the acoustic receiver array in the marine parks surrounding LHI. The continuation of the acoustic receiver array and active collaboration with the Integrated Marine Observing System's (IMOS, www.imos.org.au) Animal Tracking Facility would also increase opportunities to collect data on the presence and marine park use of other tagged marine megafauna species monitored by the IMOS infrastructure network, including over 200 tiger sharks and 590 white sharks tagged between NSW coastal waters and Norfolk Island in recent years. The recent detection of the tagged Galapagos shark in coastal NSW further highlights the potential for investigating connectivity between these regions by maintaining the array in the marine parks surrounding LHI. The array will also provide opportunities for future research on other species, such as yellowtail kingfish, which are of high importance to the local fishery, endemic doubleheader wrasse or the threatened black cod, as well as multi-species ecosystem-wide approaches.

The team is currently seeking funding to continue this effort. At a minimum, it is recommended that six new VEMCO VR2AR units (Innovasea, Canada) are purchased for deployment in the marine parks surrounding LHI, as they have a built-in acoustic release system that is highly reliable compared to the previous acoustic releases used and would therefore ensure successful retrieval of acoustic receivers in deeper sections of the marine parks surrounding LHI. These units would cost approximately $5,500 each. These acoustic receivers should be deployed at or near some of the previously used deep-water sites in the marine parks, for consistency. This would include both those in regularly fished areas and NTZs (Figure 40).

Deploying acoustic receivers at Elizabeth and Middleton Reefs could also generate information on whether the Galapagos shark population in the marine parks surrounding LHI is connected to that found at these reefs and thus would provide insights into the larger-scale movements of this species. Additionally, transmitters should be deployed on other species of management interest to take full advantage of the monitoring infrastructure in place and active collaborations developed as part of this project. For example, the team has sought additional funding for concurrent projects on yellowtail kingfish, but without success to date.

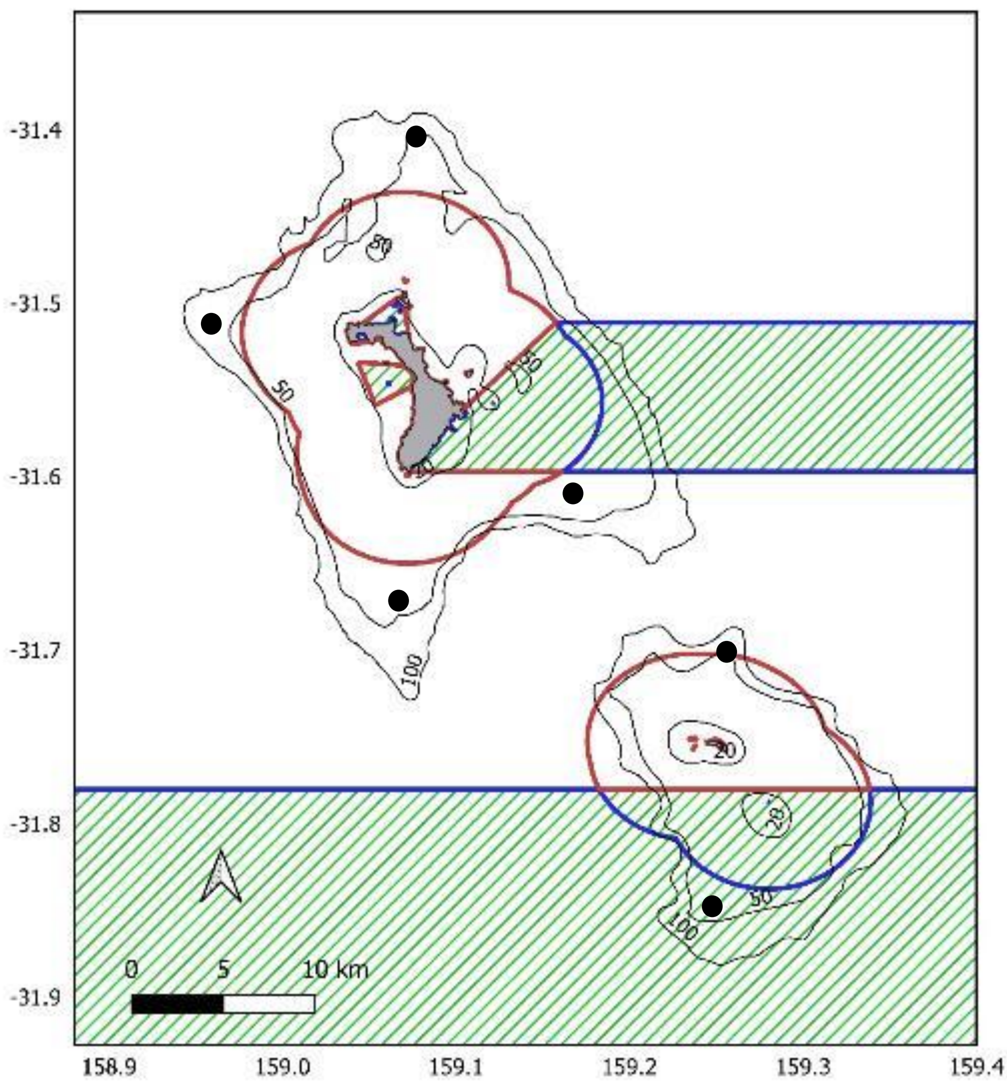


Figure 40. Priority sites for deployment of deep-water VR2AR acoustic receivers. Black points indicate proposed deep-water locations for acoustic receiver deployments. Solid dark red lines show the boundaries of the NSW State Marine Park and blue lines indicate the Commonwealth Marine Park. No-take zones are marked with hashed green lines. Solid black lines with numbers show the 20 m, 50 m and 100 m depth contours.

9.2 Testing two new electrical deterrent devices

Another important aspect of the research which could provide an applied solution would be to trial newly available shark deterrent devices specifically designed to reduce shark interactions with fishing gear, such as the OceanGuardian FISH01 and FishTek Marine SharkGuard, to assess whether they are effective at reducing Galapagos shark bycatch and depredation in the marine parks surrounding LHI. Each device would be tested using four treatments. Baited treatments would assess sharks' behavioural response to the deterrent in the presence of an attractant (bait). Unbaited treatments (controls) would determine the response of the sharks to the device itself, because Galapagos sharks are often attracted to novel objects and boats.

Footage would be analysed in EventMeasure software, with the following metrics recorded:

1) number of sharks in the field of view and their size;
2) number and direction of approaches (2 – 4 m from antennae);
3) number of interactions (<2 m);
4) minimum distance between the antennae and individual sharks;
5) number of bites on the bait bag;
6) specific behavioural responses (reaction distance and type)

Generalised Linear Mixed Models would be used to assess the influence of each treatment on the metrics above, following Huveneers et al. (2018), Abrantes et al. (2020) and Thiele et al. (2020). To test whether existing levels of shark-fisher interactions influence the effectiveness of each device, each treatment would be conducted across 21 locations characterised by different levels fishing activity (Figure 41); seven locations in each of the high fishing zones (identified using Vessel Monitoring System data), seven in low fishing zones and seven in NTZs, where no fishing occurs, to create a balanced sampling design. To avoid habituation, treatments would be selected randomly and would not be conducted consecutively at each location. Each treatment would last for 15 minutes. In total, 84 trials would be run (4 treatments across 21 locations) for each device, over eight days. The equipment setups for both devices are detailed in Figure 42.

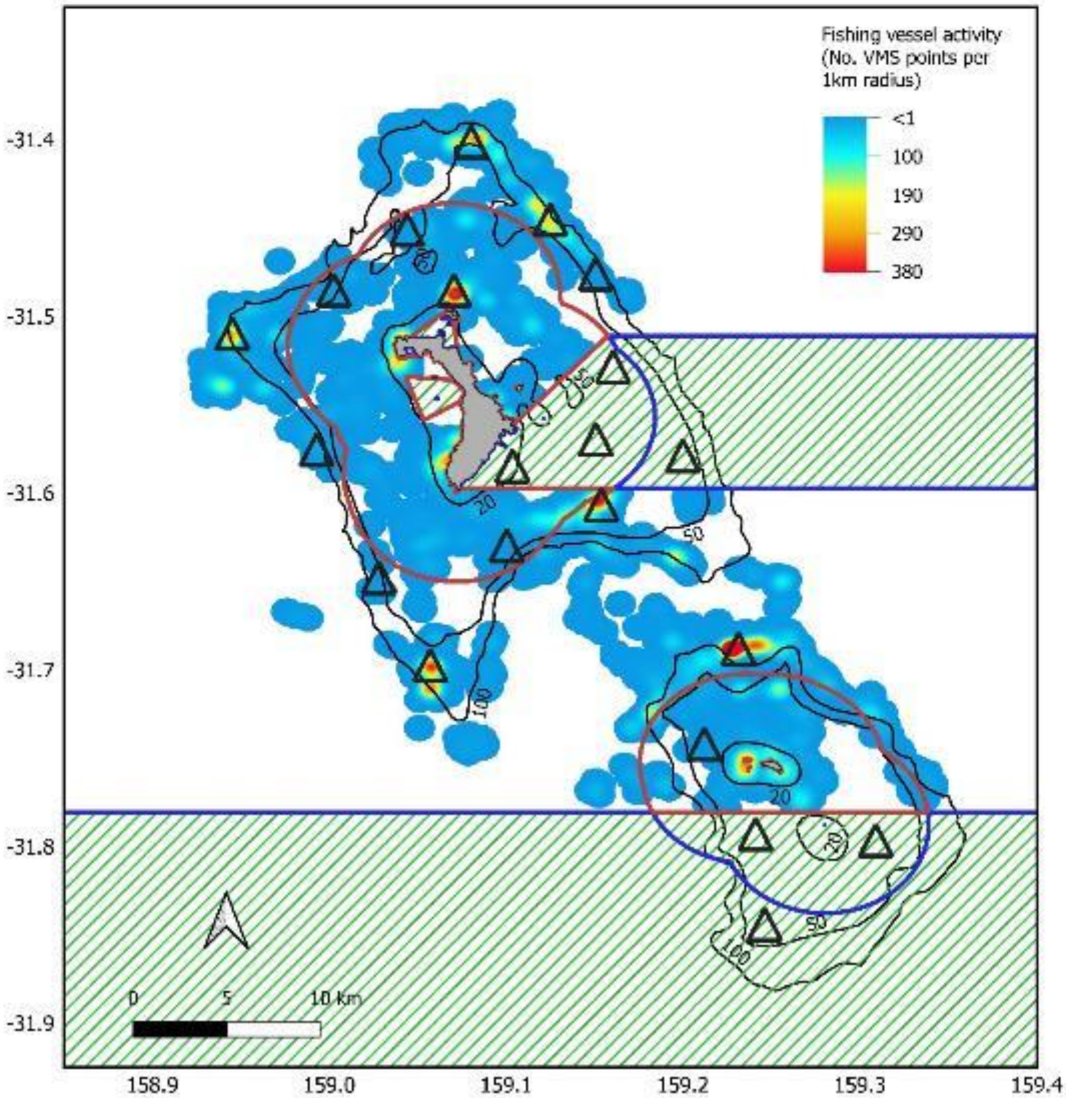
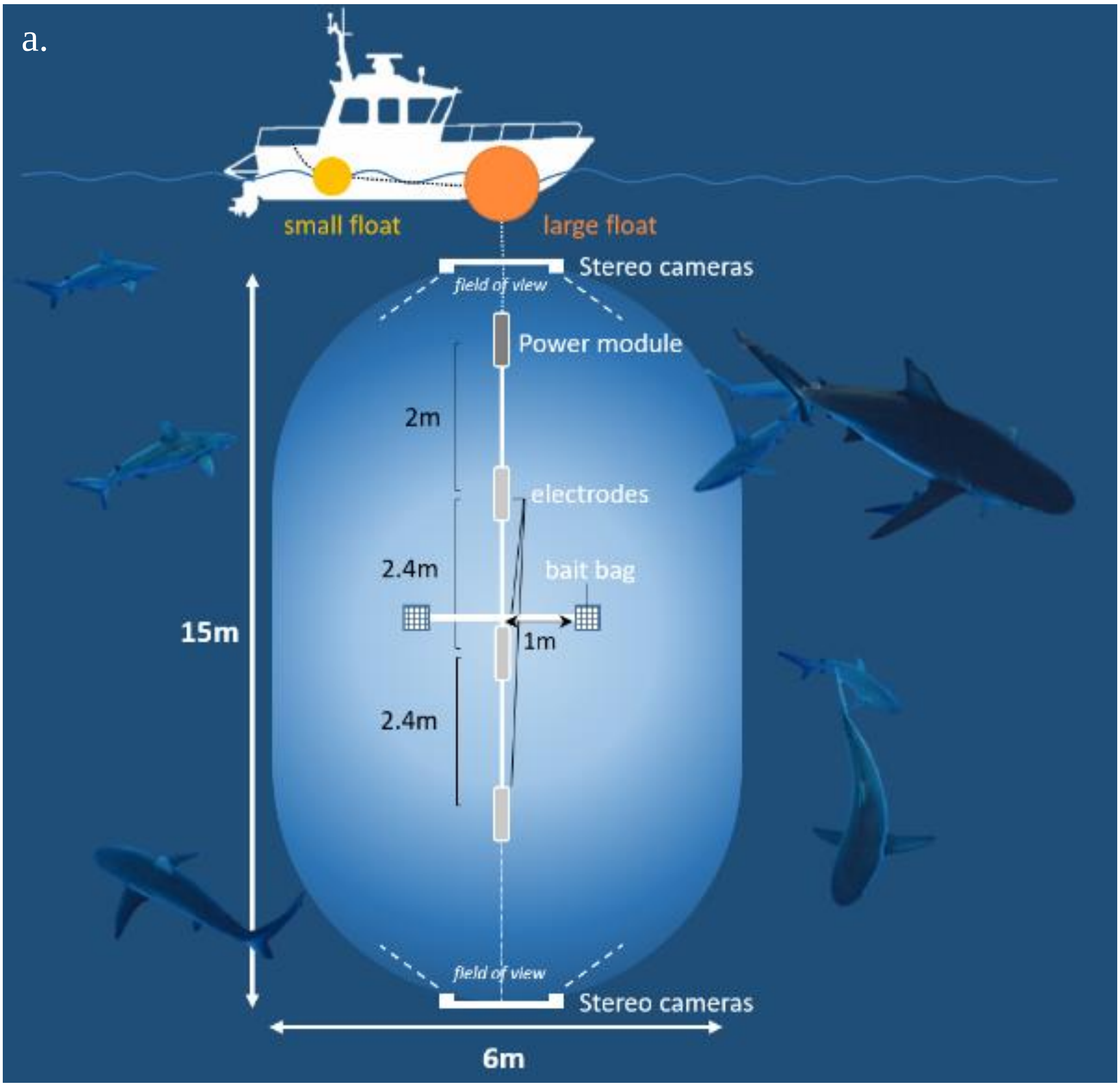


Figure 41. Map of locations for shark deterrent testing in the marine parks surrounding LHI. Black triangles indicate the proposed locations where both deterrents would be tested, covering sites with high (red areas on heatmap), low (blue areas) and no (white areas) fishing activity. Solid dark red lines show the boundaries of the NSW State Marine Park and blue lines indicate the Commonwealth Marine Park. No-take zones are marked with hashed green lines. Solid black lines with numbers show the 20 m, 50 m and 100 m depth contours.



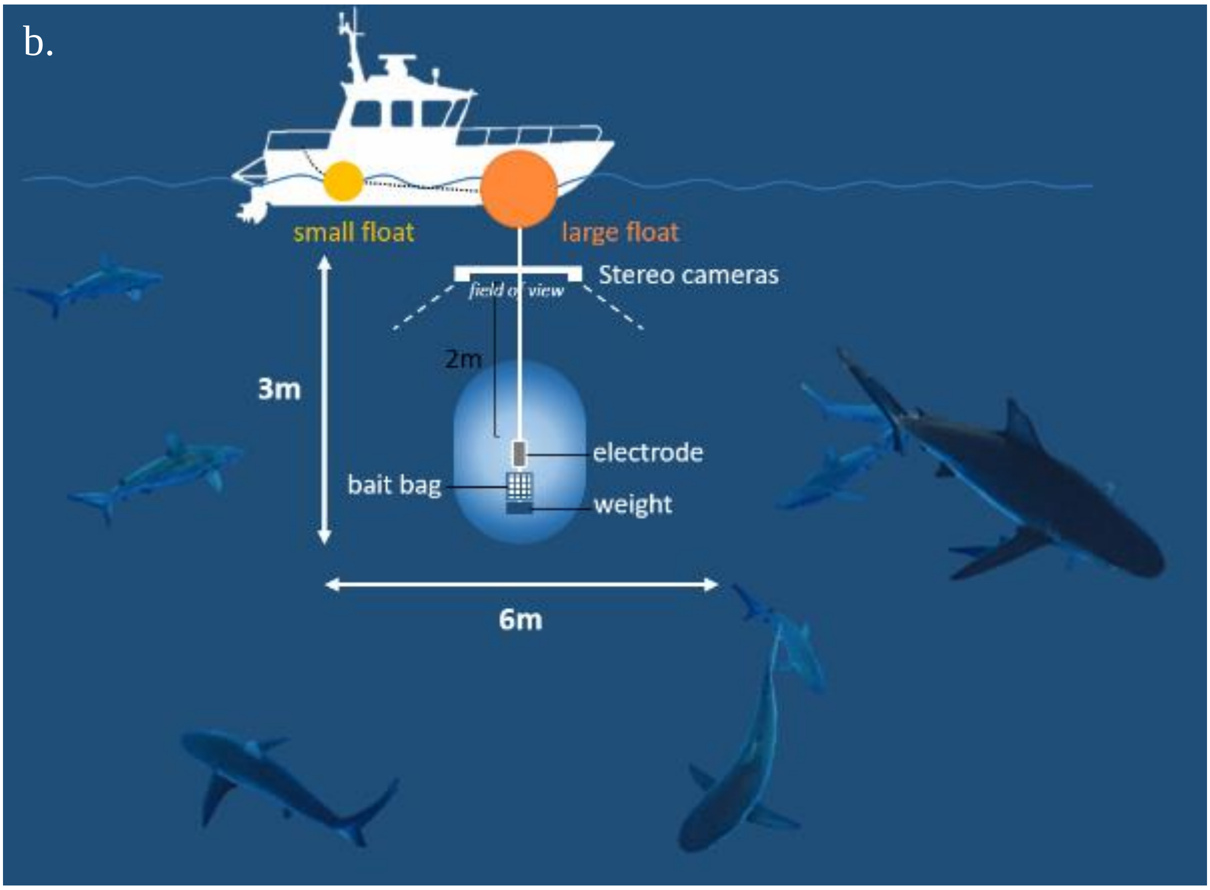


Figure 42. Equipment setups for testing shark deterrents. (**a**) the OceanGuardian FISH01 shark deterrent; (**b**) the FISHTEK Marine SharkGuard deterrent. Lighter blue areas represent the electrical field of each deterrent device.

It is anticipated that this project would cost approximately $80,000 across three years, based on the travel, operating and equipment costs involved. If found to be effective, these devices could provide a vital reduction in the occurrence of negative shark-fisher interactions, benefitting fishers and sharks alike. The results of these trials would also have significance to many other fisheries around the world where similar shark-fisher conflicts are occurring.

9.3 Generating complementary movement data using satellite tags

Satellite tagging of up to 20 Galapagos sharks with pop-up archival transmitting tag (PAT tag, also known as a PSAT) (Wildlife Computers; ~$5000 each) to collect comprehensive horizontal and vertical movement data on this species, similar to recent studies in the eastern tropical Pacific (Lizardi et al., 2020), South Pacific (Morales et al., 2021) and South Atlantic (Madigan et al., 2020). The detection of one of the tagged Galapagos sharks in coastal NSW has demonstrated that these sharks can move great distances, so satellite tagging would provide a unique opportunity to build on this and determine how regularly Galapagos sharks undertake such movements. The high-resolution movement and behavioural data generated by satellite tags would also provide increased potential to identify where and when fishers are most likely to interact with Galapagos sharks, for example under specific environmental conditions and depth ranges.

Acknowledgements

The project team would like to extend their thanks to Parks Australia (Australian Marine Parks) for generously providing the funding to undertake this research. Justin Gilligan, Sallyann Gudge and Caitlin Woods from the NSW DPI Marine Parks office on LHI are thanked for their significant support in the project, including for vessel use, deployment of acoustic receivers, logistical and administrative support and advice on the management of the NSW State Marine Park. We express our thanks to the IMOS Animal Tracking Facility based at the Sydney Institute of Marine Science for providing acoustic receivers, acoustic releases, extensive technical support and data management services. Charter fishing operators Chad Wilson, Jack Shick and Wes Young are thanked for their assistance with shark tagging and we acknowledge the support of all local fishers on Lord Howe Island, who took part in the survey, providing important information on shark interactions. Thank you to Emma Henry, Britt Anderson, Dom Anderson, Lauren Taafe, Sophie Powell, Andrew Walsh for field support. Melissa Walsh and Leonardo Nogueira de Moraes assisted with the design of the online survey of LHI residents' perceptions of Galapagos sharks. We extend our gratitude to Ian Hutton from the Lord Howe Island Museum for providing historical information on shark interactions. The Lord Howe Island Board provided resources and access to the Lord Howe Island research station for fieldwork. Thank you to Justin Gilligan, Fabrice Jaine and Ian Hutton for photography during the research, and to Andre Rerekura and Anoushka Freedman for videography. Environmental data was sourced from Australia's Integrated Marine Observing System (IMOS) – IMOS is enabled by the National Collaborative Research Infrastructure Strategy (NCRIS). It is operated by a consortium of institutions as an unincorporated joint venture, with the University of Tasmania as Lead Agent. The Government of South Australia, Department for Environment and Water and Charlie Huveneers from Flinders University are acknowledged for providing data on the tagged white shark detected at LHI, and for funding the original tagging of this shark in South Australia. Paul Butcher from NSW DPI Fisheries is thanked for providing data on the tagged tiger shark detected.

Permits

Parks Australia (Australian Marine Parks):

- Permit to conduct scientific research in the Lord Howe Marine Park (permit no. PA2018-00060-1)
- Permit for access to biological resources from Commonwealth areas (permit no. AU-COM2018-390)

New South Wales Department of Primary Industries, Marine Parks:

- Application for a Marine Parks permit for Lord Howe Island Marine Park (permit no. LHIMP/R/17005/31112017)

NSW DPI Animal Care and Ethics Committee:

- Animal research authority (permit no. ACEC REF 17/03 – LHIMP)

The University of Western Australia Human Ethics Committee:

- Human ethics approval – Online survey to understand perceptions towards Galapagos sharks amongst the Lord Howe Island community (approval no. RA/4/20/6218)

References

Aalbers, S.A., Wang, M., Villafana, C., & Sepulveda, C.A. (2021). Bigeye thresher shark *Alopias superciliosus* movements and post-release survivorship following capture on linked buoy gear. *Fisheries Research,* 236, 105857.

Abrantes, K., Barnett, A., Soetaert, M., Kyne, P.M., Laird, A., Seymour, J., Squire, L., Wueringer, B.E., Huveneers C. (2020). Can sawfish bycatch within the Northern Prawn Fishery be mitigated using an electric field? FRDC Project Report No 2016-058. Adelaide, Flinders University.

Acuña-Marrero, D., Smith, A.N., Hammerschlag, N., Hearn, A., Anderson, M.J., Calich, H., Pawley, M.D., Fischer, C., & Salinas-de-León, P. (2017). Residency and movement patterns of an apex predatory shark (*Galeocerdo cuvier*) at the Galapagos Marine Reserve. *PloS One,* 12, e0183669.

Afonso, A.S., & Hazin, F.H. (2015). Vertical movement patterns and ontogenetic niche expansion in the tiger shark, *Galeocerdo cuvier*. *PloS One,* 10, e0116720.

Agafonkin, V., & Thieurmel, B. (2017). *Suncalc: Compute Sun Position, Sunlight Phases, Moon Position and Lunar Phase. R package version 0.4*. URL: https://rdrr.io/cran/suncalc/

Akaike, H. (1974). A new look at statistical model identification. *IEEE Transactions on Automatic Control,* 19, 716–723.

Andrzejaczek, S., Gleiss, A.C., Jordan, L.K., Pattiaratchi, C.B., Howey, L.A., Brooks, E.J., & Meekan, M.G. (2018). Temperature and the vertical movements of oceanic whitetip sharks, *Carcharhinus longimanus*. *Scientific reports,* 8, 1-12.

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software,* 67, 1-48.

Beggs, H., Majewski, C., Griffin, R., Verein, P., Sakov, X., Huang, L., Garde, L., & Tingwell, C. (2013). *Report to GHRSST14 from Australia - Bluelink and IMOS.* Paper presented at the Proceedings of the GHRSST XIV Science Team Meeting, Woods Hole.

Bessudo, S., Soler, G.A., Klimley, P.A., Ketchum, J., Arauz, R., Hearn, A., Guzmán, A., & Calmettes, B. (2011). Vertical and horizontal movements of the scalloped hammerhead shark (*Sphyrna lewini*) around Malpelo and Cocos Islands (Tropical Eastern Pacific) using satellite telemetry. *Boletín de Investigaciones Marinas y Costeras-INVEMAR,* 40, 91-106.

Bonnin, L., Robbins, W.D., Boussarie, G., Kiszka, J.J., Dagorn, L., Mouillot, D., & Vigliola, L. (2019). Repeated long-range migrations of adult males in a common Indo-Pacific reef shark. *Coral Reefs,* 38, 1121-1132.

Bouchet, P. (2015). *Submarine topography as a predictor of mobile predator hotspots: Relevance and applications to conservation planning in the pelagic ocean.* PhD Thesis, Perth, University of Western Australia.

Bouchet, P., Letessier, T.B., Caley, M.J., Nichol, S.L., Hemmi, J.M., & Meeuwig, J.J. (2020). Submerged carbonate banks aggregate pelagic megafauna in offshore tropical Australia. *Frontiers in Marine Science,* 7, 530.

Braccini, M., Rensing, K., Langlois, T., & McAuley, R. (2017). Acoustic monitoring reveals the broad-scale movements of commercially important sharks. *Marine Ecology Progress Series,* 577, 121-129.

Bradford, J., & Roberts, P. (1978). Distribution of reactive phosphorus and plankton in relation to upwelling and surface circulation around New Zealand. *New Zealand Journal of Marine and Freshwater Research,* 12, 1-15.

Brooke, B.P., Woodroffe, C.D., Linklater, M., McArthur, M., Nichol, S.L., Jones, B.G., Kennedy, D.M., Buchanan, C., Spinoccia, M., Mleczko, R., Cortese, A., & Sexton, A. (2010). *Geomorphology of the Lord Howe Island shelf and Submarine Volcano: SS06-2008 Post-Survey Report Record 2010/26*. Canberra, Geoscience Australia.

Bruce, B., Harasti, D., Lee, K., Gallen, C., & Bradford, R. (2019). Broad-scale movements of juvenile white sharks *Carcharodon carcharias* in eastern Australia from acoustic and satellite telemetry. *Marine Ecology Progress Series,* 619, 1-15.

Brunnschweiler, J.M. (2009). Tracking free-ranging sharks with hand-fed intra-gastric acoustic transmitters. *Marine and Freshwater Behaviour and Physiology*, 42, 201-209.

Brunnschweiler, J.M., & Barnett, A. (2013). Opportunistic visitors: long-term behavioural response of bull sharks to food provisioning in Fiji. *PloS One,* 8, e58522.

Burnham, K.P., & Anderson, D.R. (2002). *Model selection and multimodel inference: a practical information-theoretic approach*. New York, Springer.

Calenge, C. (2021). *Package ‘adehabitatHR’. Version 0.4.19*. URL: https://cran.r-project.org/web/packages/adehabitatHR/adehabitatHR.pdf

Camhi, M.D., Pikitch, E.K., & Babcock, E.A. (2009). *Sharks of the open ocean: biology, fisheries and conservation* (Vol. 15). New York, John Wiley & Sons.

Campana, S.E., Dorey, A., Fowler, M., Joyce, W., Wang, Z., Wright, D., & Yashayaev, I. (2011). Migration pathways, behavioural thermoregulation and overwintering grounds of blue sharks in the Northwest Atlantic. *PloS One,* 6, e16854.

Carey, F., Scharold, J., & Kalmijn, A.J. (1990). Movements of blue sharks (*Prionace glauca*) in depth and course. *Marine Biology,* 106, 329-342.

Carlisle, A.B., Tickler, D., Dale, J.J., Ferretti, F., Curnick, D.J., Chapple, T.K., Schallert, R.J., Castleton, M., & Block, B.A. (2019). Estimating space use of mobile fishes in a large marine protected area with methodological considerations in acoustic array design. *Frontiers in Marine Science,* 6, 256.

Chapman, B.B., Brönmark, C., Nilsson, J.Å., & Hansson, L.A. (2011). The ecology and evolution of partial migration. *Oikos*, 120, 1764-1775.

Chapman, B.B., Hulthén, K., Brodersen, J., Nilsson, P.A., Skov, C., Hansson, L.A., & Brönmark, C. (2012). Partial migration in fishes: causes and consequences. *Journal of Fish Biology,* 81, 456-478.

Clark, E. (1959). Instrumental conditioning of lemon sharks. *Science,* 130, 217-218.

Coelho, H., & Santos, R. (2003). Enhanced primary production over seamounts: a numerical study. *Thalassas,* 19, 144-145.

Coelho, R., Santos, M.N., & Lino, P.G. (2016). Standardized CPUE of blue shark in the Portuguese pelagic longline fleet operating in the North Atlantic. *ICCAT Collective Volumes of Scientific Papers,* 72, 1044-1066.

Coffey, D.M., Carlisle, A.B., Hazen, E.L., & Block, B.A. (2017). Oceanographic drivers of the vertical distribution of a highly migratory, endothermic shark. *Scientific reports,* 7, 1-14.

Craven, P., & Wahba, G. (1978). Smoothing noisy data with spline functions. *Numerische Mathematik,* 31, 377-403.

Davis, T., Gudge, S., Henry, E., & Woods, C. (2017). *Baited Remote Underwater Video Surveys of Lord Howe Island Marine Park Fish Assemblages: 2017 Project Summary.* Sydney, New South Wales Department of Primary Industries.

de Queiroz, J.D., Bezerra, N.P., Macena, B.C., & Hazin, F.H. (2021). Back from the dead? Not really. The tale of the Galapagos shark (*Carcharhinus galapagensis*) in a remote Brazilian archipelago. *Biological Conservation*, 256, 109097.

Director of National Parks. (2018). *Temperate East Marine Parks Network Management Plan 2018*. Canberra, Director of National Parks.

Ebert, D.A., Dando, M., & Fowler, S. (2021). *Sharks of the world*. Princeton, Princeton University Press.

Edgar, G., Valentine, J., Cooper, T., Stuart-Smith, R., Gudge, S., & Kerr, I. (2010). *Ecological monitoring of reef communities at Lord Howe Island Marine Park, New South Wales, 2006-2010. Final report for the New South Wales Marine Parks Authority.* Sydney, New South Wales Marine Parks Authority.

Espinoza, M., Heupel, M.R., Tobin, A.J., & Simpfendorfer, C.A. (2015). Residency patterns and movements of grey reef sharks (*Carcharhinus amblyrhynchos*) in semi-isolated coral reef habitats. *Marine Biology,* 162, 343-358.

Espinoza, M., Heupel, M.R., Tobin, A.J., & Simpfendorfer, C.A. (2016). Evidence of partial migration in a large coastal predator: opportunistic foraging and reproduction as key drivers?. *PloS One*, 11, e0147608.

Figueira, W.F., & Hunt, B. (2017). *Lord Howe Island Marine Park Charter Fishery Summary: 2004-2015*. Sydney, New South Wales Department of Primary Industries.

Fisher, R., Wilson, S.K., Sin, T.M., Lee, A.C., & Langlois, T.J. (2018). A simple function for full-subsets multiple regression in ecology with R. *Ecology and Evolution,* 8, 6104-6113.

Fitzpatrick, R., Abrantes, K.G., Seymour, J., & Barnett, A. (2011). Variation in depth of whitetip reef sharks: does provisioning ecotourism change their behaviour? *Coral Reefs,* 30, 569-577.

Gaube, P., Braun, C.D., Lawson, G.L., McGillicuddy, D.J., Della Penna, A., Skomal, G.B., Fischer, C., & Thorrold, S.R. (2018). Mesoscale eddies influence the movements of mature female white sharks in the Gulf Stream and Sargasso Sea. *Scientific reports,* 8, 1-8.

Genin, A., & Dower, J.F. (2007). Seamount plankton dynamics. In: Pitcher, T., Morato, T., Hart, P., Clark, M., Haggan, N., & Santos, R. (eds.) *Seamounts: Ecology, Fisheries & Conservation*. Hoboken, Wiley-Blackwell, 85-100.

George, L.W., Martins, A.P., Heupel, M.R., & Simpfendorfer, C.A. (2019). Fine-scale movements of juvenile blacktip reef sharks *Carcharhinus melanopterus* in a shallow nearshore nursery. *Marine Ecology Progress Series,* 623, 85-97.

Gilman, E., Clarke, S., Brothers, N., Alfaro-Shigueto, J., Mandelman, J., Mangel, J., Petersen, S., Piovano, S., Thomson, N., Dalzell, P., Donoso, M., Goren, M., & Werner, T. (2008). Shark interactions in pelagic longline fisheries. *Marine Policy,* 32, 1-18.

Gilman, E., Clarke, S., Brothers, N., Alfaro-Shugueto, J., Mandelman, J., Mangel, J., Petersen, S., Piovano, S., Thomson, N., Dalzell, P., Goren, M., & Werner, T. (2007). *Shark depredation and unwanted bycatch in pelagic longline fisheries: Industry practices and attitudes, and shark avoidance strategies*. Honolulu, Western Pacific Regional Fishery Management Council.

Guttridge, T.L., & Brown, C. (2014). Learning and memory in the Port Jackson shark, *Heterodontus portusjacksoni*. *Animal Cognition,* 17, 415-425.

Hammerschlag, N., & Fallows, C. (2005). Galapagos sharks (*Carcharhinus galapagensis*) at the Bassas da India atoll: First record from the Mozambique Channel and possible significance as a nursery area. *South African Journal of Science,* 101, 375-377.

Hammerschlag, N., Skubel, R., Calich, H., Nelson, E., Shiffman, D., Wester, J., Macdonald, C., Cain, S., Jennings, L., & Enchelmaier, A. (2017). Nocturnal and crepuscular behavior in elasmobranchs: a review of movement, habitat use, foraging, and reproduction in the dark. *Bulletin of Marine Science,* 93, 355-374.

Hart, N.S., & Collin, S.P. (2015). Sharks senses and shark repellents. *Integrative Zoology,* 10, 38-64.

Hastie, T., & Tibshirani, R. (1986). Generalized Additive Models. *Statistical Science,* 1, 297-310.

Heagney, E.C., Lynch, T.P., Babcock, R.C., & Suthers, I.M. (2007). Pelagic fish assemblages assessed using mid-water baited video: standardising fish counts using bait plume size. *Marine Ecology Progress Series,* 350, 255-266.

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

Hearn, A., Ketchum, J., Klimley, A.P., Espinoza, E., & Penaherrera, C. (2010). Hotspots within hotspots? hammerhead shark movements around wolf island, Galapagos marine reserve. *Marine Biology,* 157, 1899-1915.

Heinrich, D., Dhellemmes, F., Guttridge, T.L., Smukall, M., Brown, C., Rummer, J., Gruber, S., & Huveneers, C. (2021). Short-term impacts of daily feeding on the residency, distribution and energy expenditure of sharks. *Animal Behaviour,* 172, 55-71.

Heupel, M., & Simpfendorfer, C. (2005). Using acoustic monitoring to evaluate MPAs for shark nursery areas: the importance of long-term data. *Marine Technology Society Journal,* 39, 10-18.

Holmes, B.J., Pepperell, J.G., Griffiths, S.P., Jaine, F.R., Tibbetts, I.R., & Bennett, M.B. (2014). Tiger shark (*Galeocerdo cuvier*) movement patterns and habitat use determined by satellite tagging in eastern Australian waters. *Marine Biology,* 161, 2645-2658.

Howard, S., Brill, R., Hepburn, C., & Rock, J. (2018). Microprocessor-based prototype bycatch reduction device reduces bait consumption by spiny dogfish and sandbar shark. *ICES Journal of Marine Science,* 75, 2235-2244.

Howey-Jordan, L.A., Brooks, E.J., Abercrombie, D.L., Jordan, L.K., Brooks, A., Williams, S., Gospodarczyk, E., & Chapman, D.D. (2013). Complex movements, philopatry and expanded depth range of a severely threatened pelagic shark, the oceanic whitetip (*Carcharhinus longimanus*) in the western North Atlantic. *PloS One,* 8, e56588.

Huveneers, C., Whitmarsh, S., Thiele, M., Meyer, L., Fox, A., Bradshaw, C.J. (2018). Effectiveness of five personal shark-bite deterrents for surfers. *PeerJ,* 6, e5554.

Huveneers, C., Jaine, F.R., Barnett, A., Butcher, P.A., Clarke, T.M., Currey-Randall, L.M., Dwyer, R.G., Ferreira, L.C., Gleiss, A.C., & Hoenner, X. (2021). The power of national acoustic tracking networks to assess the impacts of human activity on marine organisms during the COVID-19 pandemic. *Biological Conservation,* 256, 108995.

IOCCG. (2006). Remote Sensing of Inherent Optical Properties: Fundamentals, Tests of Algorithms, and Applications. In Z-P. Lee (ed.), *Reports of the International Ocean-Colour Coordinating Group, No. 5*. Dartmouth, International Ocean-Colour Coordinating Group.

Iwane, M.A., & Leong, K.M. (2020). *Socioeconomic context for fisher-shark interactions in the Marianas. NOAA Admin Report H-20-13.* Honolulu, NOAA.

Jacoby, D.M., Ferretti, F., Freeman, R., Carlisle, A.B., Chapple, T.K., Curnick, D.J., Dale, J.J., Schallert, R.J., Tickler, D., & Block, B.A. (2020). Shark movement strategies influence poaching risk and can guide enforcement decisions in a large, remote marine protected area. *Journal of Applied Ecology,* 57, 1782-1792.

Kato, S., & Carvallo, A.H. (1967). Shark tagging in the eastern Pacific Ocean, 1962-65. In Gilbert, P.W., Mathewson, R.F., & Rall, J.P. (eds.), *Sharks, skates, and rays*. Baltimore, Johns Hopkins Press, 93-109.

Ketchum, J. T., Hearn, A., Klimley, A.P., Espinoza, E., Peñaherrera, C., & Largier, J.L. (2014). Seasonal changes in movements and habitat preferences of the scalloped hammerhead shark (*Sphyrna lewini*) while refuging near an oceanic island. *Marine Biology,* 161, 755-767.

Kohler, N.E., Casey, J.G., & Turner, P.A. (1998). NMFS cooperative shark tagging program, 1962-93: an atlas of shark tag and recapture data. *Marine Fisheries Review,* 60, 1-87.

Kyne, P.M., Barreto, R., Carlson, J., Fernando, D., Fordham, S., Francis, M.P., Herman, K., Jabado, R.W., Liu, K.M., Pacoureau, N., Romanov, E., & Sherley, R.B. (2019).

Carcharhinus galapagensis. *The IUCN Red List of Threatened Species*. URL: https://dx.doi.org/10.2305/IUCN.UK.2019-3.RLTS.T41736A2954286.en

Last, P.R., & Stevens, J.D. (2009). *Sharks and Rays of Australia*. Second Edition. Collingwood, CSIRO Publishing.

Lieberman, D.A. (1990). *Learning: Behaviour and Cognition*. Belmont, Wadsworth.

Limbaugh, C. (1963). Field notes on sharks. In Gilbert, P.W., Garrick, J.A., & Schultz, L.P. (eds.), *Sharks and survival*. Boston, D.C. Heath Co, 53-94.

Linklater, M. (2009). *An Assessment of the Geomorphology and Benthic Environments of the Lord Howe Island Shelf, Southwest Pacific Ocean, and Implications for Quaternary Sea Level.* PhD Thesis, Wollongong, University of Wollongong.

Linklater, M., Hamylton, S.M., Brooke, B.P., Nichol, S.L., Jordan, A.R., & Woodroffe, C.D. (2018). Development of a seamless, high-resolution bathymetric model to compare reef morphology around the subtropical island shelves of Lord Howe Island and Balls Pyramid, southwest Pacific Ocean. *Geosciences,* 8, 11.

Litvinov, F. (2007). Fish visitors to seamounts: aggregations of large pelagic sharks above seamounts. In: Pitcher, T., Morato, T., Hart, P., Clark, M., Haggan, N., & Santos, R. (eds.) *Seamounts: Ecology, Fisheries & Conservation*. Hoboken, Wiley-Blackwell, 202-206.

Lizardi, F.L., Hoyos-Padilla, M., Hearn, A., Klimley, A.P., Galván-Magaña, F., Arauz, R., Bessudo, S., Castro, E., Clua, E., & Espinoza, E. (2020). Shark movements in the Revillagigedo Archipelago and connectivity with the Eastern Tropical Pacific. *bioRxiv*.

Luiz, O.J., & Edwards, A.J. (2011). Extinction of a shark population in the Archipelago of Saint Paul’s Rocks (equatorial Atlantic) inferred from the historical record. *Biological Conservation,* 144, 2873-2881.

Madigan, D.J., Brooks, E.J., Bond, M.E., Gelsleichter, J., Howey, L.A., Abercrombie, D.L., Brooks, A., & Chapman, D.D. (2015). Diet shift and site-fidelity of oceanic whitetip sharks *Carcharhinus longimanus* along the Great Bahama Bank. *Marine Ecology Progress Series,* 529, 185-197.

Madigan, D.J., Richardson, A.J., Carlisle, A.B., Weber, S.B., Brown, J., & Hussey, N.E. (2020). Water column structure defines vertical habitat of twelve pelagic predators in the South Atlantic. *ICES Journal of Marine Science,* fsaa222.

McLean, D.L., Langlois, T.J., Newman, S.J., Holmes, T.H., Birt, M.J., Bornt, K.R., Bond, T., Collins, D.L., Evans, S.N., & Travers, M.J. (2016). Distribution, abundance, diversity and habitat associations of fishes across a bioregion experiencing rapid coastal development. *Estuarine, Coastal and Shelf Science,* 178, 36-47.

McMillan, M., Huveneers, C., Semmens, J., & Gillanders, B. (2019). Partial female migration and cool-water migration pathways in an overfished shark. *ICES Journal of Marine Science,* 76, 1083-1093.

Meyer, C.G., Dale, J.J., Papastamatiou, Y.P., Whitney, N.M., & Holland, K.N. (2009). Seasonal cycles and long-term trends in abundance and species composition of sharks associated with cage diving ecotourism activities in Hawaii. *Environmental Conservation*, 36, 104-111.

Meyer, C.G., Papastamatiou, Y.P., & Holland, K.N. (2010). A multiple instrument approach to quantifying the movement patterns and habitat use of tiger (*Galeocerdo cuvier*) and Galapagos sharks (*Carcharhinus galapagensis*) at French Frigate Shoals, Hawaii. *Marine Biology,* 157, 1857-1868.

Mitchell, J., Schifiliti, M., Birt, M., Bond, T., McLean, D.L, Barnes, P., & Langlois, T.J. (2020). A novel experimental approach to investigate the potential for behavioural change in sharks in the context of depredation. *Journal of Experimental Marine Biology and Ecology,* 530, 151440.

Mitchell, J.D., McLean, D.L., Collin, S.P., Jackson, G., Taylor, S., Fisher, R., & Langlois, T.J. (2018a). Quantifying shark depredation in a recreational fishery in the Ningaloo Marine Park and Exmouth Gulf, Western Australia. *Marine Ecology Progress Series,* 587, 141-157.

Mitchell, J.D., McLean, D.L., Collin, SP., & Langlois, T. J. (2018b). Shark depredation in commercial and recreational fisheries. *Reviews in Fish Biology and Fisheries*, 28, 715-748.

Mleczko, R., Sagar, S., Spinoccia, M., & Brooke, B.P. (2010). *The Creation of High Resolution Bathymetry Grids for the Lord Howe Island Region*. Canberra, Geoscience Australia.

Morales, N.A., Heidemeyer, M., Bauer, R., Hernández, S., Acuña, E., van Gennip, S.J., Friedlander, A.M., & Gaymer, C.F. (2021). Residential movements of top predators in Chile's most isolated marine protected area: Implications for the conservation of the Galapagos shark, *Carcharhinus galapagensis*, and the yellowtail amberjack, *Seriola lalandi*. *Aquatic Conservation: Marine and Freshwater Ecosystems,* 31, 340-355.

Morato, T., Hoyle, S.D., Allain, V., & Nicol, S.J. (2010). Seamounts are hotspots of pelagic biodiversity in the open ocean. *Proceedings of the National Academy of Sciences,* 107, 9707-9711.

Musyl, M.K., Brill, R.W., Curran, D.S., Fragoso, N.M., McNaughton, L.M., Nielsen, A., Kikkawa, B.S., & Moyes, C.D. (2011). Postrelease survival, vertical and horizontal movements, and thermal habitats of five species of pelagic sharks in the central Pacific Ocean. *Fishery Bulletin,* 109, 341-368.

Nakamura, I., Watanabe, Y.Y., Papastamatiou, Y.P., Sato, K., & Meyer, C.G. (2011). Yo-yo vertical movements suggest a foraging strategy for tiger sharks *Galeocerdo cuvier*. *Marine Ecology Progress Series,* 424, 237-246.

Niella, Y., Wiefels, A., Almeida, U., Jaquemet, S., Lagabrielle, E., Harcourt, R., Peddemors, V. and Guyomard, D. (2021). Dynamics of marine predators off an oceanic island and implications for management of a preventative shark fishing program. *Marine Biology*, 168, 1-18.

Neilson, J., Jordan, A., Gudge, S., & Kerr, I. (2010). *Baited Remote Underwater Video Surveys of Fish Assemblages on Reef Shelf Habitats in Lord Howe Island Marine Park*. Sydney, New South Wales Department of Primary Industries.

NSW Department of Primary Industries. (2020). *NSW Recreational Saltwater Fishing Guide 2020-21*. Nowra, New South Wales Department of Primary Industries.

Papastamatiou, Y.P., Friedlander, A.M., Caselle, J.E., & Lowe, C.G. (2010). Long-term movement patterns and trophic ecology of blacktip reef sharks (*Carcharhinus melanopterus*) at Palmyra Atoll. *Journal of Experimental Marine Biology and Ecology,* 386, 94-102.

Papastamatiou, Y.P., Meyer, C.G., Carvalho, F., Dale, J.J., Hutchinson, M.R., & Holland, K.N. (2013). Telemetry and random-walk models reveal complex patterns of partial migration in a large marine predator. *Ecology*, 94, 2595-2606.

Papastamatiou, Y.P., Wetherbee, B.M., Lowe, C.G., & Crow, G.L. (2006). Distribution and diet of four species of carcharhinid shark in the Hawaiian Islands: evidence for resource partitioning and competitive exclusion. *Marine Ecology Progress Series,* 320, 239-251.

Pincock, G., (2012). False Detections: What They Are and How to Remove Them from Detection Data. Vemco Whitepaper Document #DOC-004691 v03, Halifax, Amirix Systems Inc.

Queiroz, N., Humphries, NE., Couto, A., Vedor, M., Da Costa, I., Sequeira, A.M., Mucientes, G., Santos, A.M., Abascal, F.J., & Abercrombie, D.L. (2019). Global spatial risk assessment of sharks under the footprint of fisheries. *Nature,* 572, 461-466.

Queiroz, N., Humphries, N.E., Mucientes, G., Hammerschlag, N., Lima, F.P., Scales, K.L., Miller, P.I., Sousa, L.L., Seabra, R., & Sims, D.W. (2016). Ocean-wide tracking of pelagic sharks reveals extent of overlap with longline fishing hotspots. *Proceedings of the National Academy of Sciences,* 113, 1582-1587.

Queiroz, N., Humphries, N.E., Noble, L.R., Santos, A.M., & Sims, D.W. (2012). Spatial dynamics and expanded vertical niche of blue sharks in oceanographic fronts reveal habitat targets for conservation. *PloS One,* 7, e32374.

R Development Core Team. (2015). *R studio: integrated development environment for R* (version 3.2.2). URL: www.rstudio.com.

Rees, M. (2013). *Baited Remote Underwater Video Surveys of the Lord Howe Island Marine Park Fish Assemblage: 2013 Project Summary.* Sydney, New South Wales Department of Primary Industries.

Rees, M.J., Jordan, A., Price, O.F., Coleman, M.A., & Davis, A.R. (2014). Abiotic surrogates for temperate rocky reef biodiversity: implications for marine protected areas. *Diversity and Distributions,* 20, 284-296.

Rees, M.J., Knott, N.A., Neilson, J., Linklater, M., Osterloh, I., Jordan, A., & Davis, A.R. (2018). Accounting for habitat structural complexity improves the assessment of performance in no-take marine reserves. *Biological Conservation,* 224, 100-110.

Robbins, W.D., Peddemors, V.M., & Kennelly, S.J. (2011). Assessment of permanent magnets and electropositive metals to reduce the line-based capture of Galapagos sharks, *Carcharhinus galapagensis*. *Fisheries Research,* 109, 100-106.

Rogers, P.J., Huveneers, C., Page, B., Goldsworthy, S.D., Coyne, M., Lowther, A.D., Mitchell, J.G., & Seuront, L. (2015). Living on the continental shelf edge: habitat use of juvenile shortfin makos *Isurus oxyrinchus* in the Great Australian Bight, southern Australia. *Fisheries Oceanography,* 24, 205-218.

Saunders, R.A., Royer, F., & Clarke, M.W. (2011). Winter migration and diving behaviour of porbeagle shark, *Lamna nasus*, in the Northeast Atlantic. *ICES Journal of Marine Science*, 68, 166-174.

Sherman, C.S., Heupel, M.R., Johnson, M., Kaimuddin, M., Qamar, L.S., Chin, A., & Simpfendorfer, C.A. (2020). Repeatability of baited remote underwater video station (BRUVS) results within and between seasons. *PloS One,* 15, e0244154.

Sims, D.W. (2005). Differences in habitat selection and reproductive strategies of male and female sharks. In Ruckstuhl, K.E., & Neuhaus, P. (eds.) *Sexual segregation in vertebrates.* Cambridge, Cambridge University Press, 127-147.

Sleeman, J.C., Meekan, M.G., Wilson, S.G., Jenner, C.K., Jenner, M.N., Boggs, G.S., Steinberg, C.C., & Bradshaw, C.J. (2007). Biophysical correlates of relative abundances of marine megafauna at Ningaloo Reef, Western Australia. *Marine and Freshwater Research,* 58, 608-623.

Stevens, J.D., Bradford, R.W., & West, G.J. (2010). Satellite tagging of blue sharks (*Prionace glauca*) and other pelagic sharks off eastern Australia: depth behaviour, temperature experience and movements. *Marine Biology,* 157, 575-591.

Stevenson, C., Katz, L.S., Micheli, F., Block, B., Heiman, K.W., Perle, C., Weng, K., Dunbar, R., & Witting, J. (2007). High apex predator biomass on remote Pacific islands. *Coral Reefs,* 26, 47-51.

Tascheri, R., Saavedra-Nievas, J., & Roa-Ureta, R. (2010). Statistical models to standardize catch rates in the multi-species trawl fishery for Patagonian grenadier (*Macruronus magellanicus*) off Southern Chile. *Fisheries Research,* 105, 200-214.

Thiele, M., Mourier, J., Papastamatiou, Y., Ballesta, L., Chateauminois, E., Huveneers, C. (2020). Response of blacktip reef sharks *Carcharhinus melanopterus* to shark bite mitigation products. *Scientific reports*, 10, 1-12.

Tixier, P., Lea, M.A., Hindell, M.A., Welsford, D., Mazé, C., Gourguet, S., & Arnould, J.P. (2021). When large marine predators feed on fisheries catches: Global patterns of the depredation conflict and directions for coexistence. *Fish and Fisheries,* 22, 31-53.

Tolotti, M.T., Forget, F., Capello, M., Filmalter, J.D., Hutchinson, M., Itano, D., Holland, K., & Dagorn, L. (2020). Association dynamics of tuna and purse seine bycatch species with drifting fish aggregating devices (FADs) in the tropical eastern Atlantic Ocean. *Fisheries Research,* 226, 105521.

Tweedie, M. (1984). An index which distinguishes between some important exponential families. In Ghosh, J.K., & Roy, J. (eds.), *Statistics: Applications and New Directions: Proceedings of the Indian Statistical Institute Golden Jubilee International Conference.* Calcutta, Indian Statistical Institute, 579-604.

van Herwerden, L., Almoji, D., & Choat, J.H. (2008). *Population genetic structure of Australian Galapagos reef sharks Carcharhinus galapagensis at Elizabeth and Middleton Reefs Marine National Nature Reserve and Lord Howe Island Marine Park. Final report to* *the Department of the Environment, Water, Heritage and the Arts.* Canberra, Department of the Environment, Water, Heritage and the Arts.

VEMCO, (2015). *VUE Software Manual. DOC-4399-23*, URL: http://Vemco.com/products/vue-software.

Vianna, G.M., Meekan, M.G., Meeuwig, J.J., & Speed, C.W. (2013). Environmental influences on patterns of vertical movement and site fidelity of grey reef sharks (*Carcharhinus amblyrhynchos*) at aggregation sites. *PloS One,* 8, e60331.

Vila Pouca, C., & Brown, C. (2018). Food approach conditioning and discrimination learning using sound cues in benthic sharks. *Animal Cognition,* 21, 481-492.

Walker, T.I., & Rochowski, B.E. (2019). *Squalus chloroculus*. *The IUCN Red List of Threatened Species*, URL: https://dx.doi.org/10.2305/IUCN.UK.2019-1.RLTS.T161360A68644464.en.

Watanabe, H., Kubodera, T., Moku, M., & Kawaguchi, K. (2006). Diel vertical migration of squid in the warm core ring and cold water masses in the transition region of the western North Pacific. *Marine Ecology Progress Series,* 315, 187-197.

West, G.J., & Stevens, J.D. (2001). Archival tagging of school shark, *Galeorhinus galeus*, in Australia: initial results. In Tricas, T.C., & Gruber, S.H. (eds.), *The behavior and sensory biology of elasmobranch fishes: an anthology in memory of Donald Richard Nelson.* Dordrecht, Springer, 283-298.

Wetherbee, B.M., Crow, G.L., & Lowe, C.G. (1996). Biology of the Galapagos shark, *Carcharhinus galapagensis*, in Hawai'i. *Environmental Biology of Fishes,* 45, 299-310.

White, M., Bashmachnikov, I., Arístegui, J., & Martins, A. (2007). Physical processes and seamount productivity. In: Pitcher, T., Morato, T., Hart, P., Clark, M., Haggan, N., & Santos, R. (eds.) *Seamounts: Ecology, Fisheries & Conservation*. Hoboken, Wiley-Blackwell, 65-84.

Wilson, M.F., O'Connell, B., Brown, C., Guinan, J.C., & Grehan, A.J. (2007). Multiscale terrain analysis of multibeam bathymetry data for habitat mapping on the continental slope. *Marine Geodesy,* 30, 3-35.

Wood, S. (2006). *Generalized additive models: an introduction with R*. Boca Raton, CRC Press.

Wood, S. (2008). Fast stable direct fitting and smoothness selection for generalized additive models. *Journal of the Royal Statistical Society B,* 70, 495-518.

Worm, B., Davis, B., Kettemer, L., Ward-Paige, C.A., Chapman, D., Heithaus, M.R., Kessel, S.T., & Gruber, S.H. (2013). Global catches, exploitation rates, and rebuilding options for sharks. *Marine Policy,* 40, 194-204.

Young, C.N., & Carlson, J.K. (2020). The biology and conservation status of the oceanic whitetip shark (*Carcharhinus longimanus*) and future directions for recovery. *Reviews in Fish Biology and Fisheries,* 30, 293-312.

Zuur, A., Ieno, E.N., Walker, N., Saveliev, A.A., & Smith, G.M. (2009). *Mixed effects models and extensions in ecology with R*. New York, Springer.

Appendices

Appendix 1. Questions used in the survey of LHI charter and recreational fishers

1. What type of operator / fisher are you? i.e. charter operator, recreational fisher, supply for restaurants only – one or all the above?
2. How many people are usually on your vessel fishing? Minimum and Maximum?
3. How regularly do you go out fishing?
4. How frequently do you lose hooked fish to sharks? Roughly how many times per trip?
5. Do you get part of the fish back or do the sharks usually take the whole fish and snap the line?
6. How frequently do you lose bait to sharks? How many times per trip?
7. How much gear do you lose on average per trip due to sharks taking bait/hooked fish?
8. Roughly, what would be the cost of lost gear to that?
9. At what locations do you have most issues with sharks being present/taking fish or bait? In the location groups you usually report catch i.e. lagoon, near shore, shelf LHI, shelf edge LHI, shelf pyramid, shelf edge pyramid, >250m deep?
10. Are there any locations that you go to deliberately where you know there are less sharks? If so, which are these locations?
11. How does depth influence how often depredation happens? Is there a threshold depth after which less shark interactions occur, e.g. 100m, 500m etc.?
12. Do you clean your fish on the move or at a given location? How do you think this affects the shark behaviour?
13. Do you see any seasonality in the patterns of shark depredation?
14. Do you have more issues when targeting demersal species or pelagic species?
15. Do the sharks depredate certain species of fish more than others?
16. How many sharks do you catch as bycatch per trip and per year?
17. Do you release all the sharks you catch? If no, what do you do with ones you keep?
18. Do you report all shark interactions in your catch returns/e-logbook, or only dead bycatch?
19. Is your choice of fishing gear based on reducing depredation events?
20. Do you have more success getting fish past the sharks with alvey reels, handlines, hydraulic winches vs. rod and line?
21. Do customers prefer using rod and line even if they have higher risk of losing fish? Or would they be open to changing gear types if it meant less depredation?
22. How else do you currently try to reduce shark interactions?
23. Do you think shark deterrents could be used in a practical and cost-effective way during fishing, and would you be interested in trialling one of two of them?
24. Do you ever catch other species of sharks?
25. Do you have any other comments, questions or information you would like to share about your experience fishing and with sharks within the marine parks surrounding LHI?

Appendix 2. Questions used in the ongoing social survey of LHI adult residents about their perceptions of Galapagos sharks

1. Are you currently a resident of Lord Howe Island

☐ Yes
☐ No

If you answered ‘No’ to the above question, please discontinue this survey

2. How many years in total have you lived on Lord Howe Island?

☐ less than 1 year
☐ 1-3 years
☐ 4 -10 years
☐ 11-30 years
☐ greater than 30 years

3. How many years in total have you lived off island during your lifetime?

☐ less than 1 year
☐ 1-3 years
☐ 4 -10 years
☐ 11-30 years
☐ greater than 30 years

4. How old are you?

☐ under 14 years (please discontinue the survey if this is the case)
☐ 14-18 years
☐ 18-30 years
☐ 30-50 years
☐ over 50 years

5. Do you own, operate, work for, or volunteer for any of the following? Select all that apply.

☐ Charter fishing business
☐ Accommodation business
☐ Land-based tour business
☐ Diving tour business
☐ Marine non-fishing tour business
☐ Glass bottom boat/snorkeling tour business
☐ Restaurant
☐ Board or government employee
☐ other (please specify in box below)

6. How often do you undertake the following activities at Lord Howe Island? (Please tick one box for each activity)

	Daily	Weekly	Monthly	Yearly	Rarely	Never
Snorkel or SCUBA diving						
Fish from shore						
Fish from personal boat						
Fish from charter vessel						
Surf, kayak or paddleboard						
Swim						
Spend time on beach						
Other (please specify)						

7. Where and how often do you encounter Galapagos sharks around Lord Howe Island? (Please tick one box for each location)

	Daily	Weekly	Monthly	Yearly	Rarely	Never
North Bay						
Old settlement						
North Passage						
Jetty						
Pines						
Near aquatic club beach and/or Blackburn/Rabbit island						
Erscotts or Comets Hole						
South Passage						
Lovers, Kings Beach or Salmon Beach						
Little Island						
Neds beach						
Middle beach						
Blinkies beach						
Balls Pyramid						
Admiralty Islands						
Offshore waters						
Lagoon (other than places listed above)						
Other						

8. Galapagos sharks and the environment (please answer these questions only in relation to Galapagos sharks at Lord Howe Island. Please tick one box per statement)

	Strongly agree (1)	Agree (2)	Neutral (3)	Disagree (4)	Strongly disagree (5)
Without Galapagos sharks, fish populations around Lord Howe would decrease (e.g. negative ecosystem effects).					
Without Galapagos sharks, fish populations around Lord Howe would be healthier (e.g. more kingfish)					
Galapagos sharks are vulnerable to fishing					
It would be better if there were fewer Galapagos sharks					
Galapagos sharks are a sign of a healthy ecosystem					
I enjoy seeing Galapagos sharks in the ocean.					
Galapagos sharks should be protected					
Galapagos shark populations around Lord Howe have increased over your time living on the island					
Galapagos shark populations around Lord Howe have decreased over your time living on the island					

9. Galapagos sharks and Lord Howe Island tourism (please answer these questions only in relation to Galapagos sharks at Lord Howe Island. Please tick one box per statement)

	Strongly agree (1)	Agree (2)	Neutral (3)	Disagree (4)	Strongly disagree (5)
Galapagos sharks are good for the whole of the Lord Howe Island tourism industry (including accommodation, restaurants, tours, etc.)					
Galapagos sharks are good for marine tour businesses (including glass-bottom boat tours, fishing charters, turtle tours, snorkeling, and diving tours)					
Tourists enjoy seeing Galapagos sharks					
Galapagos sharks decrease the amount of fresh fish available to local restaurants.					

10. Galapagos sharks and fishing (including both local recreational fishing and charter fishing) (please answer these questions only in relation to Galapagos sharks at Lord Howe Island. Please tick one box per statement)

	Strongly agree (1)	Agree (2)	Neutral (3)	Disagree (4)	Strongly disagree (5)
Galapagos sharks interfere with and impact upon recreational and charter fishing					
Recreational and charter fishing is a threat to Galapagos shark populations					
Galapagos sharks should be harvested to eat					
Galapagos sharks taste good					
Galapagos sharks should be culled					
Non-lethal measures should be used to reduce interactions between fishers and Galapagos sharks					
I have changed how and/or where I fish to avoid Galapagos sharks					
Catching a Galapagos shark adds to the enjoyment of my fishing trip					
I target Galapagos sharks when I go fishing					
Galapagos sharks are a threat to the other fish I want to catch (e.g., kingfish)					
If I catch a Galapagos shark, I make sure to release it in good condition					
I purposely kill Galapagos sharks that I encounter while fishing					
Galapagos sharks cost me money because they destroy my gear					
Galapagos sharks cost me money because they eat the fish on my line.					
Fishing changes the behavior of Galapagos sharks					

11. Knowledge of Galapagos shark biology

How large do Galapagos sharks grow in length?
☐ One metre
☐ Two metres
☐ Three metres
☐ Four metres

12. On average, how large are the Galapagos sharks you have seen around Lord Howe Island?
☐ Less than 1 metre
☐ 1 – 2 metres
☐ 2 – 3 metres
☐ 3 – 4 metres

13. How many Galapagos sharks do you think there are in the waters around Lord Howe Island?
☐ 10 – 100 sharks
☐ 100 – 500 sharks
☐ 500 – 1000 sharks
☐ Greater than 1000 sharks

14. How easy was this survey to understand and complete?
☐ Very easy
☐ Easy
☐ Neutral (not especially easy or difficult)
☐ Difficult
☐ Very difficult

15. Do you have any other information or opinions on sharks that you would like to share? If you have comments on other species of sharks, please specify which species. Do you have any comments on the structure and scope of the survey?