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ORIGINAL PAPER

Applying acoustic telemetry, vessel tracking and fisher knowledge to investigate and manage fisher-shark conflict at Lord Howe Island, Australia

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Abstract

Fisher-shark conflict is occurring at Lord Howe Island, Australia due to high levels of Galapagos shark (*Carcharhinus galapagensis*) depredation (where sharks consume hooked fish) and bycatch. Depredation causes costly loss of target catch and fishing gear and increased mortality of target species, and sharks can be injured or killed when bycaught. This study applied acoustic telemetry and vessel tracking from 2018 to 2021 to identify; (1) how the movements of 30 tagged sharks and activity of six fishing vessels overlapped, and (2) where key 'hotspots' of overlap occurred. Fisher surveys were also conducted to collect information about mitigating shark interactions. Residency index analysis indicated that three sharks tagged at a fish waste dumping site had markedly higher residency. Core home ranges of sharks overlapped with higher fishing activity at four 'hotspots'. Statistical modelling indicated positive linear effects of fishing activity and bathymetric complexity on shark detections and tagged sharks were present for 13% of the total time that vessels were fishing close to acoustic receivers. Spatio-temporal overlaps between shark movements and fishing activity could potentially have occurred because sharks learned to associate fishing vessels with food (i.e. hooked fish) and because fishers and sharks utilise highly productive shelf edge areas, however more research is needed to investigate these relationships. Fishers reported that rotating fishing areas and reducing time at each location, fishing deeper than 100 m, and using electric reels and lures instead of bait, reduced bycatch and depredation. The integrated approach used here identified practical methods for reducing fisher-shark conflict, improving socio-economic outcomes for fishers and conservation prospects for this unique shark population.

Keywords Human-wildlife conflict · Shark depredation · Galapagos shark · Spatial ecology · Fisheries management

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Introduction

Galapagos sharks (*Carcharhinus galapagensis*) regularly interact with fishers in the marine parks surrounding Lord Howe Island (LHI), which include the Lord Howe Island Marine Park (up to 3 nm offshore) managed by New South Wales (NSW) State Government and the Lord Howe Marine Park (from 3 to 200 nm offshore) managed by the Commonwealth Government. These interactions include depredation, where the sharks consume hooked fish, either partially or fully (Gilman et al. 2007; Mitchell et al. 2018b), and bycatch, where the sharks are incidentally caught as a non-target species (Hall 1996; Molina and Cooke 2012). Shark depredation causes costly loss of target catch and fishing gear for fishers, as well as extra mortality for the target species, e.g., the yellowtail kingfish (*Seriola lalandi*). Bycatch prevents fishers from catching their target species and also leads to loss of fishing gear, as well as injury to sharks. Large numbers of *C. galapagensis* are caught in the LHI charter fishery, ranging from 583 to 1,835 animals per year, although 97% are reported to be released (Figueira and Harianto 2022). Therefore, shark depredation and bycatch interactions are presenting a significant fisher-shark conflict in the marine parks. As a result, fishers have recently begun harvesting more sharks because they perceive that increasing shark populations are leading to more shark depredation. Additionally, some local fishers are advocating for a more systematic harvest or culling of sharks.

The LHI *C. galapagensis* population is believed to be genetically distinct (van Herwerden et al. 2008) and these marine parks may constitute a nursery area for this species, as reflected by the large number of juveniles (< 1.5 m total length) both caught in the charter fishery (Figueira and Harianto 2022) and observed on baited camera surveys (Neilson et al. 2010; Rees 2013; Davis et al. 2017), as well as the bycatch of individuals < 60 cm long bearing a visible umbilical scar (Mitchell and Camilieri-Asch, pers. obs.). The genetic isolation of this population and the possible presence of a nursery area increases the population's vulnerability to declines. Such declines have previously been observed at St Peter and St Paul Archipelago in the Atlantic Ocean, where the resident population of *C. galapagensis* was reduced to very low levels due to fishing (Luiz and Edwards 2011; de Queiroz et al. 2021).

Because of the socio-economic and biological impacts associated with *C. galapagensis* bycatch and depredation at LHI, there is a need to better understand the ecology of the species to determine how it may be influencing the occurrence of depredation and bycatch. Specifically, by identifying the sharks' movement patterns, seasonal presence, depth range and residency it may be possible to better predict when and where sharks are more likely to be encountered by fishers. Such information can then be used by fishers in a proactive way to reduce the likelihood of encountering sharks and experiencing bycatch and depredation.

Acoustic telemetry has been widely used for investigating shark movement ecology across a broad range of temporal and spatial scales (Braccini et al. 2017; Bruce et al. 2019; George et al. 2019), and for providing detailed information on habitat use and residency (Espinoza et al. 2015). Additionally, the ability to determine the overlap 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 vessel tracking using Vessel Monitoring Systems (VMS). The combination of these two technologies allows for 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). Additionally, Jacoby et al. (2020) used acoustic telemetry and illegal fishing activity data to predict the long-term movements of sharks and identify risk of exposure to fishing.

This study sought to use acoustic telemetry to investigate the movement patterns of *C. galapagensis* in the marine parks surrounding LHI and how they overlap with fishing vessel activity as monitored by VMS tracking of charter fishing vessels. Specifically, the aims of the research were to (1) identify 'hotspot' locations and times where *C. galapagensis* presence and fishing vessel activity overlapped, (2) determine the space use and residency of *C. galapagensis* within the marine parks, and how this may be influenced by fishing activity and environmental factors, (3) to learn about the nature of fisher-shark interactions and their impacts on fishers and sharks through social surveys of local fishers and analysis of shark catch data and (4) to generate an holistic, co-designed list of recommendations and best-practice guidelines to assist fishers and marine park managers in mitigating negative fisher-shark interactions.

Materials and methods

Study location

Data collection occurred in the marine parks surrounding LHI, located ~ 600 km east of the Australian mainland (Fig. 1). The marine parks cover both the LHI and Ball's Pyramid (BP) shelves, which have a combined area of 765 km^2 and reach a maximum depth of 100 m (Linklater et al. 2018). Beyond the edges of the shelves, depths increase steeply to > 2000 m. The marine parks are part of the Lord

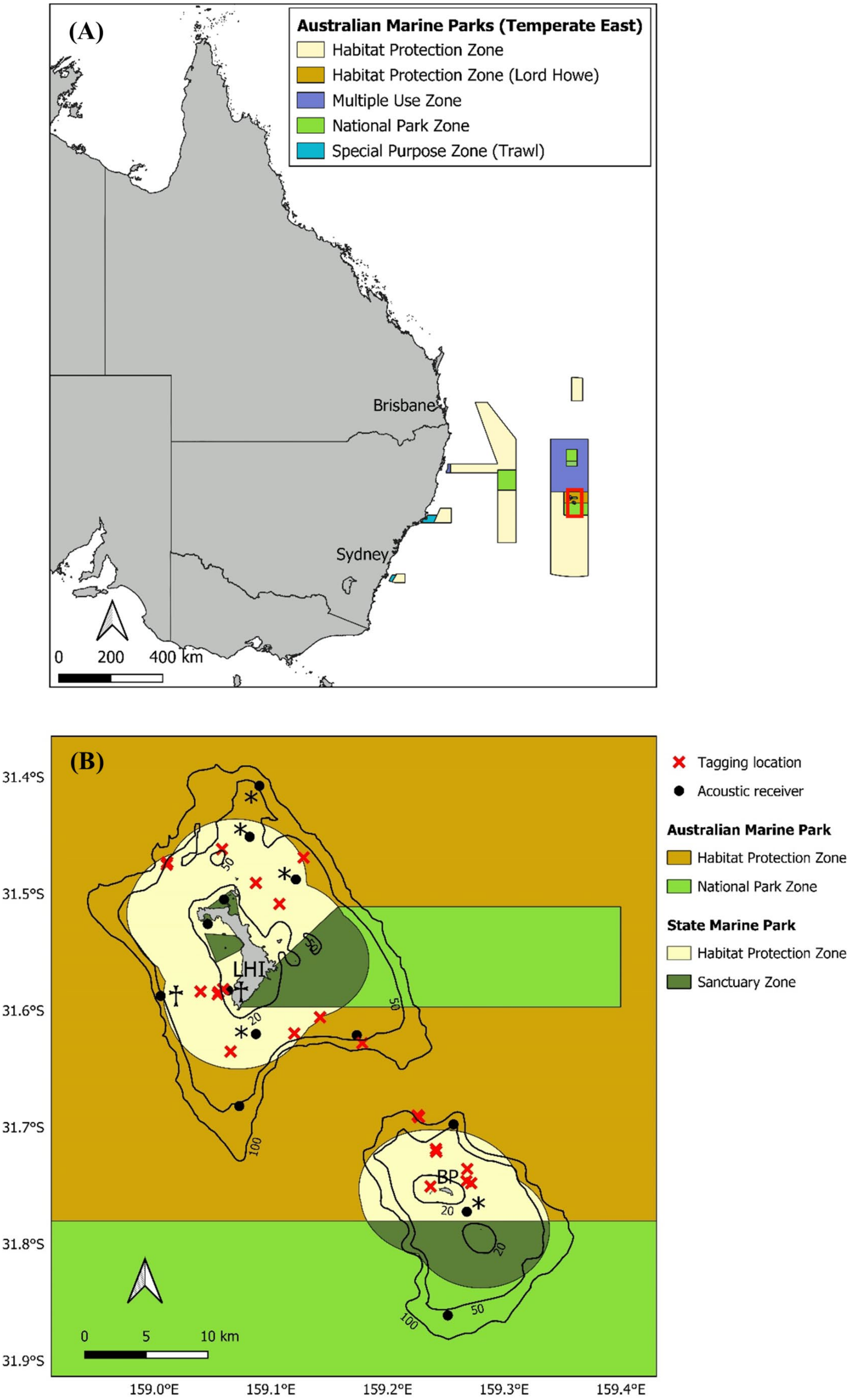

(A)
Australian Marine Parks (Temperate East)
Habitat Protection Zone
Habitat Protection Zone (Lord Howe)
Multiple Use Zone
National Park Zone
Special Purpose Zone (Trawl)
Brisbane
Sydney
0 200 400 km
(B)
Tagging location
Acoustic receiver
Australian Marine Park
Habitat Protection Zone
National Park Zone
State Marine Park
Habitat Protection Zone
Sanctuary Zone
LHI
BP
20
50
100
0 5 10 km
31.4°S
31.5°S
31.6°S
31.7°S
31.8°S
31.9°S
159.0°E
159.1°E
159.2°E
159.3°E
159.4°E

Fig. 1 (**A**) Map of Eastern Australia and the Australian Marine Parks Temperate East Network, including Lord Howe Island (red rectangle); (**B**) Detailed map showing acoustic receiver locations (black circles) and shark tagging locations (red crosses). 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

Howe Island Group World Heritage site listed in 1982 (Director of National Parks 2018). Fishing is prohibited in Sanctuary Zones and National Park Zones, which make up 27% (12,500 hectares) of the NSW State Marine Park and 8% (927,300 hectares) of the Australian Marine Park in Commonwealth waters, respectively.

Acoustic telemetry data collection

To collect data on the movement patterns of *Carcharhinus galapagensis*, 30 individuals ranging in total length from 96 to 177 cm (12 males, 18 females; Table 1) were caught throughout the marine parks surrounding LHI (Fig. 1) using line fishing. Fishing gear consisted of 14/0 Mustad™ non-offset circle hooks (with barbs crushed) baited with squid and/or pilchards, attached to a 1.5 m stainless steel wire trace, which was attached to a monofilament mainline of 100–400 lbs. Sharks were captured and brought onto the vessel for acoustic tagging, 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. The total length of the shark was measured and the shark was then rotated onto its dorsal surface to induce tonic immobility (Miranda-Paez et al. 2023), after which a small (2.5–3 cm long) incision was made in the lower abdominal portion of the shark, off the midline (to avoid the lateral abdominal and anterior intestinal veins). A V16 acoustic tag was inserted into the peritoneal cavity and the wound was closed with 3–4 interrupted, absorbable monofilament sutures, using a sterile half circle reverse cutting needle (37-mm length, thickness size 0, triangular profile, product 'HS37s', Braun MonoPlus®). The wound was sprayed with 10% betadine. Then, a tag from the NSW Department of Primary Industries Game Fish Tagging Program was inserted into the dorsal musculature of the shark to enable fishers to report if it was recaptured. Following removal of the hook, the shark was then returned to the water and its condition recorded. The tagging process took between 8 and 14 min.

An array of VEMCO VR2W acoustic receivers were deployed around the marine parks of LHI to detect tagged sharks (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 one and two and other equipment limitations. The receivers were located mostly in areas identified by fishers to be popular fishing grounds, to investigate the extent to which sharks utilised these areas and overlapped with fishing activity. One receiver was located at the southwestern end of LHI at a site where fish waste was regularly disposed, to investigate whether the dumping of fish waste was attracting sharks (Mitchell and Camilieri-Asch, pers. obs.). Two receivers were deployed in no-take zones to act as control sites (Fig. 1). Due to the limited number of acoustic receivers required to cover a large area, it was not possible to deploy more receivers in no-take sanctuary zones as controls. Acoustic receivers were retrieved and serviced every 12 months. 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. Only sharks with at least five detections were included in the analyses. Range testing was conducted in January 2021 by deploying a V16-6x-BLU-2 acoustic tag underneath a vessel at a depth of 2 m, 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 in the high-resolution vessel track against the time a detection was recorded on the receiver. Where a detection was recorded by the receiver, the precise GPS location was identified for that timepoint from the vessel track, to enable a distance measurements to be made between the vessel and the receiver in QGIS (QGIS Geographic Information System 2019). Detection ranges of 400 to 600 m were recorded for receivers in deeper water (> 20 m), with the one shallow receiver having a detection range of 400 m. For the deepwater receivers, this horizontal distance didn't take into account the depth, because the receiver was close the seabed and the tag at only 2 m depth, so the true range would be further than 400–600 m.

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 (Beggs et al. 2013) had a resolution of 0.02° x 0.02°. The 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°, from the MODIS sensor (IOCCG 2006). Percentage lunar illumination (between 0

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)	Total no. detections	Residency index
1280540	V16	96	F	21/01/2018	03:45	Northwest LHI shelf	31.473267	159.011283	8	0.002
1280541	V16	128	M	21/01/2018	04:15	Northwest LHI shelf	31.473267	159.011283	403	0.02
1280542	V16	137	F	21/01/2018	04:45	Northwest LHI shelf	31.47515	159.010833	69	0.01
1280543	V16	116	F	21/01/2018	05:35	Northwest LHI shelf	31.4618	159.05825	237	0.01
1280544	V16	121	M	23/01/2018	02:36	East LHI shelf	31.490867	159.087333	0	0
1280559 *	V16TP	127	M	23/01/2018	05:44	South LHI fish cleaning area	31.5818	159.059283	0	0
1280560	V16TP	155	F	23/01/2018	06:05	South LHI fish cleaning area	31.583833	159.039833	2410	0.21
1280561	V16TP	146	F	23/01/2018	06:15	South LHI fish cleaning area	31.58435	159.055383	8636	0.57
1280562	V16TP	136	F	23/01/2018	06:30	South LHI fish cleaning area	31.5863	159.054533	1104	0.19
1280563	V16TP	117	M	23/01/2018	21:52	South LHI shelf	31.6198	159.120267	3427	0.15
1280564	V16TP	121	M	23/01/2018	22:19	South LHI shelf	31.6198	159.120267	144	0.02
1280565	V16TP	116	M	23/01/2018	22:45	South LHI shelf	31.6198	159.120267	23	0.002
1280566	V16TP	117	F	23/01/18	23:00	South LHI shelf	31.6198	159.120267	35	0.004
1280567	V16TP	136	F	24/01/2018	00:45	South LHI shelf	31.6353	159.0656	369	0.02
1280568	V16TP	141	M	24/01/2018	04:15	East LHI shelf	31.508833	159.1075	1481	0.06
1280545	V16	116	F	24/01/2018	05:45	East LHI shelf	31.469067	159.128217	34	0.003
1280546	V16	115	M	24/01/2018	06:20	East LHI shelf	31.469067	159.128217	312	0.02
1280547	V16	156	F	26/01/2018	05:10	North BP shelf	31.689983	159.2259	45	0.01
1280548	V16	177	F	26/01/2018	05:47	North BP shelf	31.69145	159.227183	1847	0.22
1280549	V16	152	M	26/01/2018	06:05	North BP shelf	31.69145	159.227183	387	0.02
1280550	V16	138	F	3/02/2018	01:30	Close to BP	31.750883	159.237	13	0.003
1280551	V16	121	M	3/02/2018	02:21	Close to BP	31.746417	159.267733	53	0.005
1280552	V16	114	M	3/02/2018	03:03	Close to BP	31.74805	159.27185	243	0.02
1280553	V16	133	F	3/02/2018	03:19	Close to BP	31.74805	159.27185	306	0.03
1280554	V16	137	F	3/02/2018	03:42	Close to BP	31.7359	159.268467	495	0.04
1280555	V16	125	F	3/02/2018	05:14	North BP shelf	31.721017	159.241917	0	0
1280556	V16	125	F	3/02/2018	05:44	North BP shelf	31.71885	159.241633	408	0.03
1280557	V16	129	M	3/02/2018	22:41	Southeast LHI shelf	31.605917	159.14235	274	0.03
1280558	V16	115	F	4/02/2018	00:47	Southeast LHI shelf	31.628033	159.17845	1697	0.2
1280539	V16	138	F	4/02/2018	01:16	Southeast LHI shelf	31.628033	159.17845	194	0.01
1280559 +	V16TP	146	F	29/01/2019	02:50	South LHI fish cleaning area	31.584283	159.0595	279	0.05

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

and 100) was determined using the 'getMoonIllumination' function in the 'suncalc' package for R (Agafonkin and 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) and Rees et al. (2014).

Vessel monitoring system data

To determine the activity of registered charter fishing vessels in the marine parks surrounding LHI, VMS data was utilised. This VMS data was provided by the Commonwealth Government through a user agreement. VMS data was available for six charter fishing vessels from January 2018 to November 2019, after which it was only available for two charter vessels for the remainder of the study period until January 2021. Therefore, this VMS coverage does not represent the total level of charter fishing activity occurring around LHI. There are also a number of recreational fishing vessels that fish in LHI waters but do not have VMS. The VMS data was collected by the Collecte Localisation Satellites (CLS) Triton Advanced VMS units (https://www.iridium.com/products/triton-advanced/), which record latitude and longitude, speed, date and time for each vessel

Table 2 Acoustic receiver deployment details. LHI = Lord Howe Island, BP = Ball's pyramid

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 Sanctuary Zone (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 (National Park Zone)	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

every three minutes. 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 (noting that vessels always fish whilst drifting at LHI, because anchoring is prohibited). All spatial points inside the lagoon were also filtered out because the shallow water fishing that occurs in the lagoon was not the focus of this study. All VMS data was aggregated to avoid identification of individual vessels. Due to the COVID-19 pandemic, substantially lower levels of charter fishing occurred between March 2020 and October 2020.

Statistical analysis

Residency index and space-use patterns of *Carcharhinus galapagensis*

A residency index was calculated for each shark by determining the proportion of days detected from the total number of days in the study interval (D_t) (1060 days) (Kraft et al. 2023).This produced a conservative estimate of residency between 0 and 1, with 0 being no residency to 1 representing full residency, i.e. where the shark was detected every day for the 1060 day study period. To examine the space-use of sharks within the marine parks surrounding LHI, Kernel Utilisation Distribution (KUD) analysis was applied, using the package 'adehabitatHR' (Calenge 2021) in the R language for statistical computing (R Development Core Team 2015), to generate 50% 'core' and 95% 'extent' KUD areas for tagged *C. galapagensis* that were detected at ≥ 5 acoustic receivers. The 'href' reference bandwidth smoothing parameter and an output resolution of 300 were used to run the KUD analyses. There was enough datapoints to generate KUD areas for nine of the 30 sharks tagged.

Maps of KUD areas were generated in QGIS to visualise the spatial coverage of these KUD areas. A map was also produced to show the 50% and 95% KUD areas of all tagged sharks pooled, by creating a grid of 1 km cells and assigning values to each cell based on the number of individual shark KUD areas that overlapped with it. Values of 0 were assigned if no KUD area overlapped with a cell, a value of 1 for each shark 95% KUD area that overlapped with the cell or a value of 2 for each shark 50% KUD area overlapped with it. The final value for each cell was therefore the sum of all the 0,1 or 2 values from each individual shark.

Spatial and temporal patterns of fishing activity

Spatial variation in fishing activity 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. 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 for the overall study period. Spatial maps were also generated to assess the overlap of shark space use (KUD areas) and fishing activity. This was done by using the grid of 1 km cells previously generated for the shark KUD areas and combining the overall shark KUD values for each cell with the fishing activity KDE value for that cell.

To identify where shark detections and fishing vessel presence overlapped in time and space, the detections and VMS datasets were filtered to identify datapoints when sharks were detected and fishing vessels were present within the same hour on the same date and fishing vessels were within 1 km of the acoustic receiver location. This was calculated for both VMS points < 3 km.hr^{-1} and > 3 km.hr^{-1}. The length of time over which these overlaps occurred was then converted to a percentage of the total amount of time that fishing vessels were present within 1 km of all acoustic receiver locations.

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

Generalised Additive Mixed Models (GAMMs) were applied to quantify how fishing activity and environmental factors including depth, lunar illumination, sea surface temperature (SST), primary productivity (chlorophyll-*a*), bathymetric complexity and season, affected shark presence. The response variable in the GAMM 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 remained left-skewed after transformation, due to the large numbers of zeros. As a result, the Tweedie distribution was applied, being most suitable for this response data (Tweedie 1984; Tascheri et al. 2010; Coelho et al. 2016).

A full-subsets GAMM approach was used with the 'fssgam' package in R (Fisher et al. 2018). 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 to account for any spatial variation between the acoustic receiver locations. The number of receivers deployed 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 one (2018) to six in year two (2019) and three in year three (2020) (see Table 2).

To identify which predictor variables produced the best-fitting model, all variable combinations were ranked by AIC values (Akaike 1974). The most parsimonious model was determined as being within two AIC values of the lowest AIC and having the least predictor variables (Burnham and Anderson 2002; Fisher et al. 2018). A maximum of three predictor variables were allowed in this approach to prevent overfitting (Burnham and Anderson 2002; Zuur et al. 2009). The full-subsets approach also generated predictor variable importance values, which quantify the relative importance of all predictor variables tested and therefore provide another means for assessing which predictor variables have the strongest influence on the response variable (Fisher et al. 2018). Chlorophyll-*a* was included in the initial GAMMs, however due to gaps in data availability caused by numerous days with high cloud cover, this variable was omitted from the final models.

Survey of Lord Howe Island charter and recreational fishers

To collect further information on fisher-shark interactions, a survey was conducted with charter fishing operators ($n = 6$) and selected recreational fishers ($n = 4$), who together, constitute most of the fishing effort in this fishery. The survey was conducted through in person interviews and phone calls and included 25 open-ended questions to collect information on levels of fishing activity, fishing practices, gear used, the occurrence and impact of shark bycatch and depredation, and mitigation strategies that fishers used (see Supplementary Material for full list of questions). The data and information collected from this survey were collated anonymously to identify key themes.

Results

Residency index

Between January 7th 2018 and January 26th 2021, there were 24,933 detections recorded from the *Carcharhinus galapagensis* that were tagged. Of the 30 sharks tagged during this 3-year period, 28 were detected, with a minimum of eight detections for shark 1280540, up to 8,636 detections for shark 1280561. Sharks 1280544 and 1280555 were not detected across the study period. The residency index of *C. galapagensis* was highly variable across the study period, with residency index values ranging from < 0.01–0.57

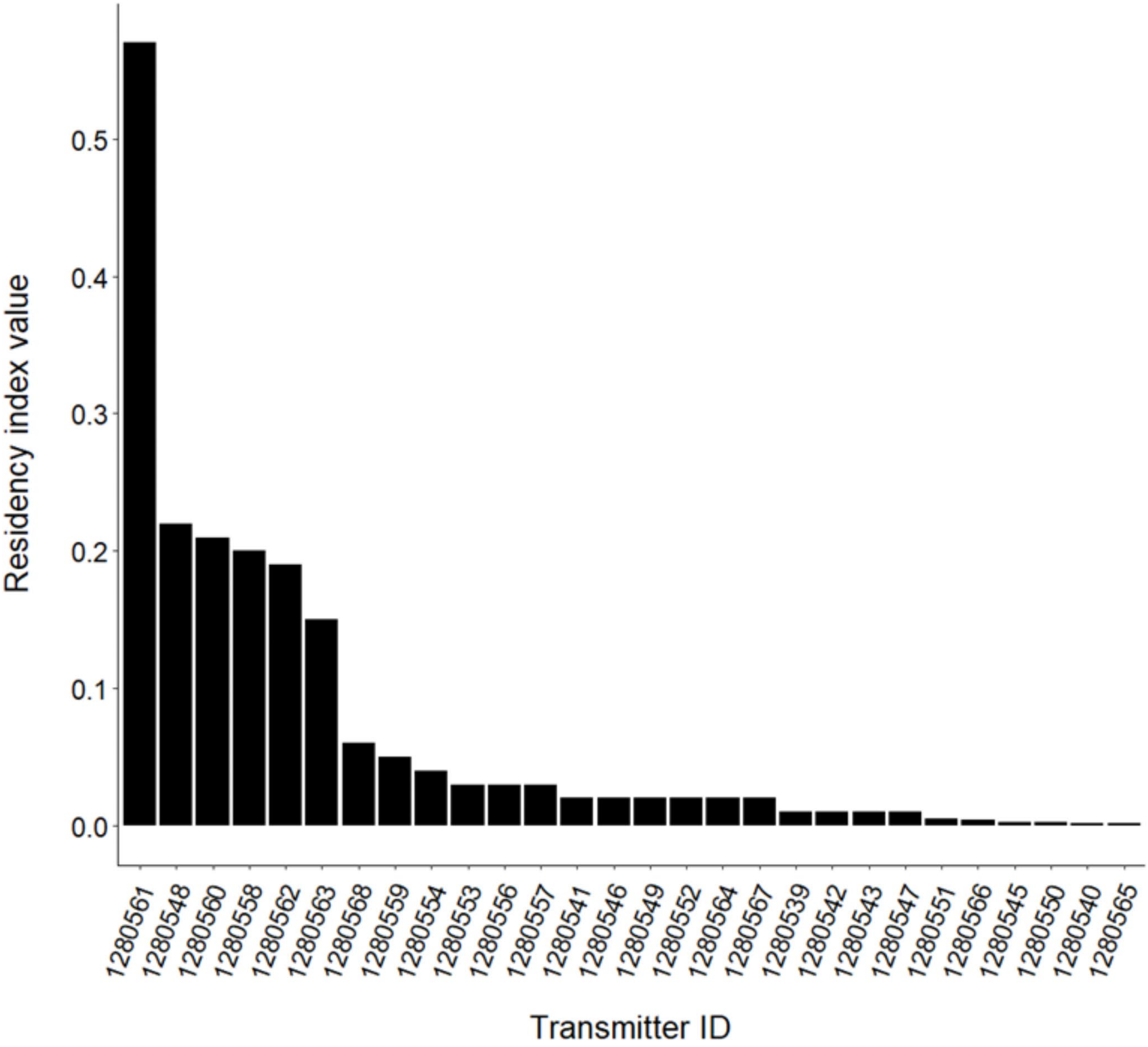


Fig. 2 Residency index (number of days detected/total number of days in study period) values for 28 *Carcharhinus galapagensis* detected between January 2018 and January 2021

(mean ± SE = 0.07 ± 0.02) (Fig. 2). The majority of tagged animals (22 out of 28) had low residency index values < 0.1, with the remaining six all > 0.15 (Fig. 2). Three of the four sharks tagged at the southwestern LHI fish cleaning area location had higher residency index values; 0.19 (shark 1280562), 0.21 (shark 1280560) and 0.57 (shark 1280561).

Home range areas of sharks

The 95% KUD areas of individual sharks showed a relatively large degree of variability, with some sharks having small home ranges centred around one or two acoustic receivers (Fig. 3d, e), whereas others had much larger home ranges, covering large parts of the LHI shelf and sometimes also the BP shelf (Fig. 3b, c, h). Five of the nine sharks for which KUD areas could be generated had 50% core home ranges centred around the northern most receiver on the LHI shelf (Fig. 3a, b, f, h, i).

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%). 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

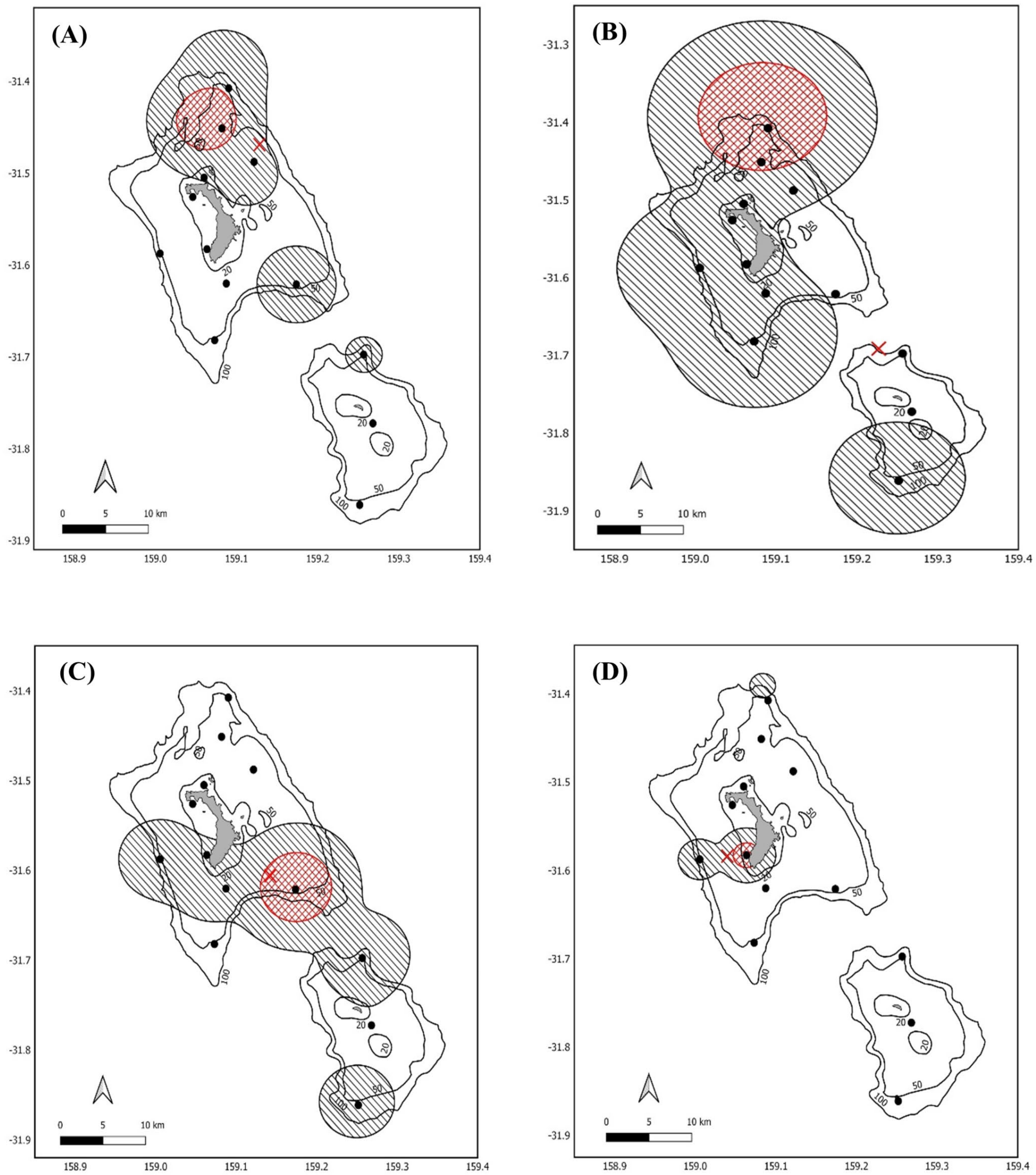


Fig. 3 Kernel Utilisation Distribution (KUD) plots for nine tagged Galapagos sharks. (**A**) shark 1280546; (**B**) 1280549; (**C**) 1280557; (**D**) 1280560; (**E**) 1280561; (**F**) 1280562; (**G**) 1280564; (**H**) 1280567; (**I**) 1280568. Black hashed areas represent 95% extent KUD, red crossed 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

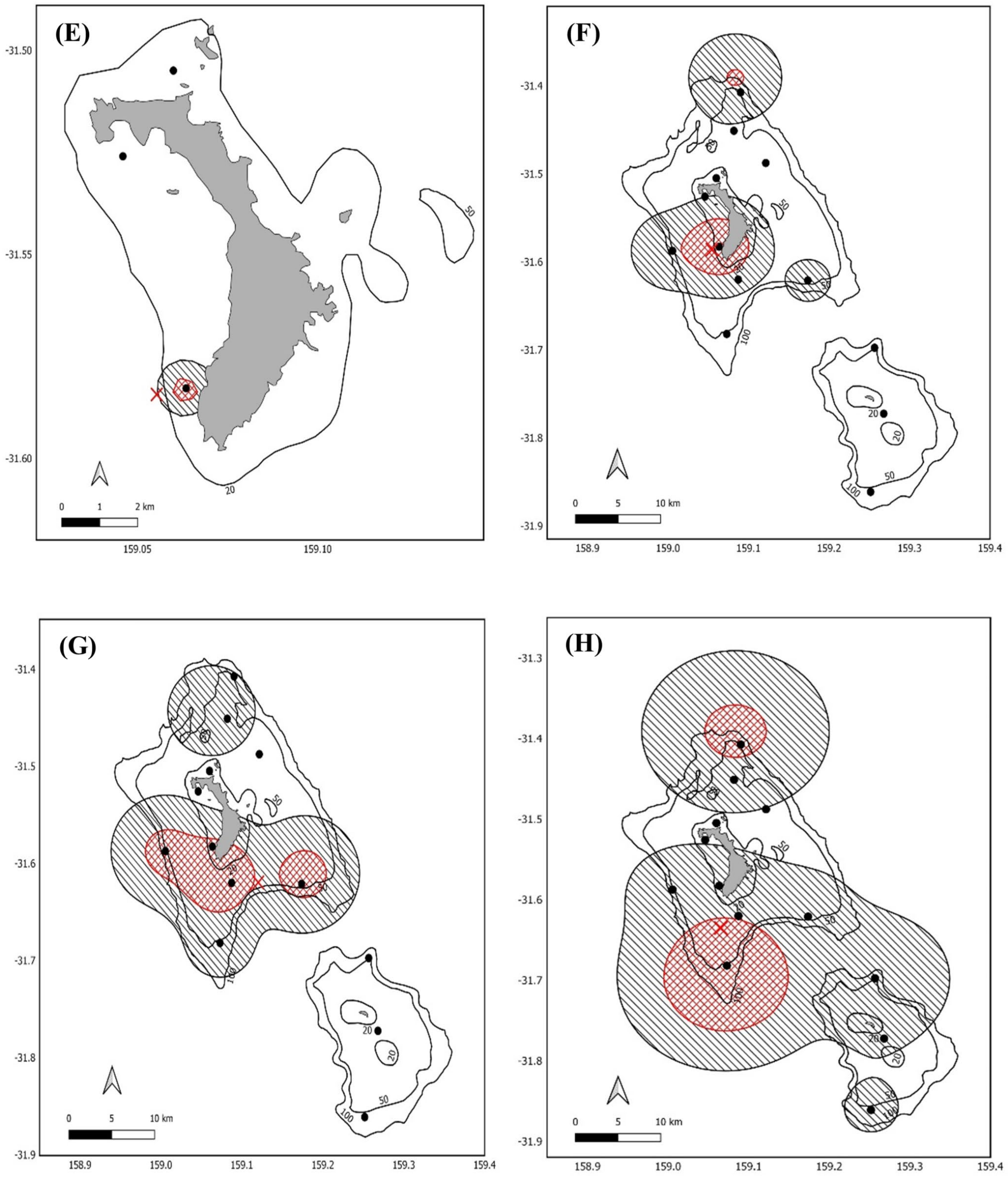


Fig. 3 (continued)

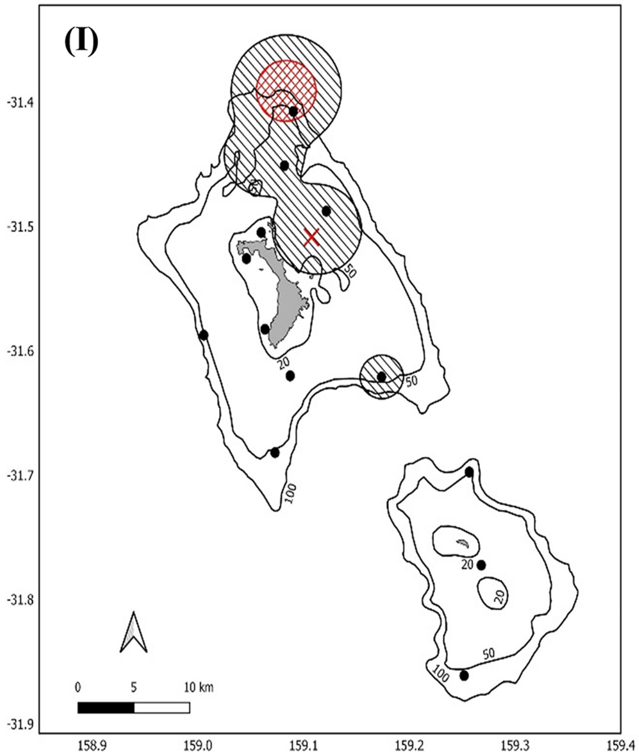


Fig. 3 (continued)

VMS points per 1 km radius; Fig. 4a). 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 (> 100 VMS points per 1 km radius; Fig. 4a) were close to the edge of the LHI and BP shelf edges, at depths between 40 and 150 m, especially along the northeast, southeast 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 to 30 m deep, particularly at the north end of LHI and around BP (Fig. 4a). The location close to the southwestern end of LHI received high levels of visitation (> 100 VMS points per km) from charter fishing vessels, which regularly cleaned fish and disposed of fish waste at this sheltered site. Raw VMS data also showed that this site was visited by at least one charter fishing vessel on 20% of days where fishing occurred.

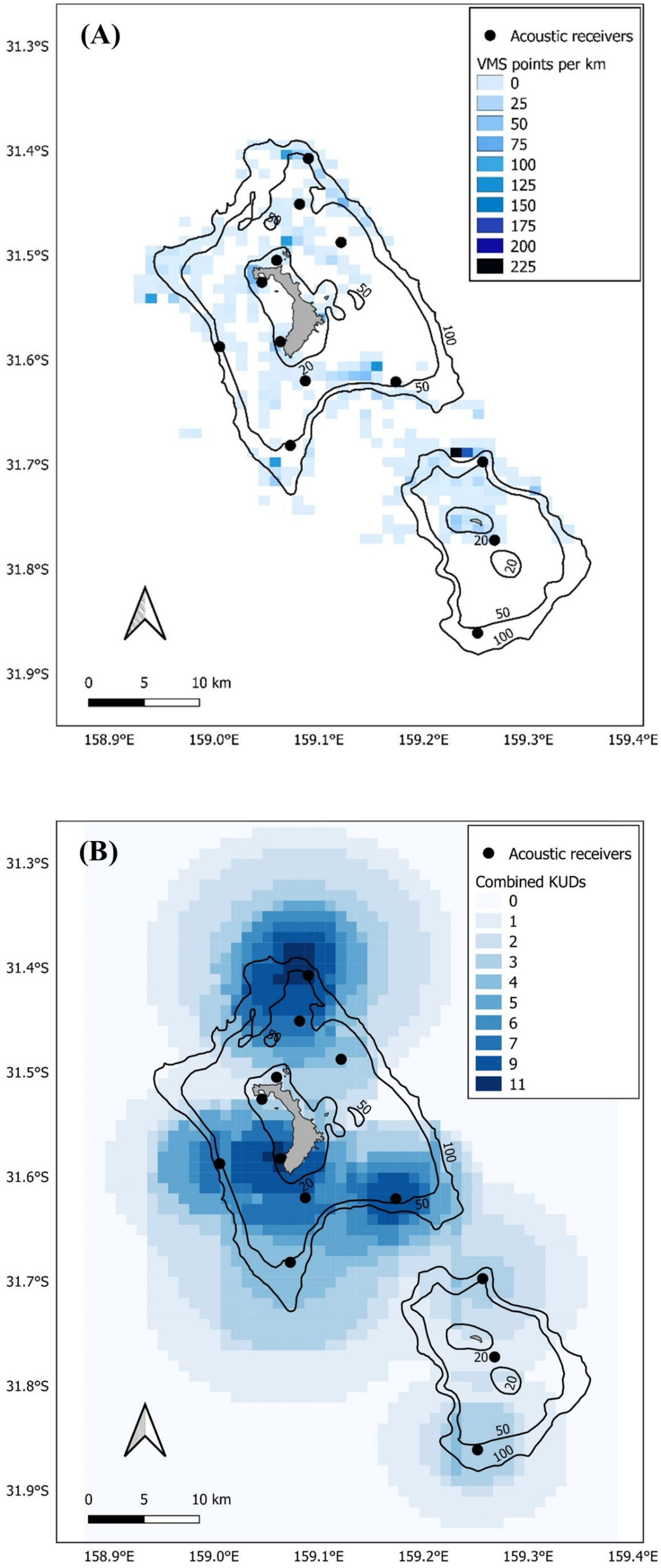
Spatial overlap between shark home range areas and fishing activity

When pooled together, the KUD areas of the nine *C. galapagensis* combined covered a large area of the LHI shelf, with high concentrations (values > 7) at the northeast section and across much of the southern LHI shelf (Fig. 4b). There was also a hotspot of overlap at the location close to the southern end of LHI shelf. The BP shelf had lower levels of usage (low values < 4) by tagged sharks (Fig. 4b). There were clear areas of high overlap (values > 66) between shark home ranges and fishing vessel activity at the four corners of the LHI shelf, near the shelf edges, and at the northern tip of LHI (Fig. 4c). The northern edge of the BP shelf and the site where fish waste was dumped at the southern end of LHI also had a high overlap between shark KUDs and fishing vessel activity (Fig. 4c).

Temporal patterns of overlap in shark movements and fishing vessel activity

There were 37 datapoints where shark detections and vessel movements overlapped in time and space (i.e. within the same hour and < 1 km from the receiver location). These occurred on 08 February 2019 at the South LHI fish cleaning area, 29 March 2019 at the Northeast BP shelf, and 11 December 2020 at the South LHI fish cleaning area. These 37 datapoints comprised a total time of 111 min. This 111 min when fishing vessels and sharks were both present represented 13% of the total time that fishing vessels were present within 1 km of receiver locations, (834 min, 278 datapoints). When including VMS points of any speed (i.e. those > 3 km.hr^{-1}), the number of overlaps was 148 over 20 days. Again, these were predominantly at the South LHI fish cleaning area, apart from on 29 March 2019 and

Fig. 4 Heatmaps of (**A**) fishing vessel activity as recorded from Vessel Monitoring System (VMS) data, with the scale showing number of VMS points in a 1 km radius; (**B**) Home range areas of nine tagged sharks combined, as represented by Kernel Utilisation Distributions (KUDs); (**C**) overlap values of (**A**) and (**B**) combined. Maps represent the period January 2018 – January 2021. Solid black lines with numbers show the 20 m, 50 m and 100 m depth contours. Black points indicate acoustic receiver locations



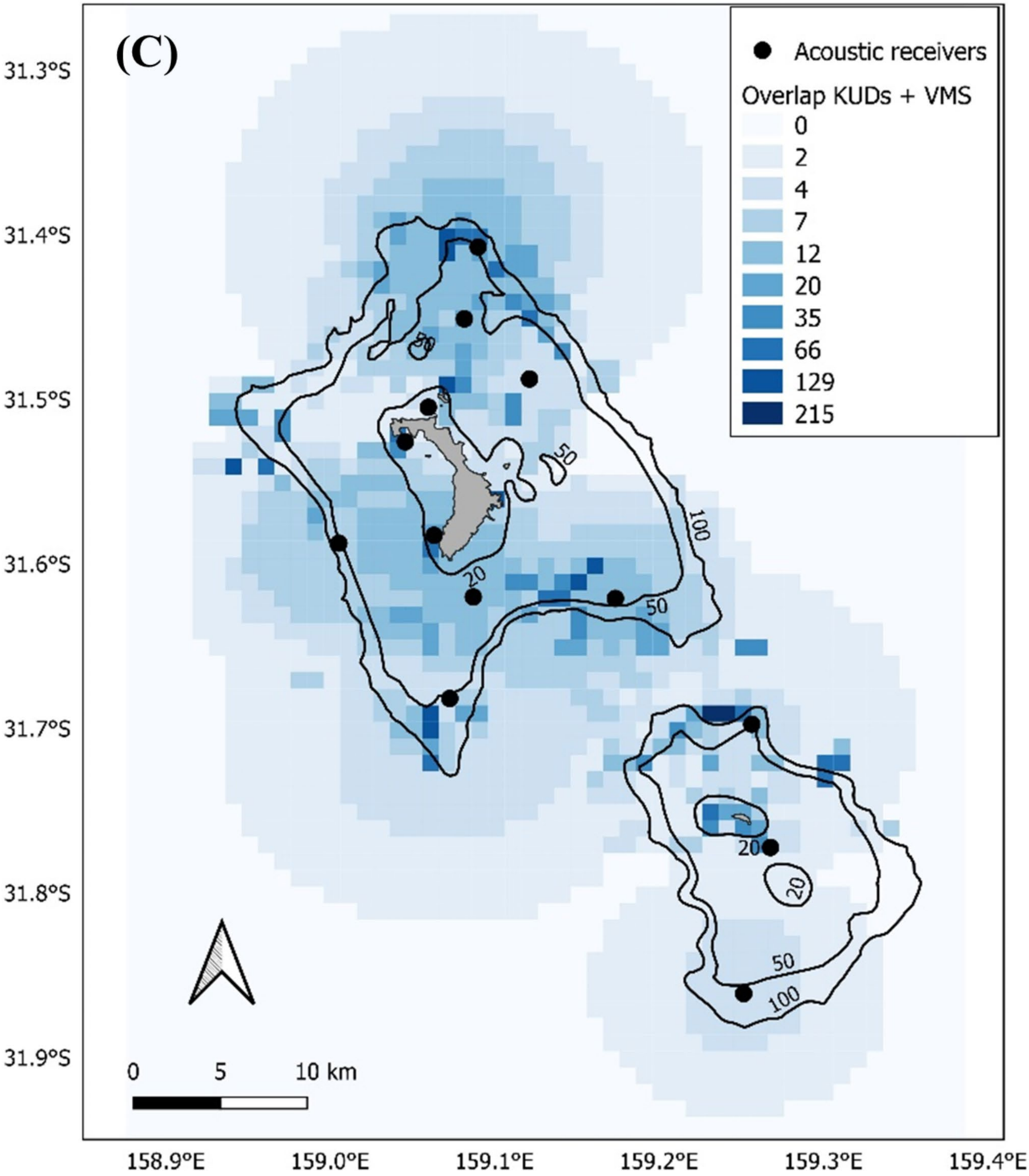


Fig. 4 (continued)

29 November 2019 at the Northeast BP shelf and on 26 December 2018 at the South LHI shelf acoustic receiver location. The 148 datapoints comprised 444 min of time when both sharks and fishing vessels were present, which equated to 10% of the total time (4332 min) that fishing vessels spent < 1 km from receiver locations.

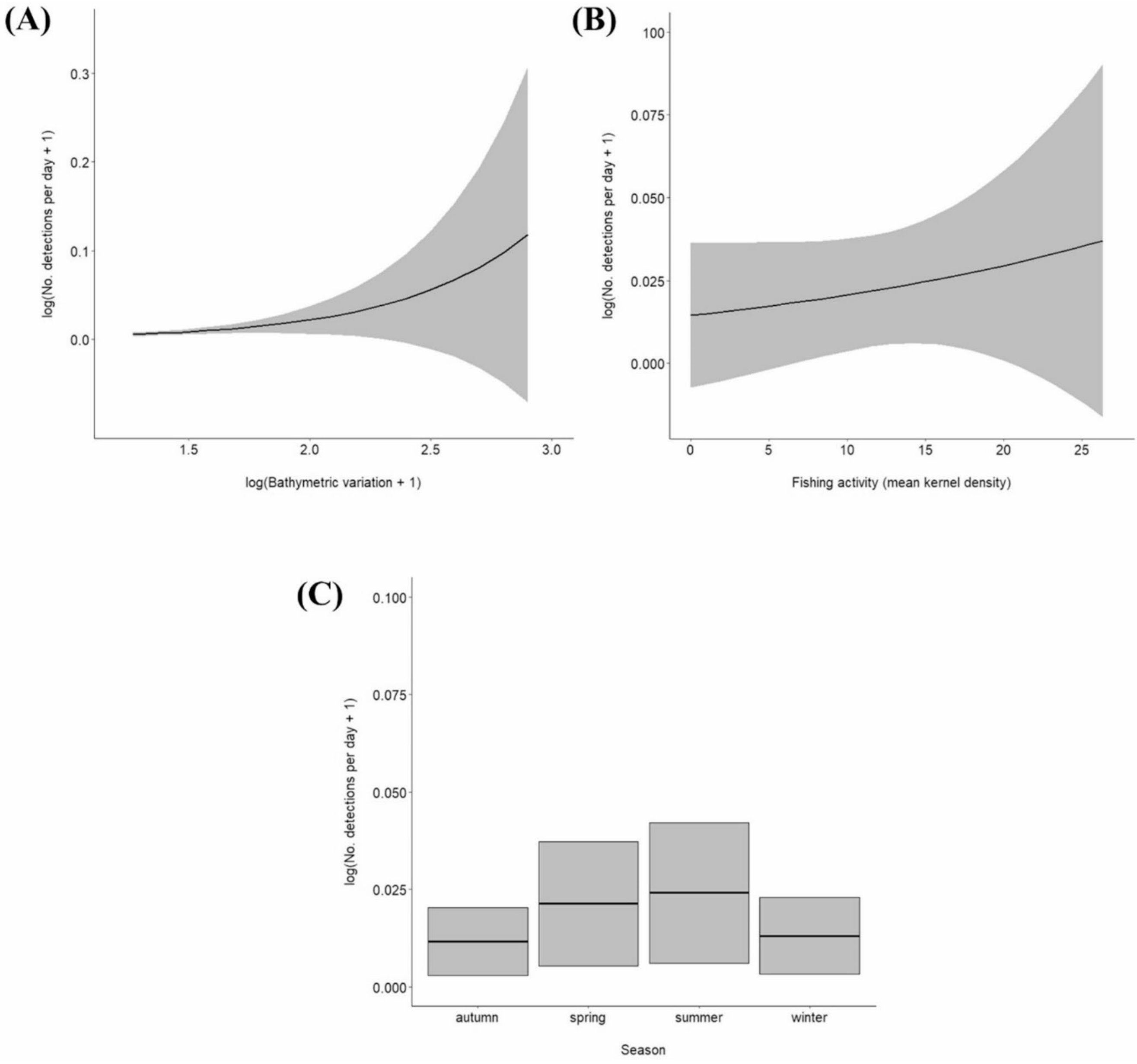


Fig. 5 Predictor plots showing the influence of the predictor variables in the best Generalised Additive Mixed Model (GAMM) on the response variable - number of *Carcharhinus galapagensis* detections per day. (**A**) Bathymetric variation (log + 1 transformed); (**B**) fishing activity (mean kernel density); (**C**) season. Solid black lines indicated the model predicted values and shaded grey areas show the 95% confidence intervals

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, and season and 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 S1). 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. Bathymetric variation displayed an increasing positive relationship with the number of *C. galapagensis* detections per day, peaking at maximum values of bathymetric variation (Fig. 5a). 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 (Fig. 5b). Season had a marked influence on *C. galapagensis* detections, with summer displaying the highest number of detections and autumn the lowest (Fig. 5c).

Survey of LHI charter and recreational fishers

The 10 fishers surveyed reported an average depredation rate of 50.6 ± 26% per trip. Gear loss was estimated to cost fishers \$96.9 ± 3.9 per trip. Depredation was reported to occur the most on the LHI shelf (by $n = 9$ out of 10 fishers), followed closely by the BP shelf ($n = 8$), then both shelves' edges ($n = 7$). Low levels of depredation were reported to occur near to shore and in the lagoon and deeper than 150 m. Seventy percent of fishers reported a clear seasonal pattern in *C. galapagensis* depredation, peaking in summer; although 30% of fishers did minimal fishing over winter. *Seriola lalandi* was reported to be most frequently depredated target species, followed by the silver trevally (*Pseudocaranx dentex*). Fishers noted that *C. galapagensis* avoided cod and other large, bottom-dwelling species (e.g. bass groper, *Polyprion moeone*), suggesting this may be due to their size and/or because they had spines.

Seventy percent of fishers reported changing their fishing practices to try to mitigate shark bycatch and depredation. The main methods included: changing locations/moving regularly (70% of fishers), using jigs and/or lures (70%), turning off their engine and/or echosounder (50%), trolling instead of drift fishing (30%), fishing shallower (< 30 m) or near the surface (< 10 m) (30%), deep fishing (> 100 m) (50%), using electric reels, winches or handlines (50%), not disposing fish waste at sea (10%) and not visiting the same fishing spots regularly (10%). The whole cohort of fishers observed that theses technique were only partially effective for reducing depredation. Some fishers believed that the historical switch from using handlines to rod and line has exacerbated depredation by sharks, because the fight time of fish is longer when using rod and reel, giving the sharks a greater opportunity to depredate hooked fish.

Regarding bycatch, fishers estimated catching 7.7 ± 4.2 *C. galapagensis* per trip. Seventy percent of fishers declared releasing all the bycaught sharks, while 30% kept some for local restaurants (on a demand basis) or for bird photography trips (where shark livers were kept to attract birds). Some fishers (20%) acknowledged having kept all shark bycatch in the past, when the commercial shark fishery was still active (25 + years ago). Only one fisher reported removing hooks from all sharks being released. In terms of logbook reporting, only one fisher stated that they report all shark interactions, including bycatch and depredation. All fishers reported cleaning fish and disposing of fish waste while in transit. Some fishers ($n = 2$) acknowledged cleaning at specific locations when the weather was rough, such as outside the north or south passages of the lagoon or at the southwestern end of LHI, as indicated previously.

Discussion

Residency index of sharks

The residency index of the tagged *Carcharhinus galapagensis* in the marine parks surrounding the acoustic receiver array at LHI was relatively low (< 0.1) for most individuals, apart from six sharks which were resident at the southwestern LHI fish cleaning area and north BP 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. With a larger array of receivers covering more fished and non-fished sites, it would be possible to explore the influence of fishing activity on residency patterns in more detail. The use of total study interval rather than the dates between first and last detection to calculate the residency index also likely led to lower values, because this method represented a more conservative approach which can underestimate true residency (Kraft et al. 2023), because it did not capture, for example, if a shark had died or left the area during the 1060 day study period.

The presence of consistent food in the form of fish waste discarded from fishing vessels, may have led to the higher residency of sharks tagged at the southwestern LHI fish cleaning area. Additionally, the occurrence of temporal overlaps, where tagged *C. galapagensis* were detected and fishing vessels present, at this site at the same time, supports the hypothesis that fishing vessel activity was influencing shark behaviour and residency. The three sharks with high residency at this location (1280560, 1280561 and 1280562) also had the smallest KUD areas, centred around this site (Fig. 3).

Spatial overlap between fishing activity and shark movements

The current study identified key areas where high overlap between *C. galapagensis* KUD areas and fishing activity occurred. The presence of bait, injured fish struggling on a hook, and/or released fish, are all factors that represent a comparatively energy-efficient food source for sharks compared to pursuing prey naturally (Mitchell et al. 2018b). Therefore, the regular occurrence of fishing and fish waste disposal in specific 'hotspots' may be leading to the formation of behavioural associations in *C. galapagensis*, 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 and Brown 2014; Vila Pouca and Brown 2018) and in wild sharks (Mitchell et al. 2020; Heinrich et al. 2021). Ecotourism provisioning, for instance, has been found to alter shark movement patterns and behaviour in some studies (Brunnschweiler and Barnett 2013; Brena et al. 2015; Mourier et al. 2021; Hammerschlag et al. 2022), although not in others (Maljković and Côté 2011; Hammerschlag et al. 2012; 2017). A recent study by Robinson et al. (2022) also investigated the spatial overlap of fishing activity and shark abundance by asking fishers to map their main fishing areas and by measuring shark abundance from Baited Remote Underwater Video (BRUV) deployments. This led to the creation of spatial overlap maps similar to the current study, which showed that outer reef habitats had the highest overlap (Robinson et al. 2022). Work by Casselberry et al. (2024) identified a discrete area in Bahia Honda, Florida, where there is a high overlap between the presence of Atlantic tarpon (*Megalops atlanticus*), great hammerhead sharks (*Sphyrna mokarran*) and fishing vessels targeting the Atlantic tarpon.

The overlap between fishing activity and *C. galapagensis* movements at shelf edges may have also occurred because these areas support higher productivity, due to current patterns bringing nutrient-rich water from depth via upwellings, as seen at other seamounts (Klimley and Butler 1988; Coelho and Santos 2003; Klimley et al. 2005; Genin and Dower 2007; White et al. 2007). These areas would therefore offer productive fishing grounds where fishers and *C. galapagensis* were both targeting the same fish species. Similar competition for resources has been documented where silky sharks and oceanic whitetip sharks (*Carcharhinus longimanus*) co-occur with tuna species, which are simultaneously targeted by commercial fishers (Tolotti et al. 2020; Young and Carlson 2020). Larger scale studies have also documented a high degree of overlap between longline fishing activity and a range of pelagic shark species (Queiroz et al. 2019).

Temporal patterns of overlap in shark movements and fishing vessel activity

Temporal overlaps between shark detections and fishing vessel presence were recorded at three of the acoustic receiver locations, although the vast majority occurred at the southwestern LHI fish cleaning area. This reflects the higher residency of sharks at this location and that fishing vessels were present at this location on 20% of days. The fact that shark detections and fishing vessel presence overlapped on 13% of the total time that fishing vessels were present and likely fishing at all receiver locations is relatively high when considering the low number of *C. galapagensis* tagged as part of this research, the large area of the shelf waters around LHI and BP (765 km^2), the small number of receivers deployed and the fact that some were lost throughout the study, as well as the small detection range of the acoustic receivers (400–600 m). Additionally, VMS data does not account for all the charter fishing activity at LHI or any of the 5–10 smaller recreational fishing vessels.

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 emphasises the possibility that *C. galapagensis* 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 *C. galapagensis* 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 *Seriola lalandi* in the marine parks surrounding LHI (Rees et al. 2018). This may reflect the fact that these areas support greater prey assemblages, and thus attract both *C. galapagensis* and *S. lalandi*, which are two of the main predator species found at LHI (Rees 2013). Additionally, larger *C. galapagensis* may prey on *S. lalandi* directly, in some cases. Season also exerted an important influence on *C. galapagensis* 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 due to more favourable environmental conditions for *C. galapagensis*, including changes in current patterns, productivity and water temperature.

Mitigating negative fisher-shark interactions

The combination of shark movement patterns and fishing vessel activity data, along with the broader contextual information collected from fishers through the survey, provides a holistic assessment of the negative fisher-shark interactions that are occurring in the marine parks surrounding LHI. It was clear that fisher-shark interactions are happening regularly and led to negative consequences for fishers, including lost bait, target fish and fishing gear, costing on average $97 per trip, as well as potential declines in charter fishing tourism. The interactions can also have negative impacts for sharks, such as injuries resulting from retaining hooks in their jaw/throat/digestive tract after being released, or mortality from harvesting. Anecdotally, this conflict is reported to have increased in the last 5–10 years. Such continued loss of revenue and customer satisfaction is detrimental to charter fishing businesses. Also, the risk of increased mortality of *C. galapagensis* due to continued high bycatch levels (Figueira and Harianto 2022) and removal of sharks by fishers could represent a threat to this population, which is considered to be genetically isolated (van Herwerden et al. 2008) and thus at greater risk of decline from anthropogenic pressures. Research from other locations where depredation is a significant concern highlights this increased risk to sharks. Casselberry et al. (2022) reported that charter fishing guides in the USA were more likely to target and harvest sharks due to experiencing depredation. Similarly, Prasky et al. (2023) found that Gulf of Mexico recreational fishers who experienced depredation rates > 10% supported fisheries management policies to either reduce or maintain shark populations at current levels. Robinson et al. (2022) found that depredation is causing a loss of support for the Maldives shark sanctuary, with 12% of fishers reporting that they kill sharks intentionally to try and reduce depredation. Likewise, Drymon and Scyphers (2017) reported that a subset of recreational fishers were unwilling to support shark conservation, due to their perception that increasing populations of large coastal shark species are threatening their fishing opportunities.

There is a pressing need to identify potential methods for reducing negative fisher-shark interactions at given locations, including LHI. The current study has identified a number of approaches for doing this. Firstly, the identification of spatial ‘hotspots’ where overlaps of shark movements and fishing vessel activity are high enables fishers to make more informed choices about selecting fishing sites to reduce the likelihood of encountering sharks. Moving sites frequently to avoid sharks can also help reduce depredation and this technique has been documented in a number of other studies as being one of the key strategies used by fishers (Iwane and Leong 2020; Tixier et al. 2021; Robinson et al. 2022; Coulson et al. 2022). However, to be effective, distances moved will likely need to be substantial (e.g. on the order of kilometres), with transiting occurring at high speed, so that the same sharks do not follow the boat. Reducing the likelihood of attracting sharks by turning off the engine and echosounder and switching from bait to lures and jigs can also bring benefits, with some LHI fishers already using these methods. Fishers in the Marianas Islands noted much lower shark depredation rates when using smaller boats with different engine types, as well as kayaks (Iwane and Leong 2020). Changing from rod and reel to electric reels or handlines, along with using heavier breaking strain line, enable hooked fish to be brought to the boat more quickly. Fishers surveyed in the current study and in Western Australia (Coulson et al. 2022), have reported making these gear changes, with some level of success. Anecdotal reports from fishers at LHI suggest that shark interactions occur most frequently between 50 m and 100 m, with sharks rarely occurring at depths beyond 150 m. This reflects depth preferences identified from satellite tagged *C. galapagensis* at other locations (Wetherbee et al. 1996; Meyer et al. 2010; Madigan et al. 2020). Some LHI fishers have thus changed their practices to only fish in deeper water where they know they will encounter fewer sharks. However, this may be limited for local charter fishing operators whose customers prefer to target *S. lalandi* between 50 and 100m.

The strong focus of the LHI charter fishing operators on this one target species (*S. lalandi*) is likely to be exacerbating the occurrence of depredation, because the *S. lalandi* co-occur in the same depths and areas as *C. galapagensis*. Diversifying the fishing strategies to target more species at different depth ranges may therefore be another approach that could reduce the frequency of shark interactions. Fishers surveyed in this project reported lower occurrence of depredation on spiny demersal fish species, such as cods, compared to pelagic species like *S. lalandi* and trevally, although these demersal species are targeted much less frequently, so the chance of observing them being depredated was lower. Avoiding the dumping of fish waste at fishing locations will also help to reduce the likelihood of sharks associating fishing vessels with food. It is therefore recommended that fish should only be cleaned at sea when moving at a reasonable speed and this should be done in a different location each time. Additionally, fish waste bins and a composting facility have recently been installed on LHI, which provide fishers with the option of retaining their fish waste for disposal on land. Fish waste is being utilised as a premium compost in other parts of Australia, and thus could be an option for LHI as well. Lastly, shark deterrent devices could be used to reduce shark depredation and bycatch at LHI. A number of commercially available devices that use electrical, magnetic or acoustic stimuli to deter sharks have recently been designed to mitigate shark depredation during fishing (e.g. OceanGuardian Fish02, Sharkbanz Zeppelin, SharkStopper, Fishtek SharkGuard, RPELX). Ongoing research in Western Australia established a methodology for testing these devices and interpreting the results, reporting that depredation rates were significantly lower when deterrents were present versus absent (Coulson et al., in review). These devices should therefore be tested at LHI to assess their effectiveness on *C. galapagensis* in this local fishery.

Conclusion

This research developed an integrated approach applying acoustic telemetry, vessel tracking and fisher consultation to understand the dynamics of fisher-shark conflict occurring at LHI. In doing so, the work has identified key approaches for mitigating this conflict, focused around developing practical measures that fishers can immediately implement themselves to manage the issue. This information has been communicated to fishers and the LHI community through a set of co-designed, best-practice guidelines (Figure S2). These guidelines are also being promoted via face-to-face meetings with fishers and through a range of media channels, including the local Marine Park newsletter, the LHI newspaper, social media avenues (DPI, Parks Australia) and via direct distribution to local fishers and residents. When managing fisher-shark conflicts in small communities, it is vital to incorporate the knowledge of fishers and local residents and the contextual background of the fishery to produce meaningful results that can be effectively and sustainably applied, to address negative impacts occurring from these conflicts. The holistic model applied here to investigate the fisher-shark conflict occurring at LHI has direct relevance to similar issues occurring in other fishing communities around the world, therefore future work should aim to use this approach to improve the sustainability of fishing and socio-economic outcomes for fishers and promote co-existence with sharks.

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Author contributions All authors contributed to the study conception and design. Fieldwork and data collection were undertaken by JDM, VCA, SG and FRAJ. Data analysis were performed by JDM and VCA. Logistical support was provided by SG, FRAJ, VP and TJL. The first draft of the manuscript was written by JDM and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability The acoustic telemetry data generated and analysed in this study is available on the Integrated Marine Observing System Animal Tracking Facility database, which is publicly accessible at: https://animaltracking.aodn.org.au/. Vessel tracking data is not publicly available due to it containing sensitive information about fishing locations.

Declarations

Compliance with ethical standards Animal ethics approval for this research was received from the New South Wales Department of Primary Industries Animal Care and Ethics Committee (permit no. ACEC REF 17/03 – LHIMP). Human ethics approval was received from The University of Western Australia Human Ethics Committee (approval no. RA/4/20/6218). Informed consent was obtained from all individual participants included in the study. The research was also covered by marine parks research permits from Parks Australia: (1) Permit to conduct scientific research in the Lord Howe Marine Park (permit no. PA2018-00060-1); (2) Permit for access to biological resources from Commonwealth areas (permit no. AU-COM2018-390) and New South Wales Department of Primary Industries, Marine Parks: 1) Application for a Marine Parks permit for Lord Howe Island Marine Park (permit no. LHIMP/R/17005/31112017).

Conflict of interest The authors have no conflicts of interest to declare.

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