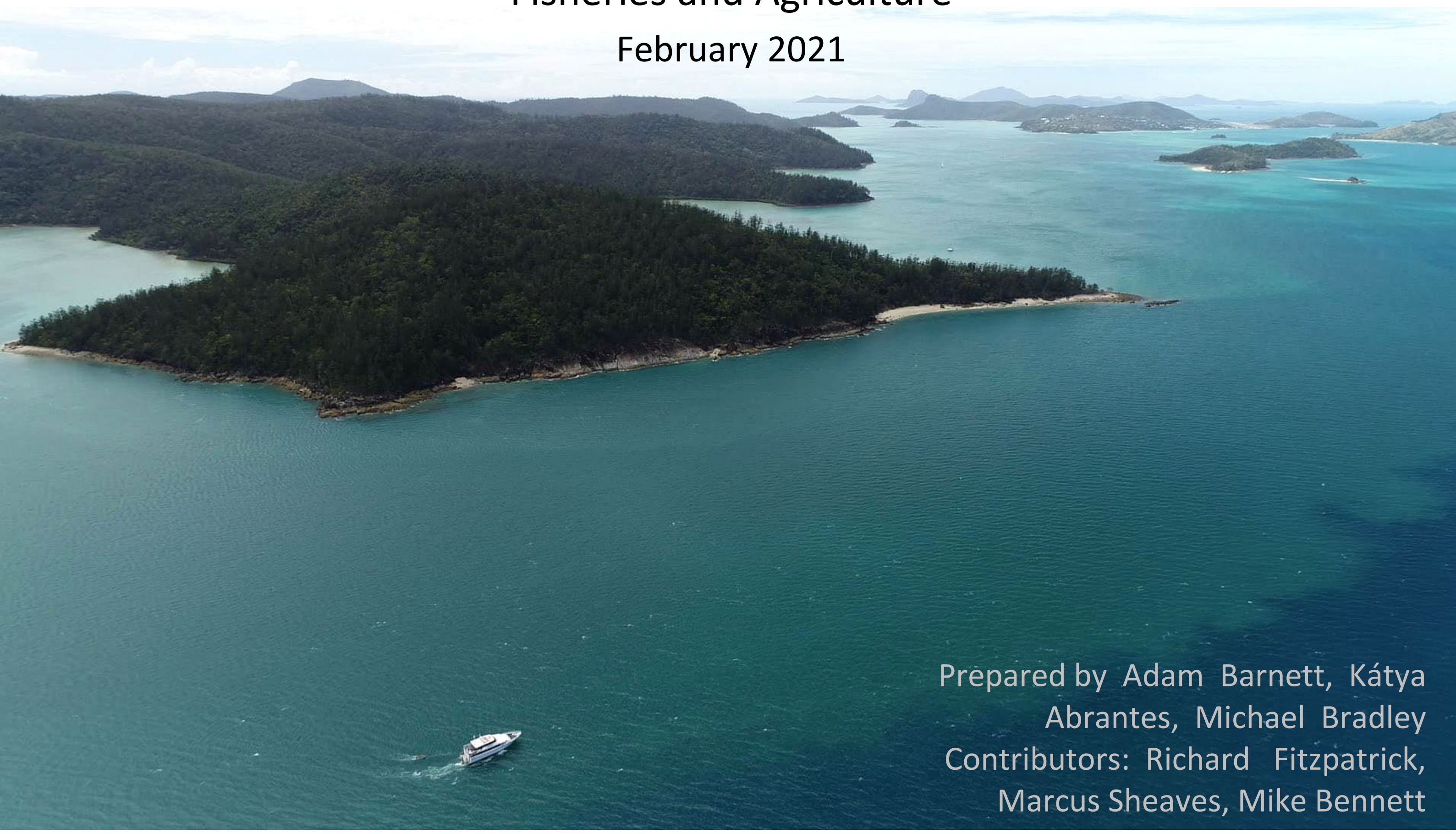
Prevalence and Behaviour of Sharks in Cid Harbour

A report for the Queensland Department of Fisheries and Agriculture

February 2021



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Executive Summary

The present study was commissioned by the Department of Agriculture and Fisheries (Queensland Government) in response to three shark bite incidents that occurred in Cid Harbour, Whitsunday Islands, between September and November 2018. The main objective of the project was to investigate the prevalence and behaviour of sharks in the Cid Harbour region, with particular focus on potentially dangerous species. A range of sampling methods were used, including catch methods (single hook droplines, longlines, surface lines, rod and reel), baited remote underwater video cameras (BRUVs), and acoustic and satellite tracking. Side-scan sonar was also trialled to assess if this method was suitable for assessing prey availability in Cid Harbour.

Eleven shark species were documented for the area, including tiger sharks and bull sharks, which together comprised 20% of the sharks caught/sighted over the five field trips. Smaller carcharinids have also been documented to bite humans (e.g. in Australia, these species have been implicated in ca. 20% of shark bites) and were the most commonly caught/sighted sharks (54% of all sharks). However, despite intensive fishing and BRUV effort throughout the study, shark catches and sightings in BRUVs were not higher than what we would expect based on previous projects the authors have worked on and the published literature.

For the tracking component of the study, 20 sharks were tagged with satellite transmitters and 43 with acoustic transmitters. Acoustically tagged sharks were tracked by an array of 20 acoustic receivers deployed in Cid Harbour and in key points around the Whitsunday Islands. Movement data suggests that sharks move through Cid Harbour as they use the broader Whitsundays region, but residency in the harbour itself was low for most individuals, with 79% of all sharks tagged visiting the harbour on less than 10% of days at liberty. Some sharks moved long distances, including a bull shark that moved to the Torres Strait and back to the Whitsundays (>2500 km round trip), another that moved ~2000 km south to Sussex Inlet NSW, and one tiger shark that moved >3700 km to the Solomon Islands.

Bull sharks and tiger sharks are two of the three species commonly implicated in shark bite incidents worldwide, and for this reason it has been speculated that these species may have been responsible for one or more of the Cid Harbour bites. In terms of shark behaviour and potential for human interactions, available information suggests that bull sharks are not a continual risk to humans in Cid Harbour, as their occurrence and residency is not high, but Cid Harbour is part of the broader movement paths of

some individuals. Likewise, tracking data shows that tiger sharks move widely over the Whitsundays region, passing through areas of high human use (such as Cid Harbour), but do not reside in particular locations for extended periods, suggesting that the risks associated with tiger sharks are not constant.

Overall, this study did not identify anything unusual about shark relative abundance or movements in Cid Harbour that may have contributed to the cluster of shark bite incidents in 2018. The results indicate that the area is similar to other inshore, turbid, locations along the Great Barrier Reef. However, the number of boats using Cid Harbour can exceed 100 per day, and many throw food scraps overboard, some intentionally attracting sharks with food. Such activities can attract sharks to a location and possibly to boats, and may contribute to an increased risk of shark bite incidents. Furthermore, the context of the shark bite incidents that occurred in Cid Harbour in late 2018, i.e. the three incidents involved people getting bitten almost instantly after jumping into the water, was unusual, again suggesting that the regular feeding/dumping food scraps from boats could have played a role in those shark bites. Stakeholders are currently working together to improve waste disposal practices in the region.

It would be valuable to continue monitoring the shark community in the Whitsundays region, including expanding into areas of high tourism use (anchorages, swimming/snorkelling and fishing areas) across the broader Whitsundays region, along with the simultaneous monitoring of environmental conditions (e.g. turbidity, rainfall, water temperature). Information obtained would be useful for the development of appropriate, site-specific, shark mitigation strategies, e.g. limiting in-water activities at peak times of shark occurrence or during unfavourable conditions (e.g. high turbidity), or closing certain areas to swimming. Furthermore, since the overlap in site use by different stakeholders (e.g. snorkelers and fishers) has been proposed as a contributing factor to negative shark interactions, information on both shark and human behaviours could be used in the development of localised shark bite mitigation strategies. A longer-term shark behavioural study also has the potential to contribute information for the science behind the current shark safety (SharkSmart) guidelines.

Introduction

Although the probability of a shark biting a human is extremely low, the number of shark bite incidents has increased over the last three decades (Chapman and McPhee 2016, Ryan et al. 2019). Any increase in shark-human incidents leads to disproportionate media coverage, drawing public interest and often escalating public concerns (Chapman and McPhee 2016, Ryan et al. 2019, Hardiman et al. 2020). Over the last decade, there have been clusters of shark bite cases around Australia, where a number of people were bitten over a relatively short period of time in a given area, e.g. in southern Western Australia (2012-2013), northern NSW (2015-2016) and more recently in the Whitsundays, Central Queensland (2018-2019). The rise in shark incidents and, in particular, what drives these clusters has been debated, and in some part attributed to human population growth and an increased number of people participating in marine-based activities (Chapman and McPhee 2016). It is predictable that the more people in the water, the higher the chances of someone being bitten, but an increase in water-based activities such as fishing and live-aboard boating can also increase the chances of attracting sharks to areas heavily used by humans. Other factors implicated in an increase of shark bite numbers include changes in prey availability, changes in environmental conditions (e.g. climate change, habitat degradation), changes in sharks' behavioural patterns (e.g. movements and distributions; including changes due to human activities) and increased shark abundance (Chapman and McPhee 2016). However, for the vast majority of locations where shark bites occurred, there is limited information about the local shark community. Often, basic information, such as which shark species occur in the area, their relative abundance or behaviour, is lacking, hindering an understanding of the drivers of the observed increase in shark-human interactions. Understanding shark occurrence and behaviour is critical for predicting areas/times of greater risk and developing appropriate, site-specific shark mitigation strategies (Payne et al. 2017; Lemahieu et al. 2017, Lagabrielle et al. 2018, Soria et al. 2019; Lee et al. 2019).

The Whitsundays region of Central Queensland is one of the two largest tourism hubs in the Great Barrier Reef Marine Park (Great Barrier Reef Marine Park Authority 2019). Most of its visitors and locals engage in in-water (snorkelling, diving, spearfishing) and on-water activities (fishing, bare boat charters). However, despite being heavily used for human activities, until the cluster of shark bites in late 2018 and late 2019, the region had not had a history of negative shark interactions. Prior to 2018, only four nonfatal shark bites were recorded in the region, spread between 1977 and 2000 (International Shark Attack File).

In response to three shark bite incidents that occurred in a short time frame (between September and November 2018) in Cid Harbour, Whitsunday Island, the Department of Agriculture and Fisheries (DAF, Queensland Government) commissioned a scientific study to investigate the prevalence and behaviour of sharks in the Cid Harbour region. The initial one-year project was expanded to mid-2019 through additional funding provided by the Australian Government's National Environmental Science Program, which allowed for two further sampling trips to be undertaken, an expansion of the acoustic array and testing side-scan sonar for assessing prey availability in Cid Harbour.

The specific aims of the present study are therefore to 1) identify the shark species that occur in Cid Harbour and estimate their relative abundance, with a particular focus on species that are potentially dangerous; 2) describe the sharks' movement behaviour, including habitat use and residency within Cid Harbour and in the broader Whitsundays region; and 3) test methods that could be used to assess prey availability in Cid Harbour, to investigate if prey availability could be a factor driving shark occurrence and/or movement behaviour. Shark occurrence and behavioural data is also interpreted in the context of the behaviours of recreational water users (Smith et al. 2020). The overall objective is to provide information that could assist in developing solutions to mitigate shark bite risk in the Whitsundays region in the future.

Methods

This study was conducted in the Whitsunday Islands, with a particular focus on the area between Sawmill Bay and Dugong Beach (Cid Harbour), where the three shark bite incidents took place (Fig. 1). Five week-long field trips were conducted between December 2018 and January 2020 (December 2018, June 2019, September 2019, December 2019 and January 2020) to investigate the species composition, occurrence and behaviour of the shark community using Cid Harbour. A range of sampling methods was used:

1. catch methods (single hook droplines, longlines, surface lines, rod and reel) were used to estimate the relative abundance and seasonality of shark species using Cid Harbour;
2. baited remote underwater video cameras (BRUVs) were used to complement catch data in describing the shark community and species' relative abundance, and also to obtain information on the availability of potential shark prey;
3. side-scan sonar imagery was used together with BRUV data to assess prey availability; and
4. acoustic and satellite tracking were used to study the movement behaviour of shark species that could potentially be responsible for the shark bite incidents.

Catch methods

Single hook droplines

In each field trip, eight to 10 single-hook droplines were deployed per day between sunrise and sunset (approximately 5:30 h to 18:30 h), at depths between 2 and 20 m (Fig. 2). Hook sizes were 16/0, 18/0 and 20/0, and bait was predominately a mixture of mullet, mackerel and tarpon species. Droplines were continuously monitored (visually) from the mother boat and physically checked hourly, ensuring captured sharks were attended to quickly. Droplines were mainly focused around the Sawmill Bay to Dugong Beach area of Cid Harbour (Figure 2), where most boats anchor.

Longlines

Bottom-set longlines were set in 4-7 m of water, mainly close to where the shark bites occurred (Fig. 2). Longlines consisted of 200 m lead core lines with 27-30 hooks per line (12/0 circle hooks). The smaller hook size was used to target smaller sharks. Longlines were checked hourly. Due to limiting weather conditions (wind), longlines were only set on two days on the first, third and fourth trips, and four days on the second and fifth trips.

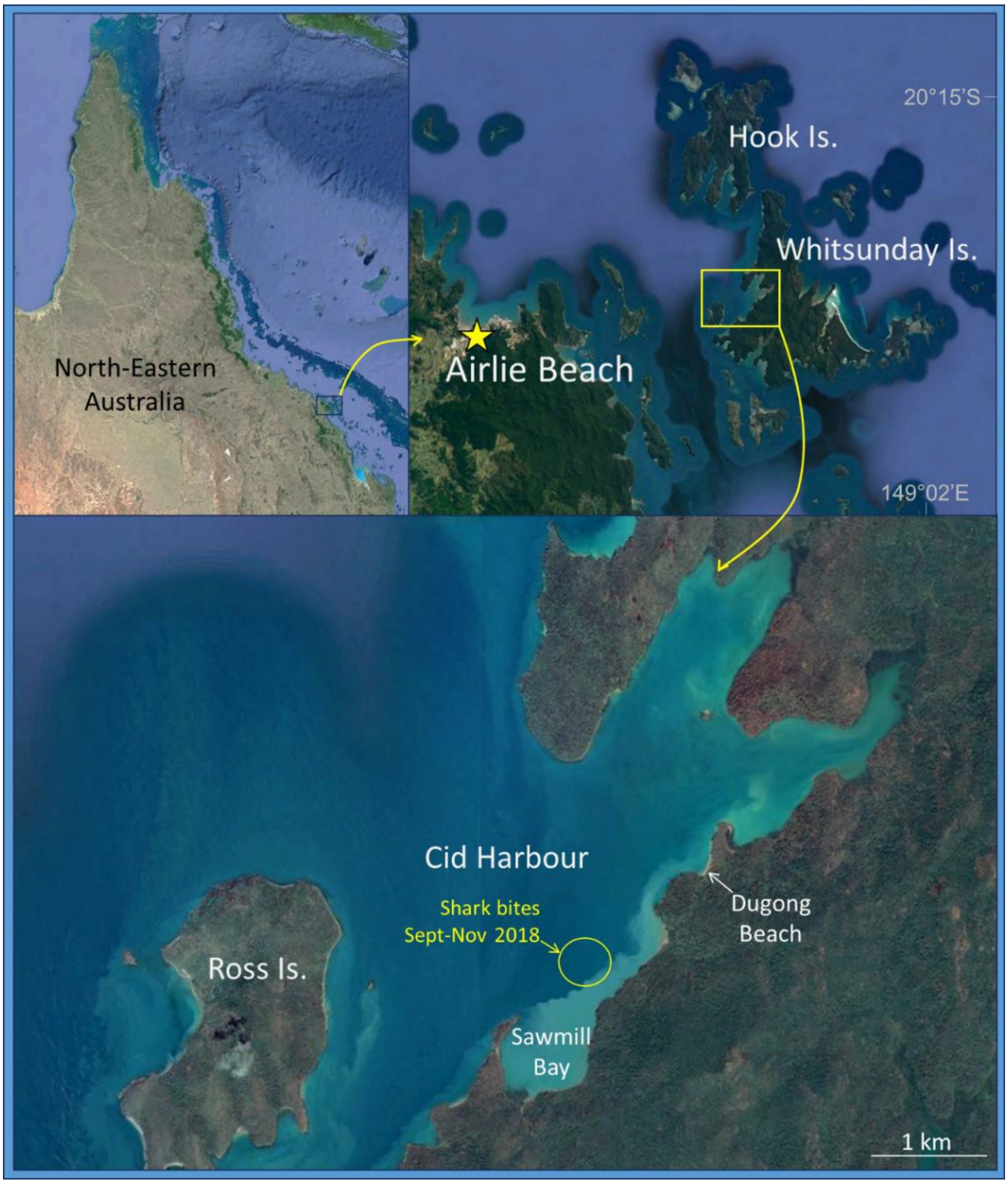

Figure 1. Study area, showing the location of the Whitsundays in north-eastern Australia, the Whitsunday Island and Cid Harbour, including the location of the shark bite incidents that took place in late 2018. Map sources: Google, Landsat/Copernicus, Google, Terrametrics, and Google, CNES/Airbus.

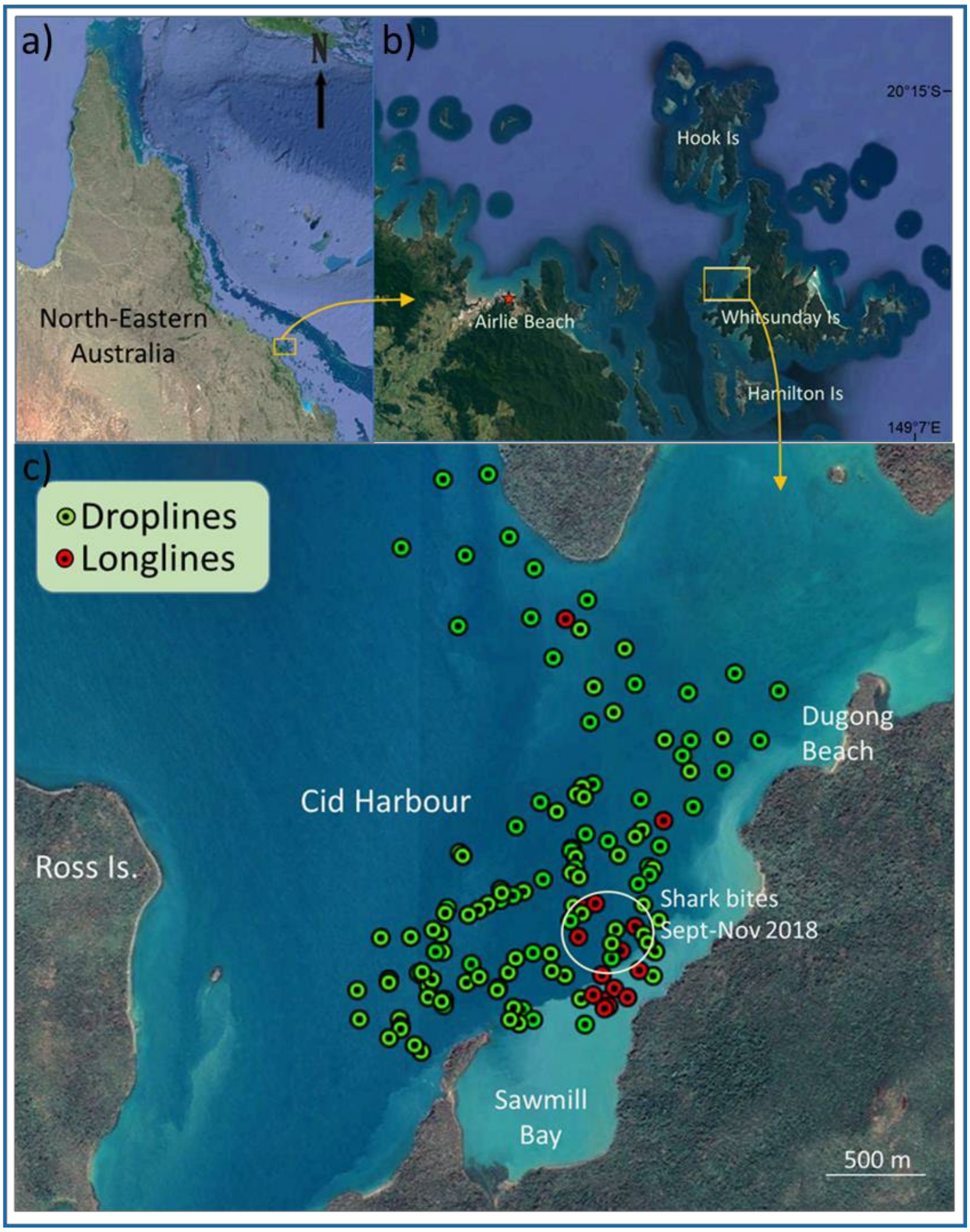

Figure 2. Study area, showing a) & b) the study area in north-eastern Australia, and c) the locations of the droplines and longline sets and area where the shark bites occurred. Map sources: a) Google, Landsat/Copernicus, b) Google, Terrametrics, and c) Google, CNES/Airbus.

Supplementary sampling

Besides the systematic use of drop- and longlines, sharks were also targeted late afternoon and at night using rod and reel. Night sampling included a surface line with bait and a berley pot (first two nights of the first trip, set for 3 h each night) and rod and reel (most nights of the second and third trips), from the back of the boat. On the third trip, two droplines were also set between 17:45 h and 22:00 h on one night in 5 m deep water amongst the boats anchored for the night.

We also present catch data collected by the shark control contractor that operated between 21 and 29 September 2018, following the first two shark bite incidents. In that work, three single hook droplines were set per day, between 6:30 h to 19:00 h. Hooks used were Mustad 4480DT size 14/0 “J” hook, and bait was whole mullet. Lines were set overnight for two nights.

Baited remote underwater video cameras (BRUVs)

Baited remote underwater video cameras (BRUVs) were set throughout Cid Harbour in a range of habitats to complement catch data in identifying the shark species using the broader Cid Harbour region (Fig. 1). BRUVs were set at least 500 m apart, at depths between 1 and 19 m. Approximately 1 kg of pilchards was used as bait per BRUV. Sampling included the full depth range and habitats (soft bottom and hard structure) found throughout the Cid Harbour area (Fig. 3), in an attempt to gain information on the species using the broader region. BRUV surveys were conducted during daylight hours, and samples below a minimum visibility threshold for the majority of the deployment (<0.5 m - where the bait box was persistently obscured) were discarded from the analyses. The vessel was maintained at >100 m from the cameras to reduce the impact of boat presence on animal behaviour.

Video footage was reviewed to record shark occurrence, and sharks present in each video sample were identified to the lowest taxonomic level possible. Classification was based on patterns of shading, body shape, fin shape and position. Identifications were reviewed by a panel of researchers (authors of this report and C. Duffy, pers. comm.).

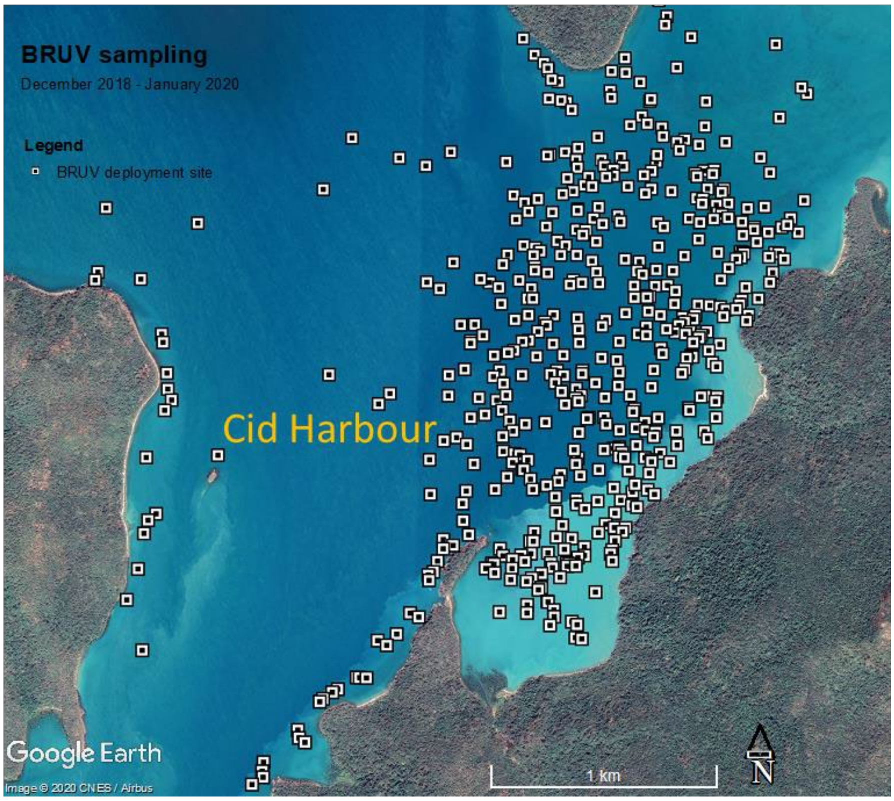

Figure 3. Locations of the BRUVs deployed (white squares) in this study. See Fig. 1 for the location of the mapped region within Australia.

Prey availability

Two techniques were used to identify and quantify potential shark prey using Cid Harbour: BRUVs and side-scan sonar. BRUVs were used to quantify the faunal presence at relatively small spatial scales, giving fine taxonomic resolution. Sonar transects were used to quantify faunal presence over a broader section of Cid Harbour, giving a large spatial 'snapshot' of what was in the harbour during the sampling window. Only one side-scan transect was performed on the June and September 2019 trips, to test if the technique could be used in Cid Harbour under typical conditions. Promising results from these two trips saw the side-scan component incorporated into the project in the December 2019 and January 2020 field trips.

BRUVs. BRUV deployments carried out for shark species identification (see section above) were also used to record the occurrence of potential prey groups. Where possible, animals were identified to species level. Potential prey observed were classified into broad categories: turtles, rays (all batoids), large pelagic fish, large schooling fish, and remoras (noting that remoras are not important shark prey).

Side-scan sonar. Sonar imaging was used to identify and quantify the presence of prey aggregations in Cid Harbour. This method is most commonly used to map the seabed and its benthic habitats (e.g. Dura et al. 2004, Kaeser and Litts 2010), but can also be useful to estimate fish densities (e.g. Gerlotto et al. 2000, Vine et al. 2019), study swimming behaviour (e.g. Rose et al. 2005) and in species surveys (e.g. Gonzalez-Socoloske et al. 2009, Papastamatiou et al. 2020). Briefly, as the boat moves, the side-scan sonar emits a sonar pulse multiple times a second. This pulse is then reflected off underwater objects (including animals) and the time it takes for the pulse to return to the sonar receiver is used to measure how far away the object is. The side-scan unit then converts the information obtained by the successive echoes to produce a 2- dimensional 'map' of the underwater seascape and objects within it. The quality of the reflected signals is also assessed to interpret object size and composition. See Daniel et al. (1998) for detailed methodology. A Humminbird 1199CI HD side-imaging device was used, with a swath width of 25 m at a frequency 800 kHz. Both side imaging and down imaging were captured during each transect. Side imaging provides wide coverage of benthic topography, allowing midwater objects to cast accurate shadows. Down imaging provides a high-definition coverage of the water column immediately underneath the boat.

Sonar imaging transects were carried out parallel to the shore on the second and third field trips (June and September 2019), only one 2.5 km long side-scan transect was conducted through the mid-section of the bay, to test the effectiveness of this methodology in identifying potential shark prey in Cid Harbour. Following initial success, structured sampling of the whole bay was conducted (Fig. 4), with two transects performed in December 2019 and 11 on the final field trip (January 2020). This resulted in approx. 10 km long tracks through the inner-, mid- and outer- sections of the bay, designed to give information on spatial variability in prey composition and availability (Fig. 4). Scans on known targets were also performed to ground-truth the classification of scan signals (January 2020).

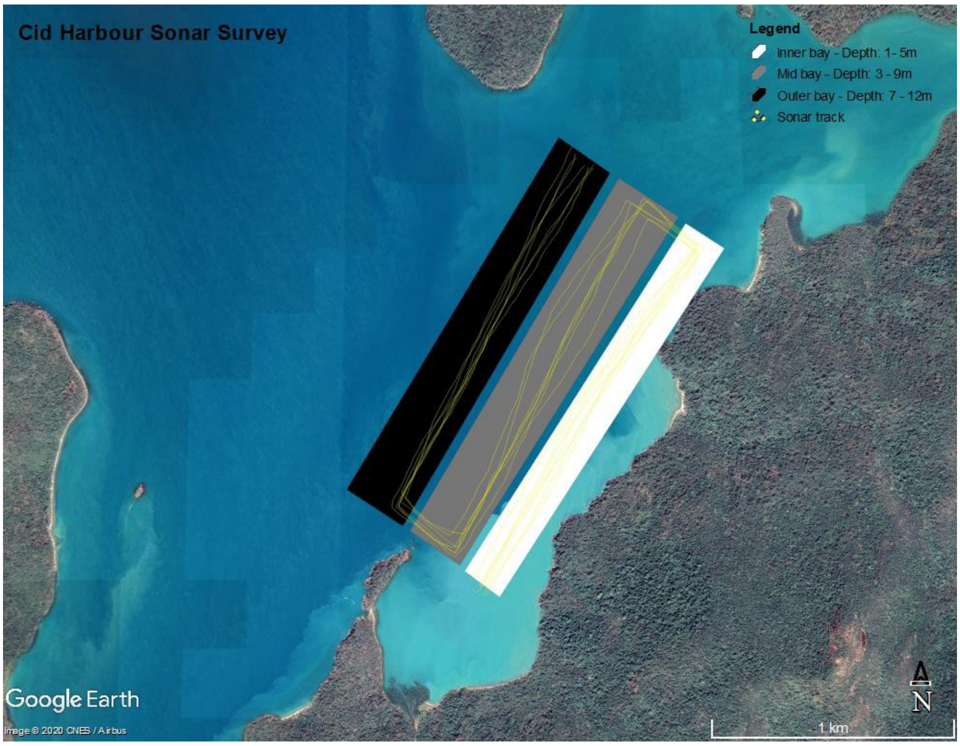

Figure 4. Location of side-scan sonar transects performed within Cid Harbour, showing the different sections of the bay sampled in December 2019 and January 2020 (inner-, mid- and outer-bay). Yellow lines show the path of each transect.

Sonar imaging recordings were visually interpreted to identify the detected animals and record their location within the bay. Initial review of these surveys revealed detections of marine megafauna (e.g. turtles, marine mammals, large sharks, rays, etc.), schooling fish and large-bodied fish. For large animals, although the type of animal could be identified in many cases (e.g. shark, turtle), often this was not possible so all large animals (sharks, rays, dolphins, turtles, dugongs) were grouped into the 'marine megafauna' category. Ground-truthed sonar imagery of known faunal targets was collected opportunistically during each trip and used to develop typologies and decision rules for the three major faunal groups: marine megafauna, schooling fish and large-bodied fish. Both side- and down- imaging were used to assess faunal type. The main aim of this component of the project was to test if side-scan sonar would be effective for estimating prey availability, so the available data is limited. Side-scan sonar data were analysed to provide a preliminary snapshot of the variability in prey availability in the bay over space and time, noting that further sampling would be required to enable a detailed and more meaningful analysis.

Tracking shark movements

Potentially dangerous shark species (tiger sharks, bull sharks and smaller carcharinids, hammerhead sharks; West 2011) were tagged with acoustic and/or satellite tags so their movements could be tracked.

Acoustic tracking

In December 2018, 10 VR2 acoustic receivers were deployed in Cid Harbour (Receivers 'C' in Fig. 5), including one receiver at the southern entrance to the harbour (Gate 1) and three at the northern entrance (Gates 2-4). These receivers effectively gated Cid Harbour and therefore detected any tagged sharks leaving or entering the broader harbour area. The remaining six receivers were deployed in the Sawmill Bay area, in the area where shark bites occurred, on the 'do-not- swim' signs moored in response to the shark bites. The acoustic array was designed to monitor shark movement behaviour in the area where the shark bites occurred (Fig. 5) and where boats anchor, and to provide information about the residency of tagged sharks in Cid Harbour.

In June 2019, an additional 10 receivers were deployed around the broader Whitsunday Islands area (Receivers 'W' in Fig. 5) to better understand the broader movements of sharks in the region. The 10 additional locations were chosen based on being popular anchorages, tourist destinations, or for being channels between Islands, and therefore potential transit routes.

Acoustic transmitters were surgically implanted into the body cavity of sharks through a small incision (Fig. 6). The incision was then sealed with surgical sutures and the shark released. Species of no potential threat to humans (e.g. tawny nurse sharks), individuals too small to tag (most spot-tail sharks) or not in good condition from capture (e.g. some hammerhead and spot-tail sharks) were not tagged and were released as quickly as possible.

The dates each acoustically tagged shark was detected by Cid Harbour receivers (receivers C1-C6 and Gate 2-Gate 4 - see Fig. 5) were plotted on a timeline to visually interpret the temporal pattern of use of the area. Residency indices were calculated, as the proportion of days each individual was detected, in relation to the total number of days monitored. Residency indices range from 0% for individuals that were never detected after tagging, to 100% for individuals that were detected every day following tagging. For individuals that were also fitted with satellite tags, their movements were determined after leaving Cid Harbour.

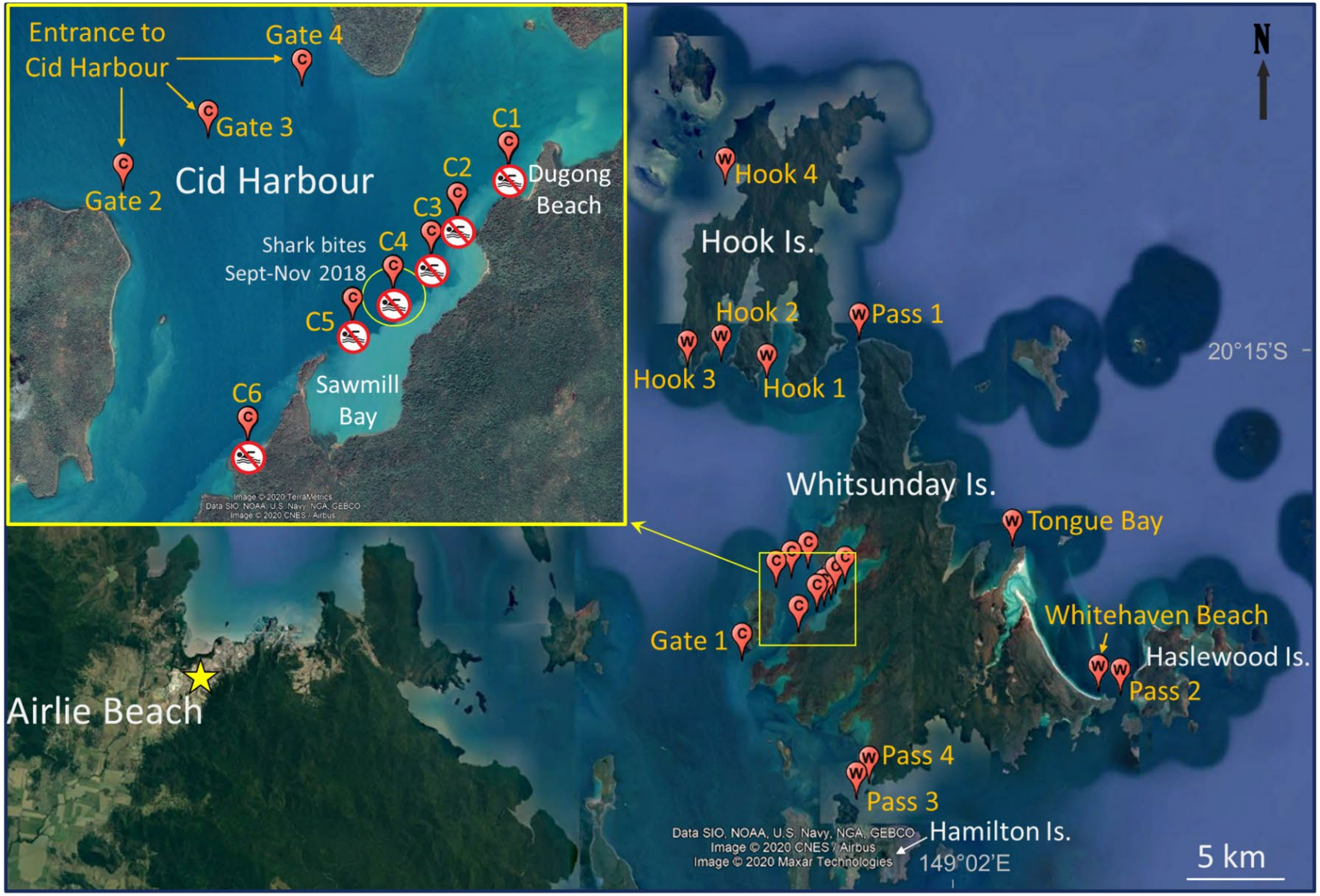

Figure 5. Locations of the acoustic receivers deployed around Cid Harbour in December 2018 ('C' receivers) and around the Whitsunday Islands in June 2019 ('W' receivers). Inset map shows the location of the six receivers attached to 'do-not-swim' signs. The names of the receivers are in yellow. See Figure 1 for detailed location of the mapped region within Australia.

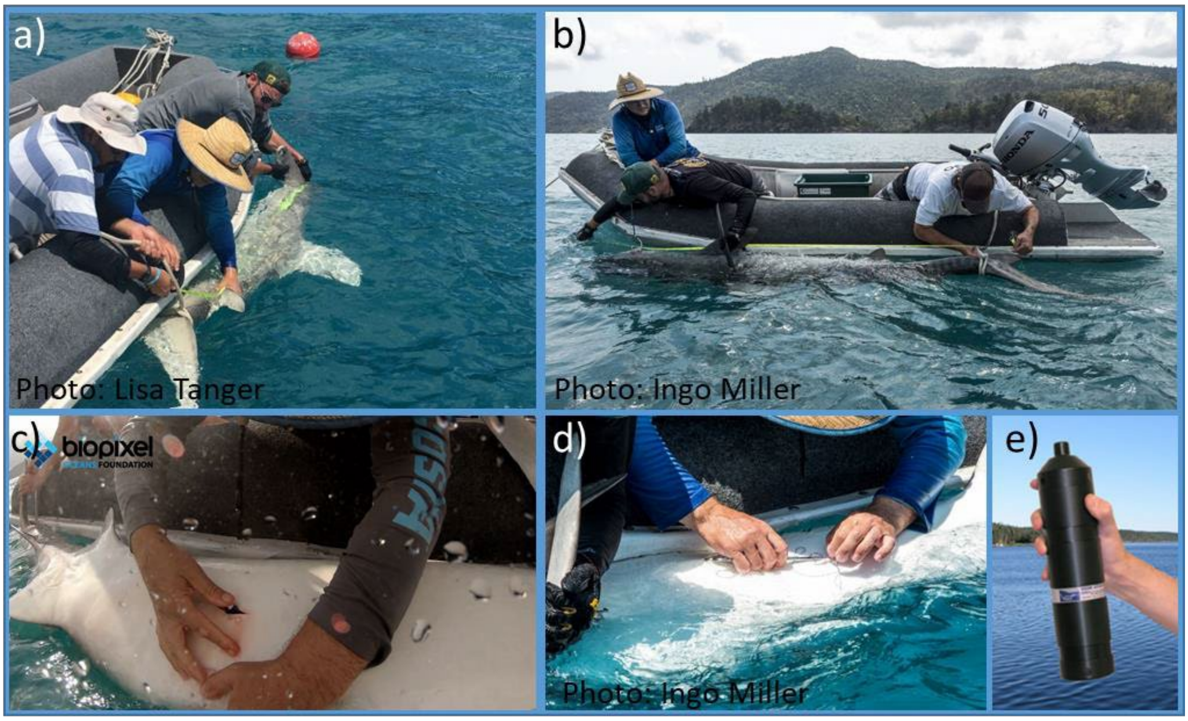

Figure 6. Photographs illustrating the process of a) and b) securing and measuring a shark, c) inserting an acoustic tag into a shark's body cavity, d) suturing the incision after inserting an acoustic tag, and e) an acoustic receiver.

The seasonality in the use of Cid Harbour was investigated with circular statistics using the software package Oriana v.4.02 (Kovach Computing Services). Input data was the calendar month (1-12) for each day a shark was detected by Cid Harbour receivers. Only individuals for which one year of data was available were included. For tiger sharks, data from 01/06/19 to 31/05/20 were used, which allowed the analysis of nine individuals. For the remaining species, a whole year of acoustic data was only available for two or less individuals, and therefore too small for a meaningful analysis. However, although a whole year of data was only available for two bull shark individuals, seasonality analysis was also conducted for this species, given the potential of this species to be responsible for shark bites (McPhee 2014). Rayleigh's uniformity test was used to determine if the data were uniformly distributed throughout the 12-month annual cycle.

To investigate the use of the area where the shark bite incidents occurred (and where vessels moor for the night) in more detail, the time of arrival at the Sawmill Bay area (receivers C1-C6) and visit durations were investigated with circular statistics. Here, a new visit was recorded when a shark was not detected for more than 1 h, and visit durations were calculated as the time difference between the last and first detections. When only one detection was recorded, visit duration was considered to be 1 min.

Rayleigh's uniformity test was used to test for homogeneity in data distribution throughout the 24-h daily cycle. In addition, the times between consecutive visits (inter-visit times) were also calculated. The aim of these analyses was to identify usage patterns in this area, e.g. if sharks use this area at particular times of the day and, when occurring in the area, how long they remain. This analysis was done separately for tiger sharks, for bull sharks, and for smaller carcharhinids (from hereon referred to as 'small whalers', that includes the blacktip group of sharks (*Carcharhinus sorrah*, *C. limbatus*, *C. tilsoni*, *C. melanopterus*) and whitecheek sharks (*C. coatesi*).

To analyse the use of the other monitored locations around the Whitsunday Islands, timelines were constructed where detections of each individual were plotted for each location. For tiger, bull and spot-tail sharks, the daily (hourly) pattern in the use of Cid Harbour and other monitored locations was investigated with circular statistics, where input data were the number of days each individual was present, for each of the 24 hours of the day. The number of visits and visit durations were also calculated. Other species were not included in these analyses as they were not/were rarely detected by the other Whitsundays receivers.

To analyse the density of movement flow between all pairs of receivers, chord diagrams, or connectivity plots, were computed, using the R (R Core Team 2019) package '*Circlize*' (Gu et al. 2014). In chord diagrams, each receiver or group of receivers is represented around a circle by a different colour, and the movements of sharks from one receiver to the others are drawn as arcs connecting the receiver of origin to the receiver of destination. The direction of movement is indicated by the colours of the flow bars: at their origin, the arcs are the same colour as the adjacent receiver, while at the destination the arcs are in a different colour. Tick marks along the plot circumference indicate the number of movements between the two locations, so that the thickness of the connecting bars represents the strength of flow of movements between two receivers. For this analysis, receivers at the entrance to Cid Harbour (Gates 2-4) were grouped into the 'Entrance to Cid Harbour' area, receivers C1-C6 grouped into 'Sawmill Bay area', and Receivers Pass 3 and Pass 4, deployed at the passage between the Whitsunday Island and Hamilton Island, were also grouped (see Fig. 5 for receiver locations). Chord diagrams were only constructed for tiger, bull and spot-tail sharks as for the other species only a small number (≤3) of individuals was tagged, with only one or two individuals detected after tagging.

Satellite tracking

Smart position and temperature (SPOT) satellite transmitters were attached to the dorsal fins of large shark species known to break the water surface (Fig. 7). Satellite tagging data will complement acoustic telemetry data by providing information on the sharks' broad scale movements. This information will be useful to help determine how Cid Harbour fits into the broader movements of the species tagged. Data from satellite locations (date & time, latitude, longitude) were used to track the movements of each shark. Before analyses, locations of class Z (i.e. that indicate that the tag transmitted a signal but the location could not been determined) were removed, and remaining locations plotted to visually detect locations on land and obvious outliers, for removal. The R package '*SDLfilter*' (R Core Team 2019) was also used to remove locations indicative of unrealistic swimming speeds, i.e. greater than 5 m.s^{-1}.

Figure 7. Fitting a satellite transmitter to a bull shark (top) and a tiger shark (bottom). Photos by Lisa Tanger.

To determine how the Whitsundays area fits in each shark's broader habitat use, location positions of sharks with more than 50 detections and of all tiger sharks combined were used to estimate core area use and home ranges. This was done using kernel density estimates (KDEs) using the '*adehabitatHR*' package (Calenge 2019) in R (R Core Team 2019), where the 50% KDE indicates core use areas and the 95% the overall home ranges. For bandwidth estimation, the least-square cross validation method was used, as it produces the best home-range size estimates and best identifies patches of high use (Gitzen et al. 2006). Computed data were exported as shapefiles and processed in ArcGIS (v. 10.7).

Results

Catch methods

Across the five field trips, single hook droplines sets were deployed over 30 days, totalling 2844 hours fished (Table 1). Eighty-two sharks of nine species were caught using droplines, giving an overall catch per unit effort (CPUE) of 0.03 ind.hr^{-1}, which was similar for the five trips (Table 1). Small carcharhinids (*Carcharhinus sorrah*, *C. limbatus/tilsoni, C. melanopterus* and *C. coatesi*), had the highest dropline CPUE of 0.013 ind.$hook^{-1}$.hr^{-1}). This was followed by 0.008 ind.$hook^{-1}$.hr^{-1} for tiger sharks, and 0.002 ind.$hook^{-1}$.hr^{-1} for both bull and hammerhead sharks. Longlines were set for a total of 91 hours, with 17 sharks caught, corresponding to a CPUE of 0.2 sharks per longline set (per hour) and 0.0005 ind.$hook^{-1.}hr^{-1}$ (Table 1).

Overall, including both longlines and droplines, spot-tail sharks (*Carcharhinus sorrah*) were the species most commonly caught, followed by tiger sharks (*Galeocerdo cuvier*) (Table 2). A total of 22 tiger sharks were captured, including one female and one male that were each caught three times. The majority of baits on both droplines (see Table 3) and longlines remained intact, i.e. did not catch any animal and the bait was not removed from the hook. There was no bycatch on the longlines, and the only other animals caught on a dropline were five catfish (*Netuma thalassinus*), one grouper (*Epinephelus* sp.) and one black marlin (*Istiompax indica*).

Table 1. Summary of fishing effort and catches per trip, and average number of boats anchored per night (± SD) in Cid Harbour. CPUE is number of sharks per hour for droplines, and number of sharks per hook per hour for longlines. For longlines, numbers in parentheses following the number of hours fished indicate the total number of hook hours used.

Trip	No. days fished	No. hours fished	No. sharks caught	CPUE	No. of boats
Droplines					
Dec 2018	6	465	17	0.04	2.7 ± 2.6
Jun 2019	7	572	17	0.03	13.0 ± 3.3
Sept 2019	6	527	18	0.03	51.2 ± 14.1
Dec 2019	5	540	18	0.03	4.3 ± 2.3
Jan 2020	6	740	12	0.02	6.2 ± 2.0
Total	**30**	**2844**	**82***	**0.03**	
Longlines					
Dec 2018	2	11.3 (53)	6	0.0100	
Jun 2019	4	23.8 (120)	1	0.0004	
Sept 2019	2	12.7(60)	1	0.0013	
Dec 2019	2	13.0 (59)	4	0.0052	
Jan 2020	4	30.6 (111)	5	0.0015	
Total	**14**	**91.4 (403)**	**17**	**0.0005**	

* This includes four tiger shark recaptures, as two individuals were recaptured twice.

Table 2. Species composition and size range of sharks caught on single hook droplines, longlines and rod-and-reel fishing combined, over the course of the five trips. n = number of sharks caught. Number of sharks tagged with acoustic (AT) and satellite tags (ST) is also indicated.

				No. tagged	
Species	Scientific name	**Size range (cm)**	**n**	AT	ST
Spot-tail shark	*Carcharhinus sorrah*	50 - 173	36	8	-
Tiger shark	*Galeocerdo cuvier*	230 - 386	22*	18	15
Tawny nurse shark	*Nebrius ferrugineus*	153 - 261	13	-	-
Bull shark	*Carcharhinus leucas*	203 - 307	7	7	3
Whitecheek shark	*Carcharhinus coatesi*	77 - 100	7	1	-
Great hammerhead shark	*Sphyrna mokarran*	185 - 293	5	2	1
Scalloped hammerhead shark	*Sphyrna lewini*	152 - 171	3	1	1
Blacktip complex	*Carcharhinus limbatus/tilsoni*	100 - 195	5	3	-
Blacktip reef shark	*Carcharhinus melanopterus*	126 - 153	3	3	-
		TOTAL	**101**	**43**	**20**

* Four of the tiger shark captures were recaptures, as two individuals were recaptured twice.

Table 3. Percentage of dropline sets retrieved with the bait intact, i.e. that did not catch any animal and bait was not removed from the hook.

Trip	No. sets	% untouched hooks
Dec 2018	465	95.3
Jun 2019	572	92.5
Sept 2019	527	88.4
Dec 2019	540	85.0
Jan 2020	740	91.2
	Total: 2844	**Average: 90.5%**

The number of boats overnighting in Cid Harbour was generally <12, with the exception of the September 2019 field trip (Table 1), when 31-69 boats were present per night. Average seawater temperature during the field trips ranged from 22 to 28°C (data from https://seatemperature.info), and there was no relationship between water temperature and total number of sharks caught, nor between water temperature and numbers of any individual shark species (regression analysis, $p > 0.05$ in all cases; see Fig. 8).

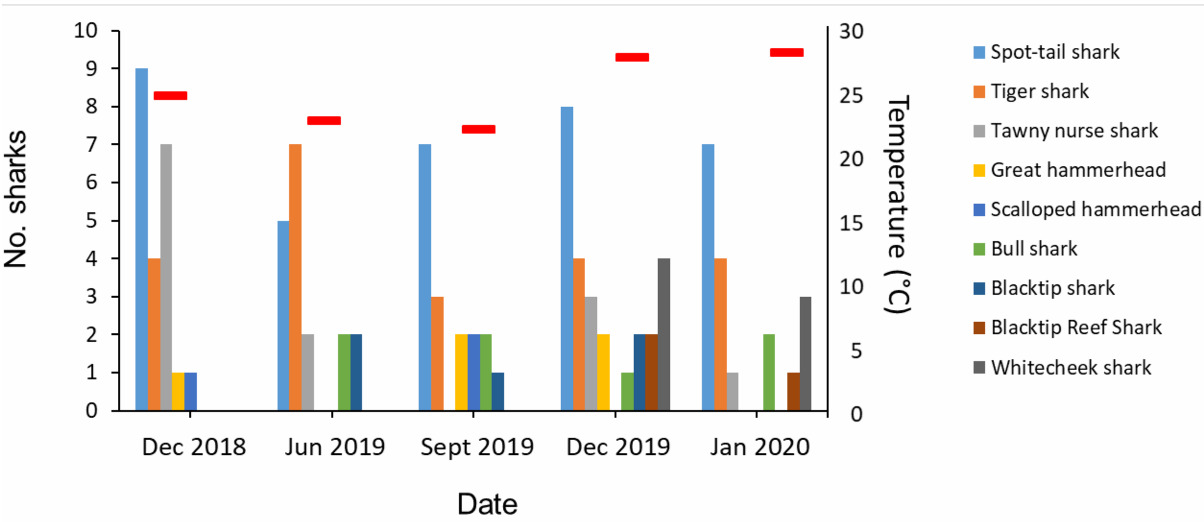

Figure 8. Number of sharks of each species caught in each field trip, and average water temperature for the days when fishing took place (horizontal red bars).

Rod and reel fishing in the late afternoon caught four whitecheek sharks and one spot-tail shark, all smaller than 1 m. Night sampling did not catch any sharks. The surface lines with bait and berley (set for 3 h on the first two nights of the first trip) did not catch anything, and the bait was intact. Rod and reel fishing at night between 19:30 h and

22:00-23:00 h, used from the second trip onwards, yielded one white-spotted wedgefish (*Rhynchobatus australiae*). Two droplines that were set between 17:45 h and 22:00 h on one night (September 2019) amongst the anchored boats, also did not lead to any captures. The shark control contractor that fished in September 2018, immediately after two shark bite incidents, caught five tiger sharks and one common blacktip shark (*Carcharhinus limbatus*), from 216 day-time fishing hours. The contractor also reported that most baits were intact, including when lines were set overnight.

Baited underwater video cameras (BRUVs)

BRUV sampling was carried out on all five trips, resulting in high replication and high spatial coverage of Cid Harbour (see Fig. 3). A total of 511 deployments and 664 hours of deployment time were obtained from the range of available depths (Fig. 9).

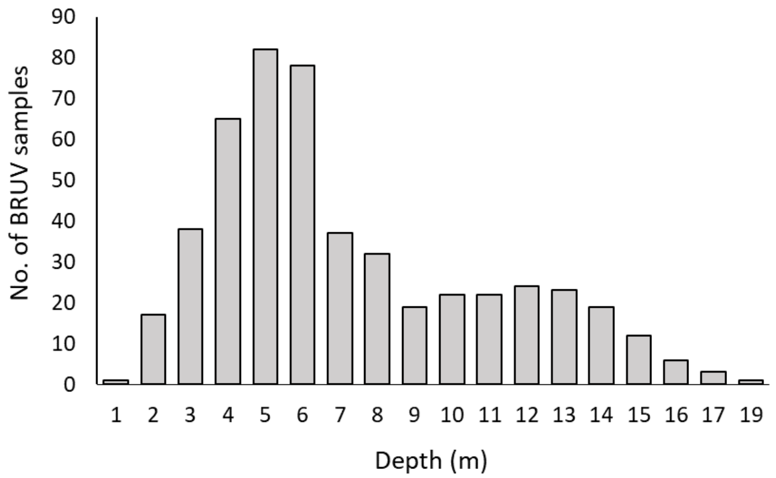

Figure 9. Number of BRUV samples taken at each depth throughout Cid Harbour.

BRUV results show that a number of shark species use Cid Harbour (see Fig. 10 for examples of images obtained by BRUVs), at relatively low abundance. BRUV deployments returned 48 distinct shark detections, from five families (Table 4). The most commonly encountered species was the whitecheek shark *Carcharhinus coatesi* (13 detections), followed by blacktip sharks (*Carcharhinus limbatus/tilstoni*) (eight detections), both of which were encountered in all five field trips. Two species were seen in BRUVs but not caught by fishing gear: the snaggletooth shark (*Hemipristis elongata*) and brownbanded bamboo shark (*Chiloscyllium punctatum*). Two species were also caught in fishing gear but not recorded in BRUVS: bull sharks and blacktip reef sharks. Total shark detections were relatively consistent between sampling periods (Table 4).

Figure 10. Examples of images registered by the BRUVs deployed in Cid Harbour.

Table 4. Summary of shark detections in BRUV deployments in Cid Harbour. Maximum number of individuals observed in a single video frame (MaxN) is shown for each species. Cumulative MaxN per sampling period per hour of deployment was used to calculate mean MaxN for each sampling period. Grand total includes unidentifiable shark detections.

	MaxN			Mean MaxN.hr^{-1}					
Family/Species	**Tot**	**Mode**	**Highest**	**12/18**	**06/19**	**09/19**	**12/19**	**01/20**	**Tot**
Carcharhinidae									
Carcharhinus coatesi	13	1	1	0.03	0.01	0.03	0.03	0.01	0.02
Carcharhinus limbatus/tilstoni	8	1	2		0.01	0.01	0.02	0.01	0.01
Carcharhinus sorrah	2	1	1					0.01	0.00
Galeocerdo cuvier	1	1	1	0.03					0.00
Carcharhinus sp.	5	1	2		0.01			0.03	0.01
Ginglymostomatidae									
Nebrius ferrugineus	3	1	1	0.03				0.01	0.00
Hemigaleidae									
Hemipristis elongata	4	1	1		0.01	0.01			0.01
Hemiscylliidae									
Chiloscyllium punctatum	5	1	1	0.03	0.02		0.01		0.01
Sphyrnidae									
Sphyrna lewini	2	1	2				0.01		0.00
Sphyrna mokarran	2	1	1			0.01	0.01		0.00
Grand total*	**48**	**1**	**1**	**0.11**	**0.05**	**0.07**	**0.08**	**0.08**	**0.07**

BRUV deployments often returned low visibility samples, with visibility <2 m in 38% of deployments, and <1 m in 7%. In particular, shallow locations within the harbour were often very turbid. However, visibility was consistently high enough to lead to BRUV samples where the bait-box was visible. Periods of limited visibility were often caused by sediment disturbance by fauna trying to feed on the bait. Reduced visibility is likely to reduce sightings of sharks that do not closely approach the bait-box, and reported occurrence rates must be interpreted as minimums. However, on nearly all occasions observed under favourable visibility conditions, sharks closely approached the bait-box, suggesting that if a shark is attracted to the BRUV they would likely be sighted at the bait box.

When BRUV data was added to catch data, no relationship between water temperature and shark encounters was present for any species, nor for all shark species combined (regression analysis, $p > 0.05$; see Fig. 11).

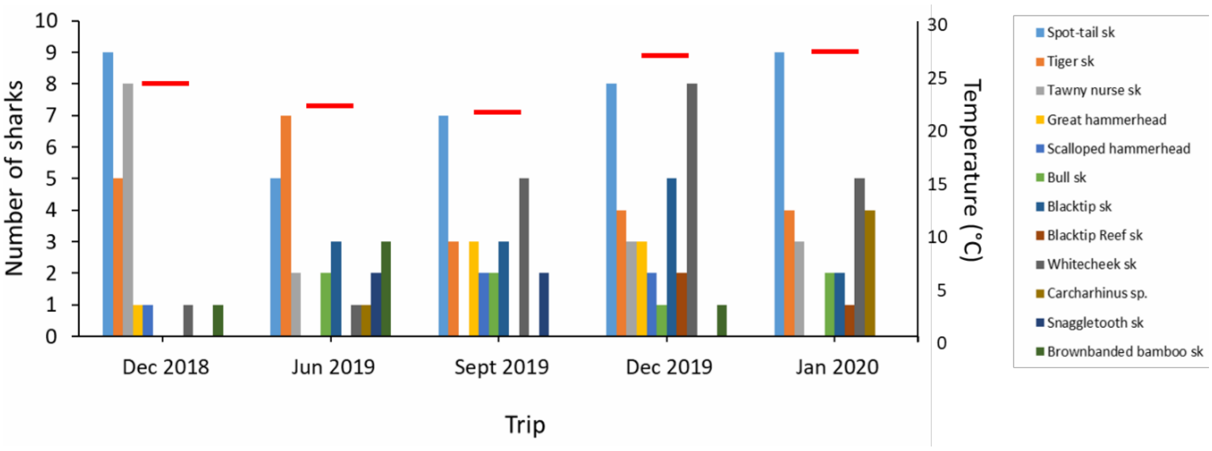

Figure 11. Combined number of sharks of each species caught (all fishing methods) and detected in BRUV samples for each field trip, and average water temperature for the days when fishing took place (horizontal red bars).

Prey availability

Side-scan sonar

Side-scan sonar was useful to identify a range of potential shark prey using Cid Harbour (e.g. see Fig. 12). Although the number of transects conducted is limited, preliminary results suggest a seasonal variation in prey composition and availability in Cid Harbour that is worth further investigation. Indeed, marine megafauna (which includes marine reptiles (i.e. turtles), marine mammals (e.g. dolphins) and sharks) were encountered at a higher rate in September 2019 than in any other period (Fig. 13). However, data do not suggest substantial seasonal variation in large fish or schooling baitfish (Fig. 13), suggesting that the observed variability in shark species composition and relative abundance in Cid Harbour (Fig. 11) is not likely to be related to the availability of these prey.

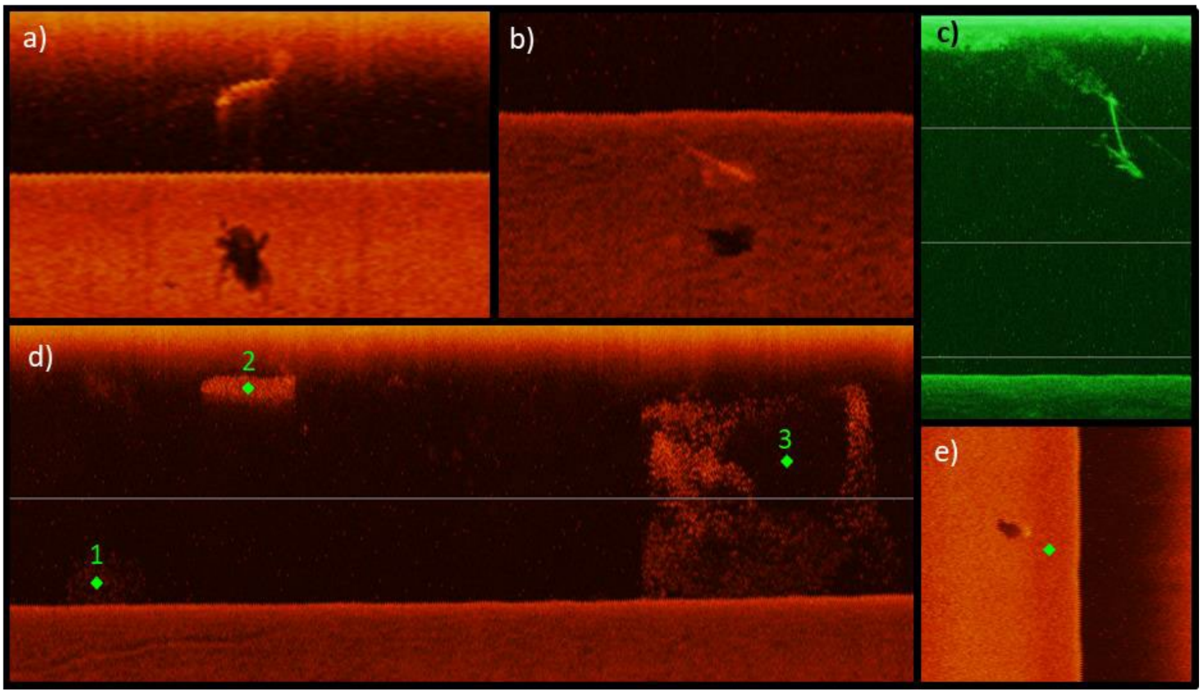

Figure 12. Examples of sonar signals for a) a sea turtle, b) a stingray, c) a shark caught in a dropline, d) fish, where green dots indicate (1) small fish in a dispersed school, (2) small fish in a tight school and (3) large fish in a complex school and e) an unclear image of a large animal that could not be identified to species, and was therefore placed in the 'marine megafauna' category.

Preliminary results suggest that different fauna tend to occur in different parts of the bay. Scans were carried out parallel to shore at three different distance intervals (Fig. 4), providing a snapshot of fauna using the inner-, mid- and outer- bay areas. Based on 11 scans carried out during the January 2020 trip, there appears to be spatial differences in the distribution of different faunal groups (Fig. 14). Large fish tend to be encountered more frequently in the outer-bay, schooling baitfish in the mid-bay, and marine megafauna were encountered regularly in all of these areas in similar frequencies (Fig. 14).

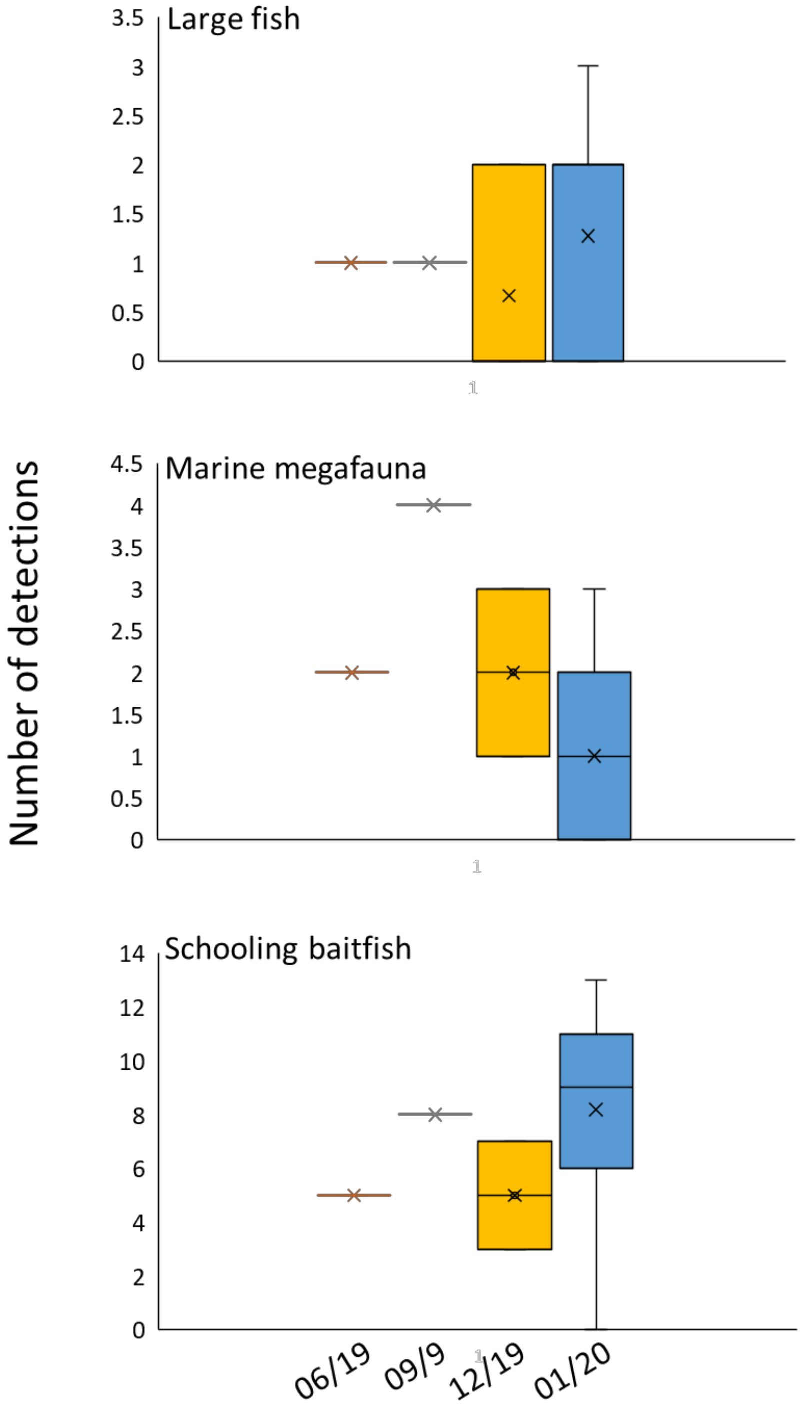

Figure 13. Boxplots showing the number of detections of large fish, marine megafauna and schooling baitfish in side-scar transects conducted in the mid-section of the bay, by sampling period. Note that plots for June 2019 and September 2019 are based on data from one only transect, while for the December 2019 and January 2020, plots are based on two and 11 transects, respectively.

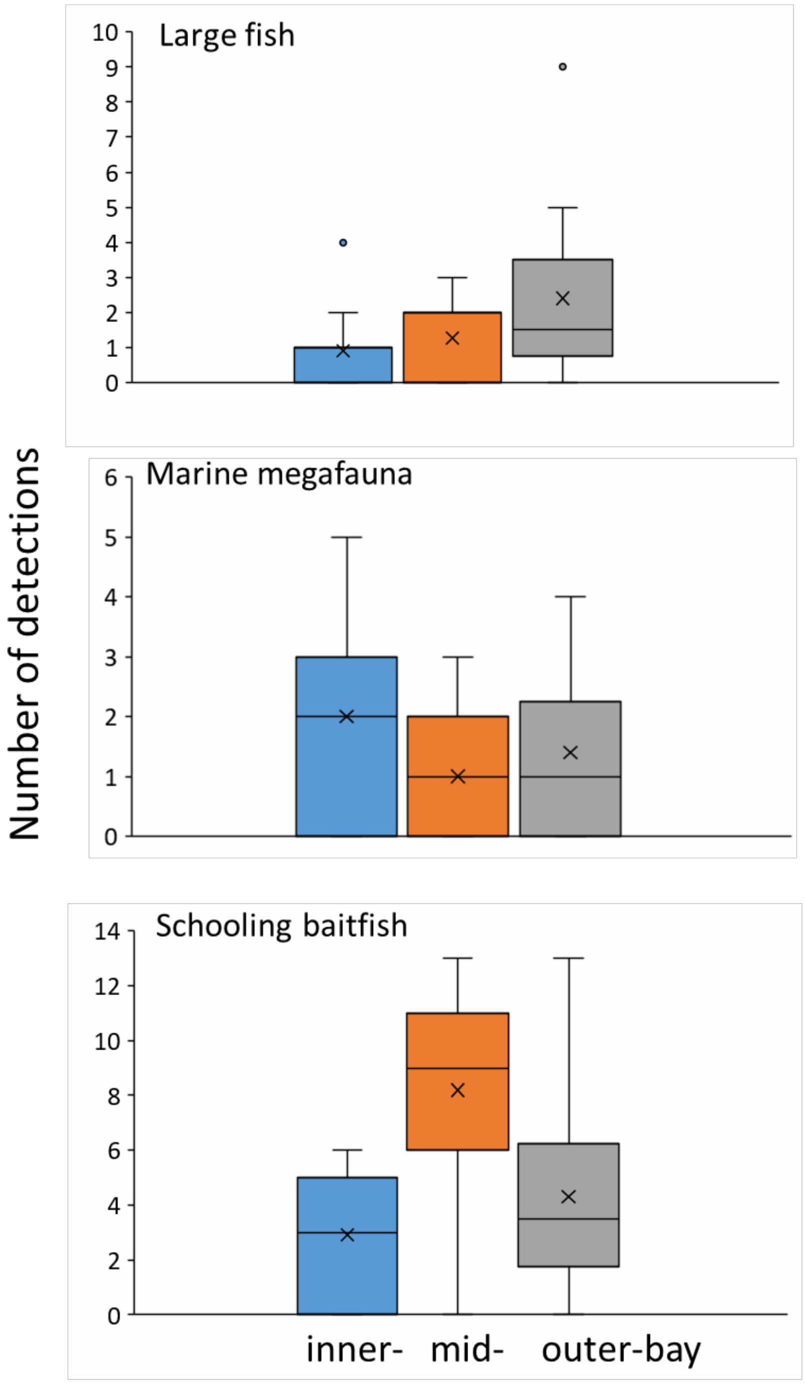

Figure 14. Boxplots showing the detections of large fish, marine megafauna and schooling baitfish in the sonar side-scans by harbour section (inner- mid and outer-bay areas; see Figure 4). Analysis based on data from two scans conducted in December 2019, and 11 in January 2020.

BRUVs

BRUV data shows that a variety of faunal groups occur in Cid Harbour. The different groups presented here each encompass several species, but are typically dominated by a few key species (Table 5). Schooling baitfish, which were commonly encountered in sonar scans, were not encountered on BRUVs. This is likely because schooling baitfish do not typically inhabit the demersal habitat sampled by BRUVs. In addition, the bait used, which is attractive to predatory fish, is unlikely to attract small pelagic planktivores, given that the bait used was itself a small pelagic planktivore (Clupeidae). Rays, remoras and large schooling fish were frequently encountered (>10% of deployments) in all sampling periods.

Table 5. Main Faunal groups detected in sonar scans, and their relationship to faunal groups detected in BRUV deployments, along with typical (i.e. most common) species of each group observed in BRUV deployments.

Sonar classification	Faunal groups observed in BRUVs	Typical species observed in BRUVs
Marine megafauna	Turtles	Green sea turtle (*Chelonia mydas*)
	Rays	Mangrove whipray (*Urogymnus granulatus*), Australian whipray (*Himantura australis*), white-spotted wedgefish (*Rhynchobatus australiae*)
Large fish	Large pelagic fish	Giant queenfish (*Scomberoides commersonnianus*), spotted mackerel (*Scomberomorus munroi*)
	Large schooling fish	Yellowtail fusilier (*Caesio cuning*), fringefin trevally (*Pantolabus radiatus*)
	Remoras	Common remora (*Remora remora*)
Schooling baitfish	*Not detected*	*Not detected*

Temporal differences in abundance were evident in some groups (Fig. 15). The most striking pattern is that of large pelagic fish, which occurred much more frequently during winter sampling periods (June and September). This is likely attributable to the seasonal migration of *Scomberomorus* species along Australia's east coast (Begg et al. 1997). Remoras also show a strong seasonal pattern, occurring more frequently in the summer months (December, January).

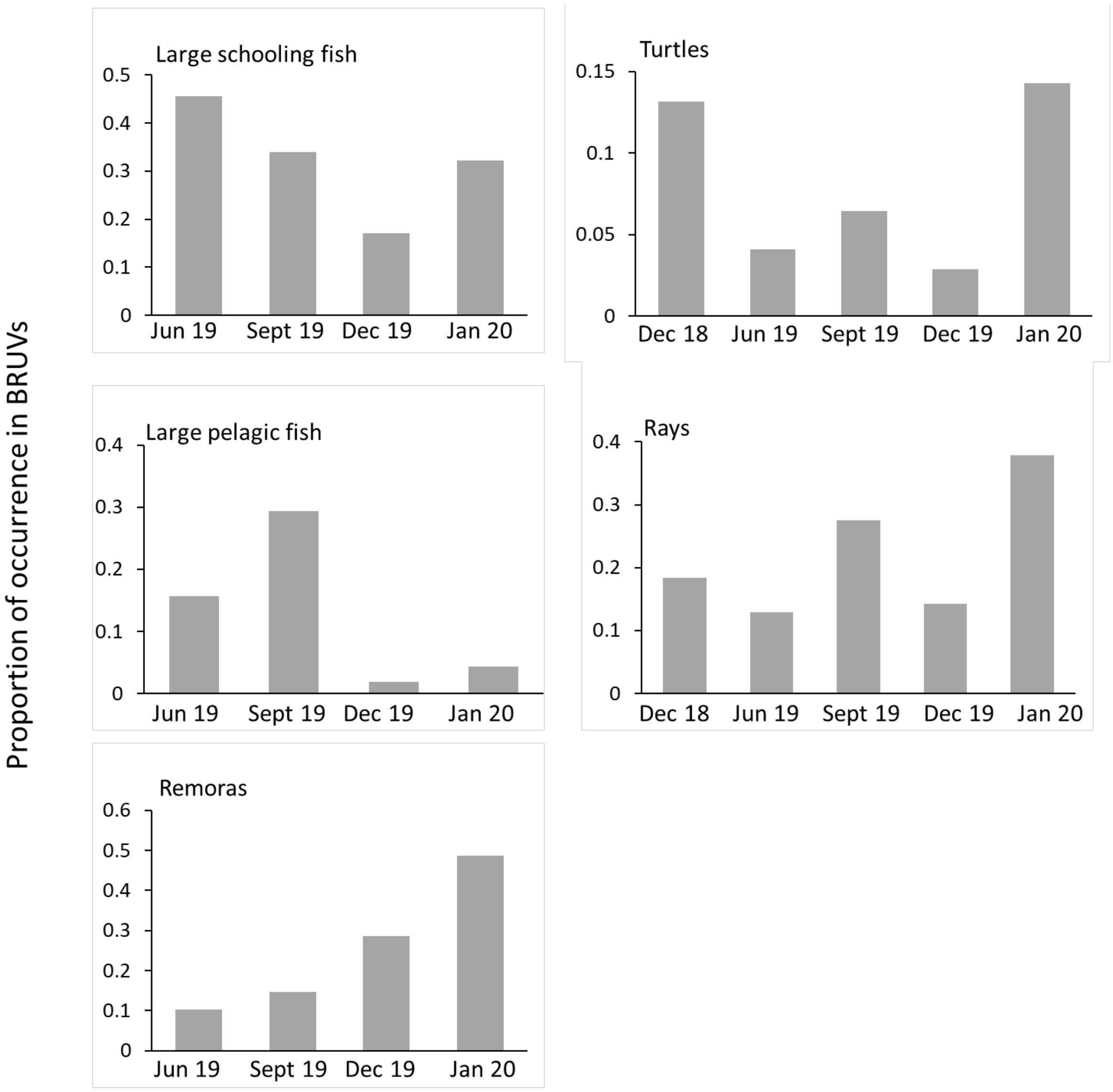

Figure 15. Proportion (0-1) of BRUV deployments containing each group of potential prey, per sampling trip. Note that for the first sampling period (December 2018), only data on turtles and rays were recorded, and therefore data for the remaining groups is not presented for this first sampling period.

Shark movements and residency behaviour

Movement and residency behaviour was assessed for 20 sharks that were tagged with satellite transmitters (ST) and 43 with acoustic transmitters (AT), including 18 individuals that were tagged with both types of tags (Tables 2 and 6).

Table 6. Details of sharks tagged with acoustic (AT) and satellite (ST) transmitters, including sex, size, date tagged and transmitter numbers.

Species	Sex	Size (cm)	Date tagged	AT #	ST #
Tiger shark	F	242	Dec 2018	64004	175019
Tiger shark	F	340	Dec 2018	64003	176411
Tiger shark	M	230	Dec 2018	28255	175018
Tiger shark	F	285	June 2019	12809	175011
Tiger shark	F	386	June 2019	12807	173761
Tiger shark	M	264	June 2019	64007	41820
Tiger shark	M	316	June 2019	64006	41821
Tiger shark	M	335	June 2019	12808	173762
Tiger shark	F	300	Sept 2019	12798	178947
Tiger shark	F	330	Sept 2019	12799	175014
Tiger shark	F	321	Dec 2019	5018	178942
Tiger shark	F	370	Dec 2019	64005	178943
Tiger shark	F	310	Dec 2019	12803	
Tiger shark	F	231	Dec 2019	12805	
Tiger shark	M	245	Dec 2019	12802	178941
Tiger shark	F	360	Jan 2020	5022	178945
Tiger shark	M	265	Jan 2020	5023	
Tiger shark	M	330	Jan 2020	5024	178946
Bull shark	M	245	June 2019	12810	
Bull shark	M	283	June 2019	12812	175012
Bull shark	M	203	Sept 2019	12795	
Bull shark	M	230	Sept 2019	12796	
Bull shark	F	307	Dec 2019	5019	
Bull shark	F	288	Jan 2020	5025	178952
Bull shark	M	261	Jan 2020	5021	178955
Spot-tail shark	F	173	Dec 2018	28254	
Spot-tail shark	F	113	June 2019	28256	
Spot-tail shark	F	120	June 2019	12814	
Spot-tail shark	F	125	Sept 2019	6157	
Spot-tail shark	M	137	Sept 2019	12797	

Table 6 (cont.) Size (total length, in cm) and sex of sharks fitted with acoustic (AT) and satellite (ST) transmitters.

Species	Sex	Size (cm)	Date tagged	AT #	ST #
Spot-tail shark	F	115	Dec 2019	6161	
Spot-tail shark	F	125	Dec 2019	12801	
Spot-tail shark	F	110	Jan 2020	6160	
Great hammerhead	F	241	Dec 2018		175016
Great hammerhead	F	293	Dec 2019	7439	
Great hammerhead	F	270	Dec 2019	7448	
Scalloped hammerhead	M	171	Dec 2018		175017
Scalloped hammerhead	M	152	Sept 2019	7438	
Common blacktip shark	F	160	June 2019	12811	
Common blacktip shark	M	195	June 2019	12813	
Common blacktip shark	F	170	Dec 2019	12800	
Blacktip reef shark	M	126	Dec 2019	12804	
Blacktip reef shark	F	153	Dec 2019	12806	
Blacktip reef shark	F	138	Jan 2020	5020	
Whitecheek shark	F	80	Dec 2019	6158	
			TOTAL	**43**	**20**

Satellite tracking

Of the 20 sharks fitted with satellite transmitters, 15 were tiger sharks, three bull sharks, one a great hammerhead and one a scalloped hammerhead (Table 6). Tiger sharks became the focus of the satellite tracking component of the present study as 1) tiger sharks surface regularly enough to transmit positional information, allowing the collection of meaningful data, and 2) tiger sharks were the most commonly caught species of large shark. Satellite tracking using transmitters fixed to the dorsal fin has rarely been used for bull sharks (Graham et al. 2016). However, given the stakeholders' interest in bull sharks, the effectiveness of satellite tracking for this species was tested by tagging three bull shark individuals.

Tiger sharks

In general, tiger sharks had large home ranges and spent most of their time in the broader Whitsundays region, moving between the coast, nearshore islands and offshore reefs (Figs. 16-18). Most tracked tiger sharks did not move much further north than Townsville or much further south than Mackay (Figure 16a). One exception was shark ST

#178942 (321 cm long female, tagged in December 2019), that moved away from the Whitsunday area soon after tagging (see AT #5018 in Fig. 22) and in a period of two months swam >3700 km to the Solomon Islands (Figs. 16 & 17). The second exception was shark ST #41821, a 316 cm male that was tagged in July 2019 and moved ~800 km to a seamount in the Coral Sea just north of Fraser Seamount (part of the Tasmantid Seamount Chain, ~290 km east of Bundaberg) in February 2020 (Figs. 16 & 17).

In addition to the sharks tagged in the present study, a female tiger shark tagged (at 375 cm TL) in Kiama (NSW) in December 2017 by the New South Wales Department of Primary Industries was detected by the Tongue Bay acoustic receiver on the 31st August 2019, >1800 km from the tagging site. It remained in the area for two days, after which it left, to return in October 2019 for two weeks, when it used the Tongue Bay area, along with Whitehaven Beach and Cid Harbour.

Even among the 13 sharks with less extreme movements, there were clear differences in movement patterns. Some sharks made movements out to the Coral Sea and back (e.g. sharks ST #178941, #178943, #175014, #176762 and #175019), others remained close to the coast throughout the tracking period (e.g. sharks ST #176411 and #178946), others moved between reefs offshore from Townsville to well south of Mackay, ~400 km away (ST #175011, #178947, #173761 and #178943) (see Fig. 17 and Fig. 18). Accordingly, the tagged individuals had highly variable home range and core area sizes (Table 7). Eight out of the nine tiger sharks for which these metrics could be estimated (i.e. that had >50 detections) had home ranges <1,715,000 ha and core areas <327,000 ha, whereas individual #178942, which moved to the Solomon Islands, had a much larger home range size of >14,230,000 ha, and a 2,095,647 ha core area. There was also a high variability among the other eight individuals, as three individuals had home ranges between ~217,000 and ~350,000 ha (core areas between ~37,000 and ~84,000 ha), three between ~460,000 and ~900,000 ha (core areas between ~96,000 and ~144,000 ha), and two between ~1,660,000 and ~1,710,000 ha (core areas between ~267,000 and ~326,000 ha; Table 7).

Although the core areas of all individuals were large (Table 7), for most individuals these overlapped with the region around the Whitsunday/Hook Islands (Fig. 19). The only exception was tiger shark #178942, the shark that moved to the Solomon Islands, and #178946, for which the core area was just south of the Whitsunday Island, but still in the Whitsundays region (Fig. 19). All individuals used a number of spatially separated areas as core area, as indicated by well separated 50% KDEs regions (Fig. 17), meaning they moved to different areas that they used for considerable amounts of time, and did not remain in one area throughout the tracking period.

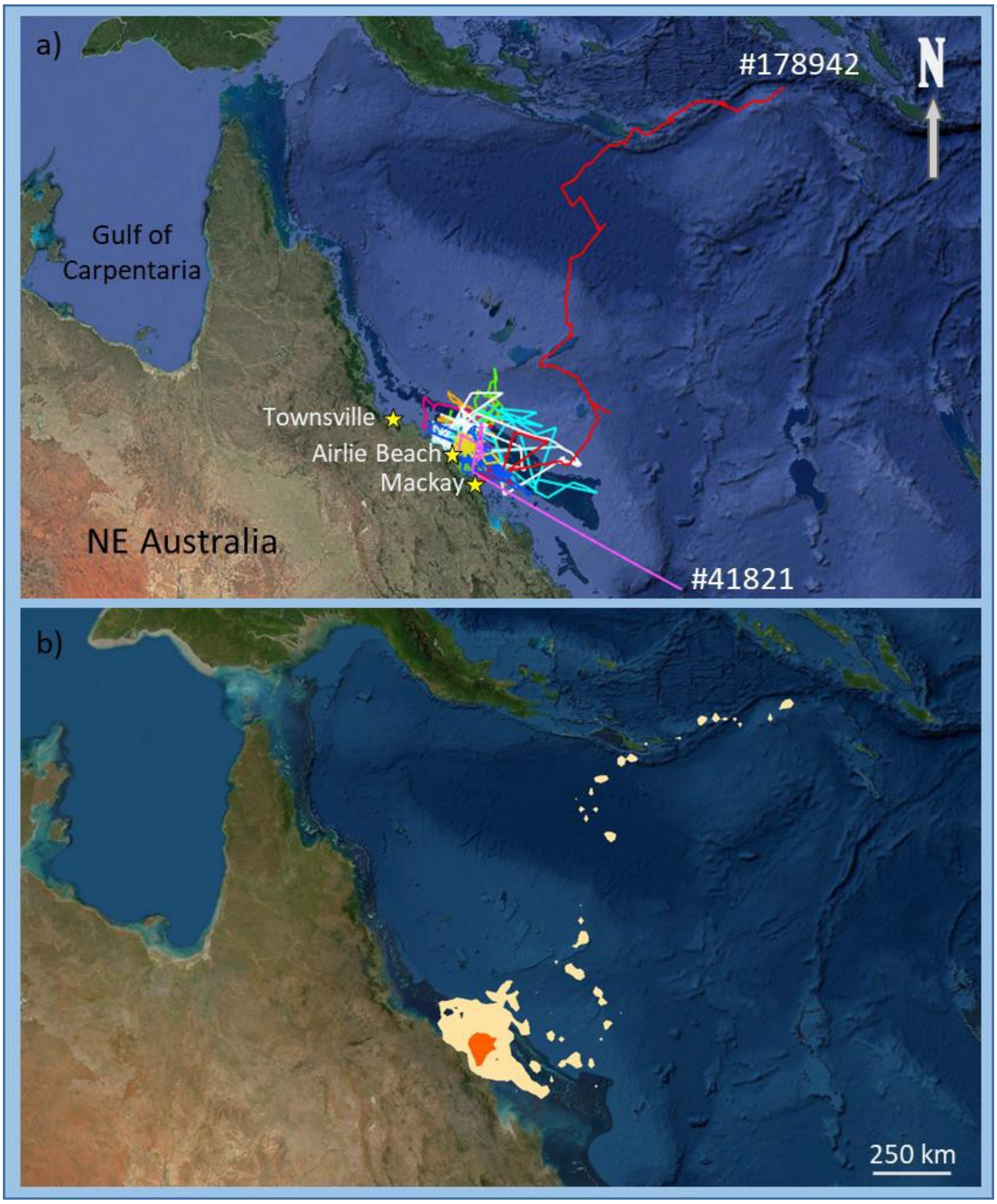

Figure 16. Satellite tracking data showing a) the tracked movements of the 15 tiger sharks that were fitted with satellite transmitters, and b) the extent of 50% (in orange, representing the core area) and 95% (in yellow, representing the home range) kernel density estimates calculated from data from all tracked tiger sharks combined. The tracks of the two tiger sharks that made the most extreme movements are indicated (ST #178942 and ST #41821) in a).

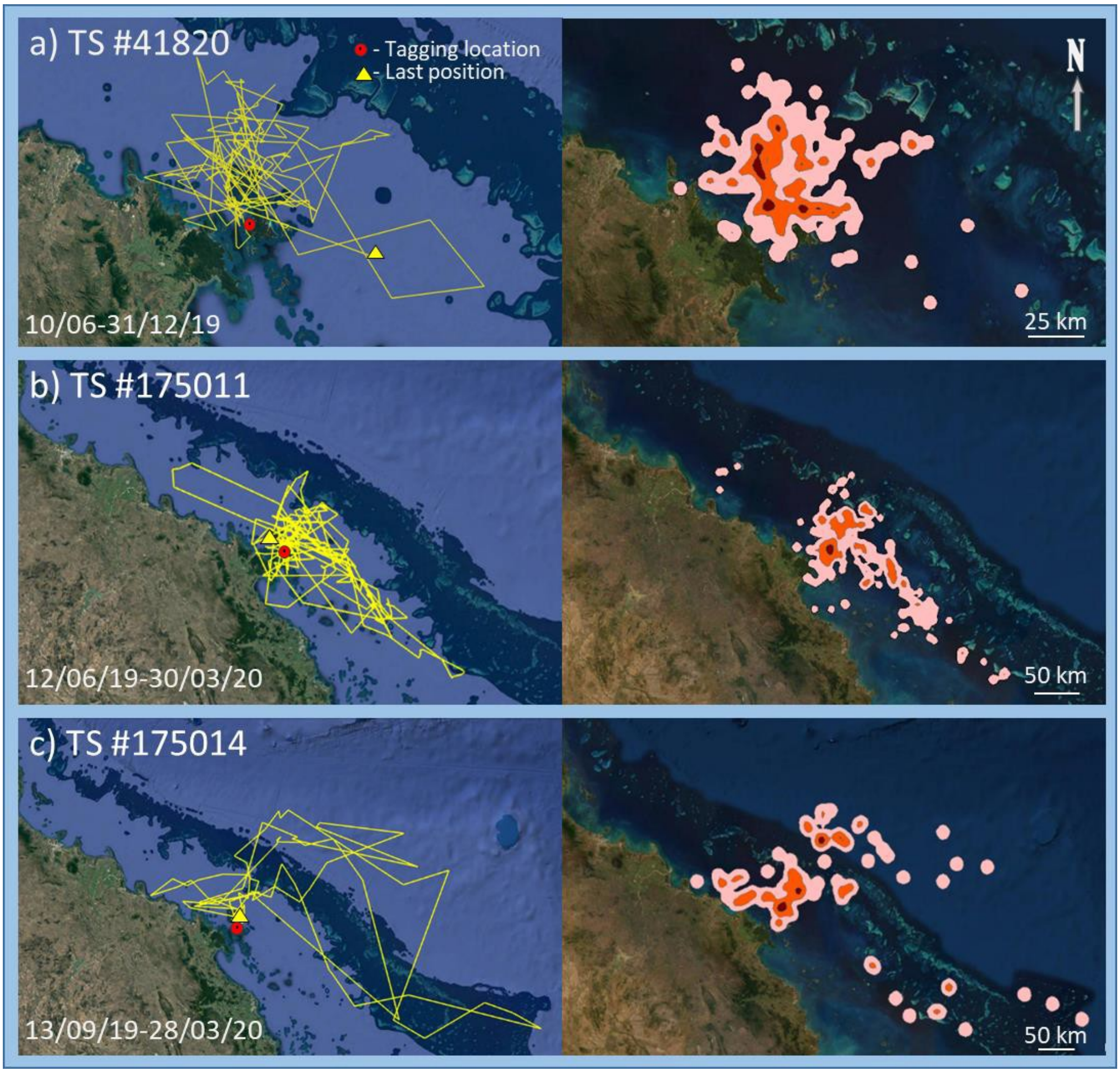

Figure 17. Satellite tracks (left panels, Maps source: Google, Landsat/Copernicus) of the tiger sharks tagged with satellite transmitters that had more than 50 satellite positions (i.e. for which kernel density estimates (KDE) were computed (left panels). Right panels - extent of the 10% (brown), 50% (orange, representing the core habitats) and 95% (light pink, representing home ranges) fixed-kernel density estimates; maps created in ESRI ArcGIS v. 10.1, imagery sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, Swisstopo, and the GIS User Community.

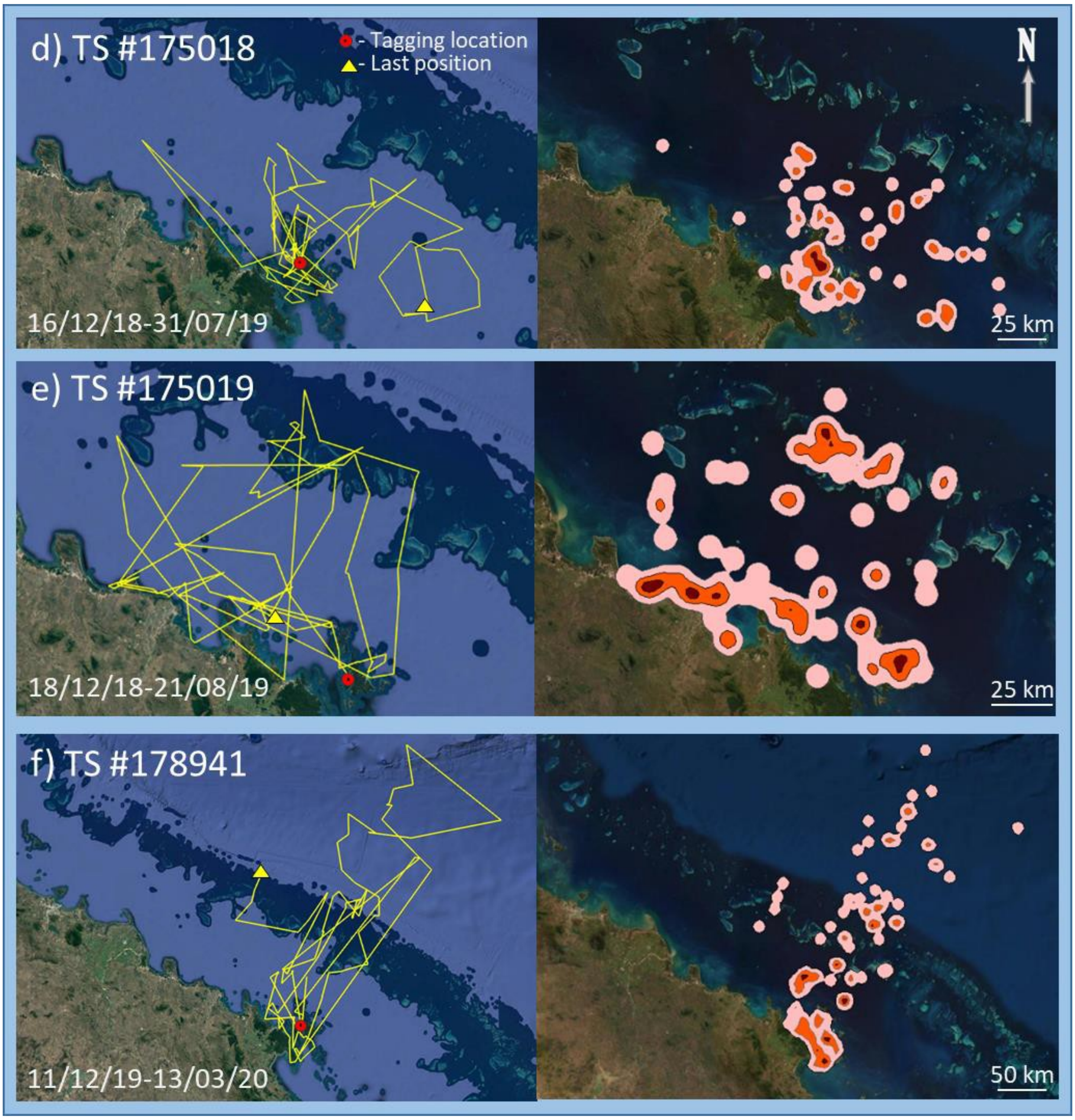

Figure 17 (cont.) Satellite tracks (left panels, Maps source: Google, Landsat/Copernicus) of the tiger sharks tagged with satellite transmitters that had more than 50 satellite positions (i.e. for which kernel density estimates (KDE) were computed (left panels). Right panels - extent of the 10% (brown), 50% (orange, representing the core habitats) and 95% (light pink, representing home ranges) fixed-kernel density estimates; maps created in ESRI ArcGIS v. 10.1, imagery sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, Swisstopo, and the GIS User Community.

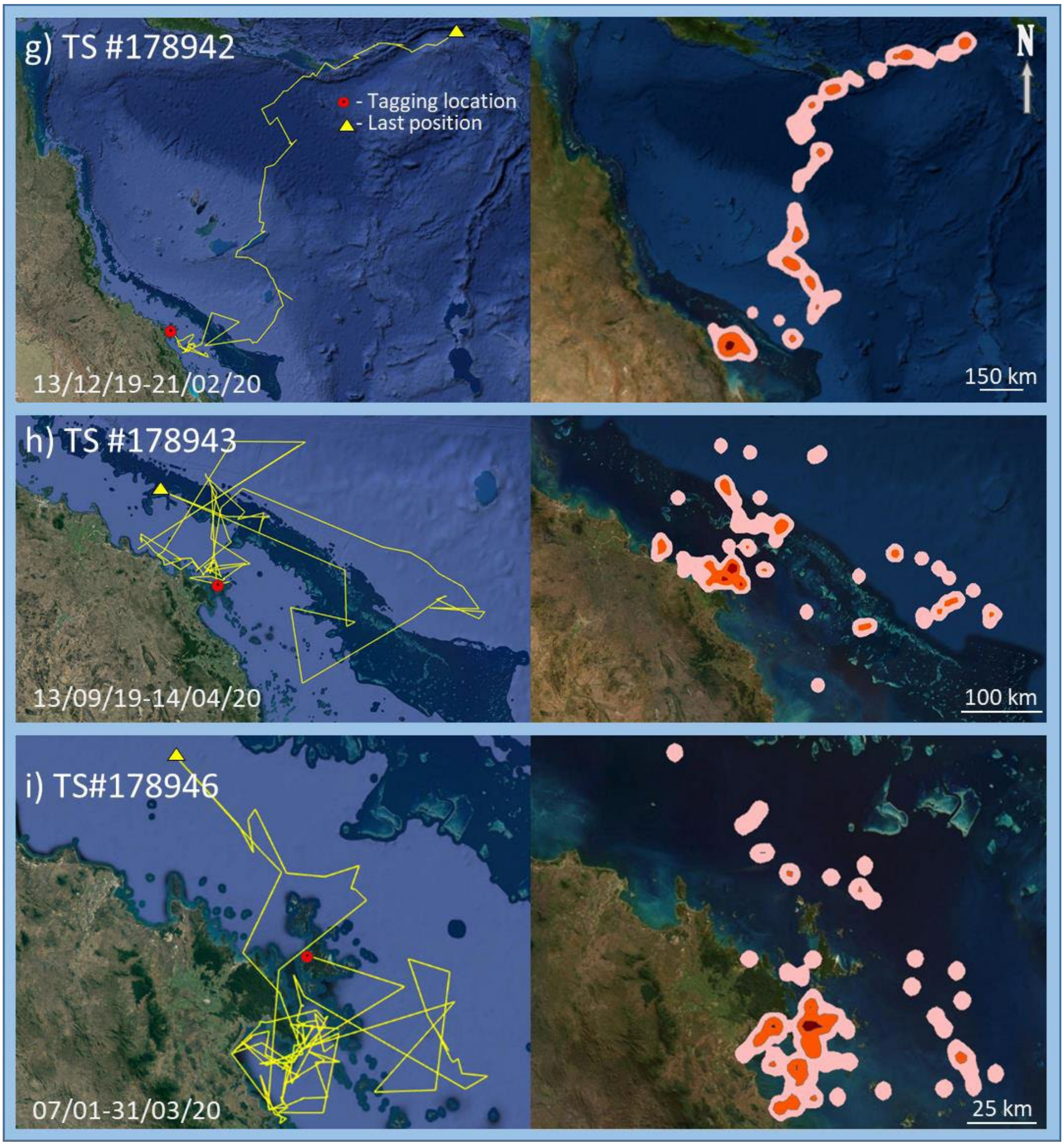

Figure 17 (cont.) Satellite tracks (left panels, Maps source: Google, Landsat/Copernicus) of the tiger sharks tagged with satellite transmitters that had more than 50 satellite positions (i.e. for which kernel density estimates (KDE) were computed (left panels). Right panels - extent of the 10% (brown), 50% (orange, representing the core habitats) and 95% (light pink, representing home ranges) fixed-kernel density estimates; maps created in ESRI ArcGIS v. 10.1, imagery sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, Swisstopo, and the GIS User Community.

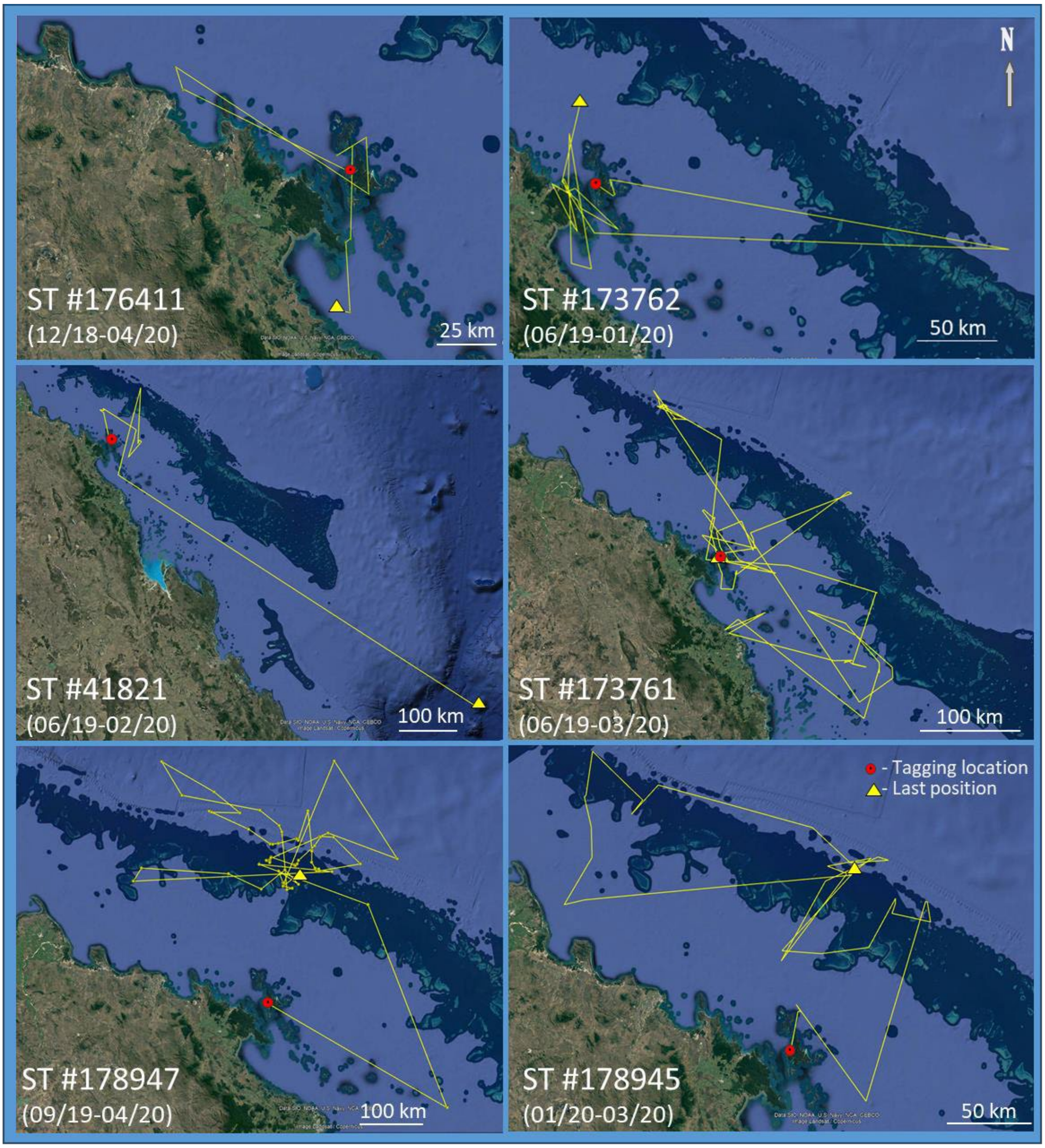

Figure 18. Satellite tracks showing the movements of the tiger sharks tagged with satellite transmitters that had less than 50 satellite positions by April 15th 2020. Date range represents the tagging month to month of last detection. Maps source: Google, Landsat/Copernicus.

Table 7. Home range area (95% KDE) and core areas (50% KDE) for the sharks for which more than 50 satellite detections were available.

ID	No. locations	Core area (ha)	Home range (ha)
Tiger sharks			
All indiv. combined	1585	578,273	7,174,504
175011	298	144,142	897,788
175014	104	326,118	1,714,187
175018	118	44,229	233,185
175019	102	96,786	459,788
178941	129	131,906	764,247
178942	176	2,095,647	14,230,129
178943	101	266,679	1,661,492
178946	108	37,285	217,214
41820	210	83,662	351,503
Great hammerhead			
175016	246	5,245	53,258

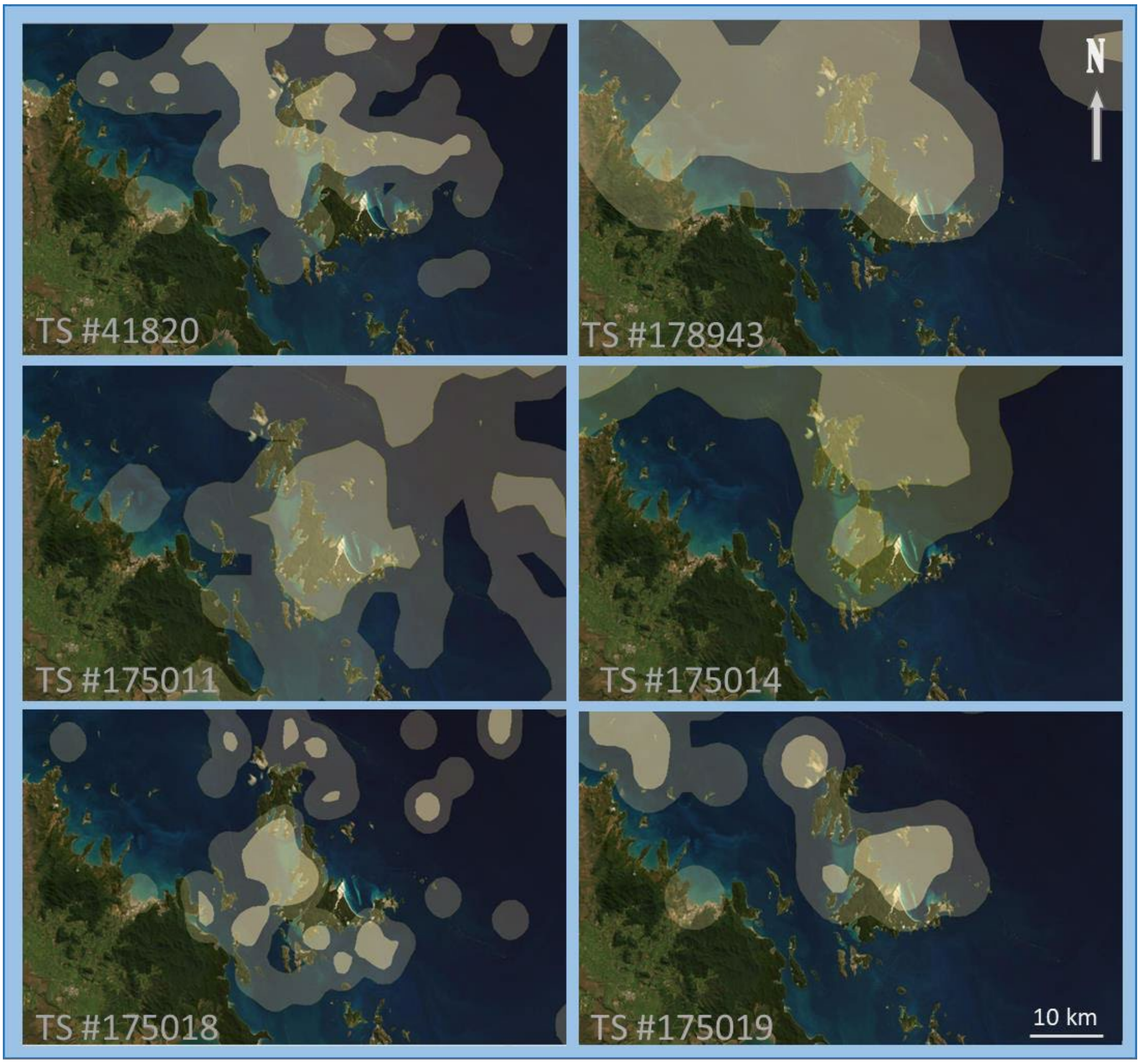

Figure 19. Extent of the 50% (darker highlight) and 95% (lighter highlight) kernel density estimates (KDEs) of the tiger sharks tagged with satellite transmitters, while focusing on the area around Whitsunday Island, to illustrate how the Island fits within each individual's habitat. 50% KDE indicates the core habitat, and the 95% contour the overall home ranges. Maps created in ESRI ArcGIS v. 10.1, imagery sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, Swisstopo, and the GIS User Community).

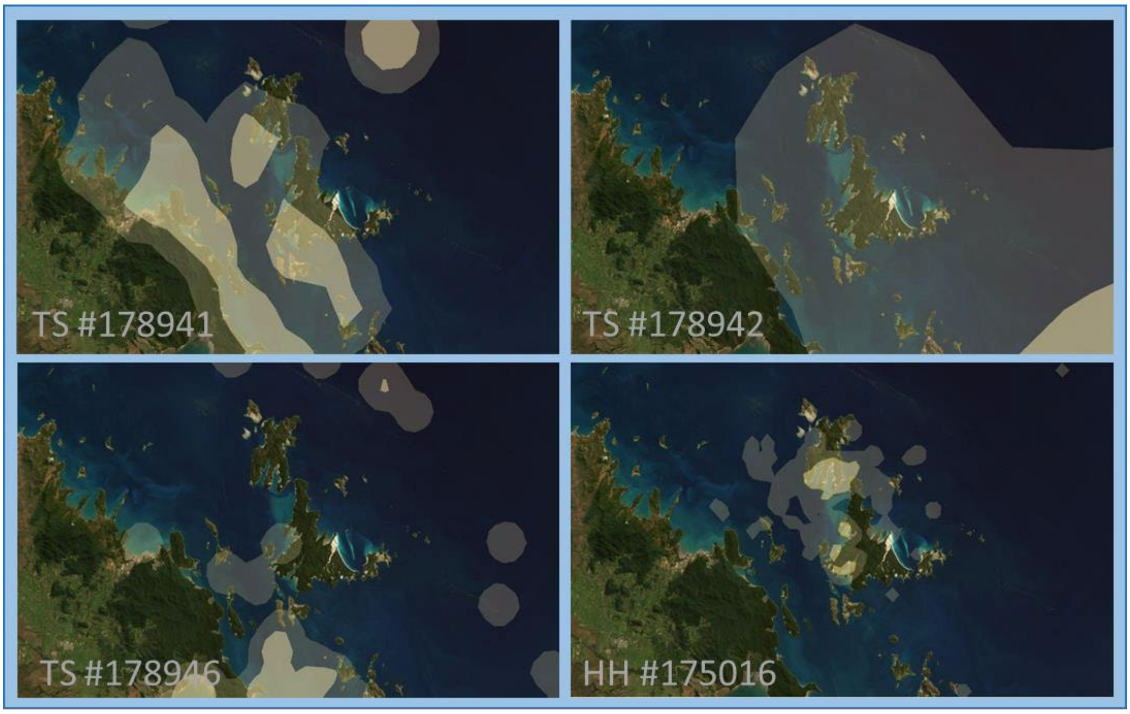

Figure 19 (cont.) Extent of the 50% (darker highlight) and 95% (lighter highlight) kernel density estimates (KDEs) of the tiger sharks tagged with satellite transmitters, while focusing on the area around Whitsunday Island, to illustrate how the Island fits within each individual's habitat. 50% KDE indicates the core habitat, and the 95% contour the overall home ranges. Maps created in ESRI ArcGIS v. 10.1, imagery sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, Swisstopo, and the GIS User Community).

Bull sharks

Satellite tracking of the three bull sharks tagged produced little data, likely because this species does not spend enough time at the surface for positioning information to be sent to satellites. Nevertheless, data obtained provides interesting insights into bull shark spatial behaviour, and clearly show that bull sharks can move large distances. The three individuals made very distinct movements (Fig. 20). Bull shark ST #175012 (283 cm TL male), tagged in June 2019, swam northwards, reaching the Torres Strait (1280 km away) 26 days after tagging, and then moved south again and within two months it was detected by the acoustic receivers in Cid Harbour. It then remained in the Whitsunday area, where it was sporadically detected between September 2019 and July 2020 (when receivers were downloaded) in Cid Harbour (see *Acoustic tracking* section below). Bull shark ST #178952 (288 cm female) was tagged in early January 2020 and moved >360 km southeast to the outer reef immediately after tagging, where it remained for a month before moving to the Torres Strait (Fig. 20). The third tagged bull shark (261 cm male, ST #178955), also tagged in early January 2020, remained in the Whitsunday region until last detected in March 2020.

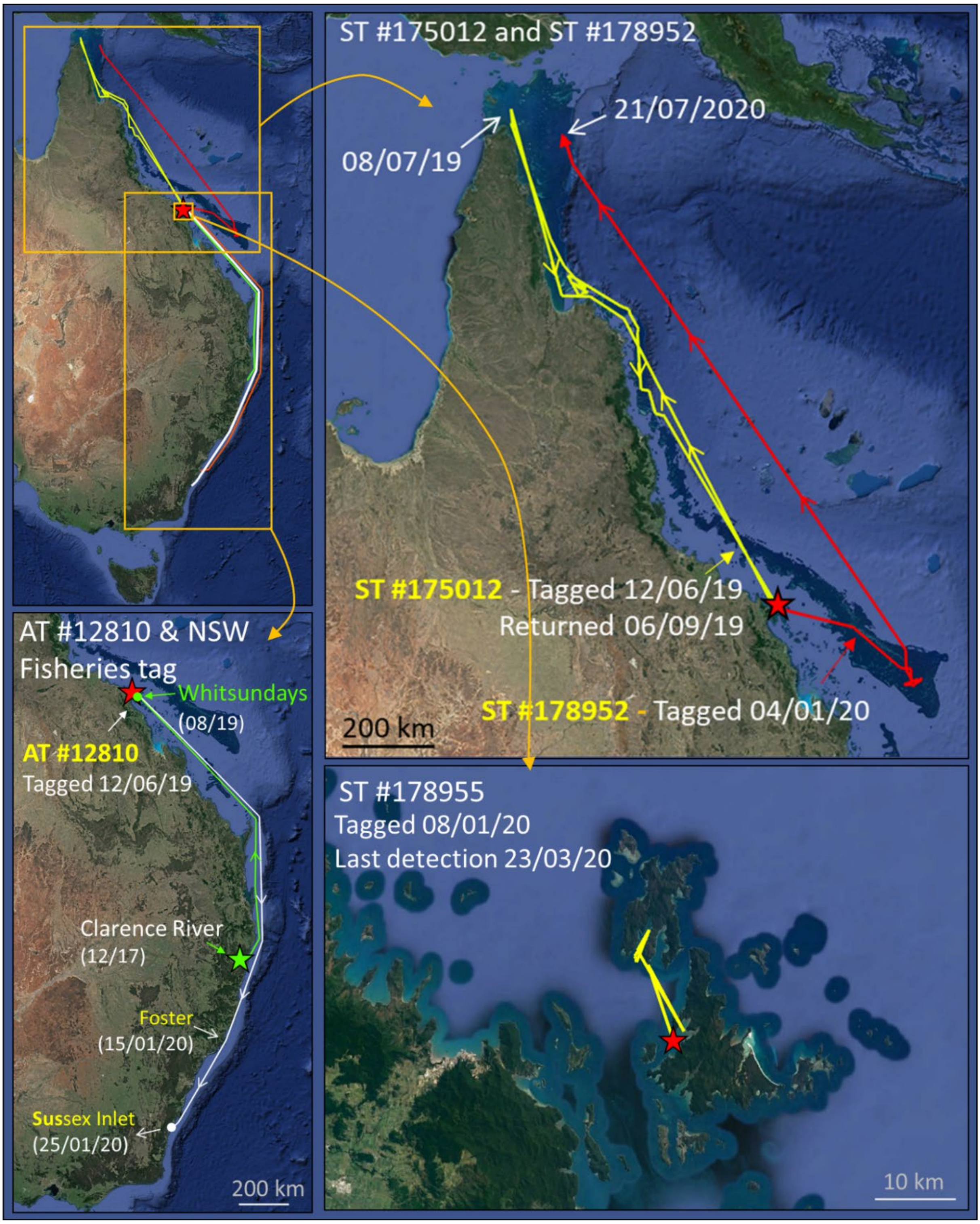

Figure 20. Movements of the three satellite tagged bull sharks, along with one acoustically tagged bull shark that was detected by acoustic receivers from other studies, and one acoustically tagged bull shark tagged near the Clarence River (by the New South Wales Department of Primary Industries; in green) and detected by the Whitsundays receivers almost two years later, showing the variability in movements among individuals and the long distances moved. Red stars indicate the tagging site for sharks tagged in the present study (Cid Harbour), and green star indicates the tagging site of the bull shark acoustically tagged by the NSW Department of Primary Industries. Map source: Google, Landsat/Copernicus.

Movement information could also be obtained from a 245 cm acoustically tagged male (AT # 12810) that was tagged in June 2019 and was detected by NSW Fisheries' acoustic receivers in January 2020 at Foster (NSW), and then at Sussex Inlet in late January 2020 (Fig. 20), representing a straight path movement of ~2000 km within seven months. In addition, a female bull shark tagged by NSW Fisheries in December 2010 (145 cm TL) near the Clarence River, ~1200 km away, was also detected by the receiver array at Cid Harbour (receiver Gate 4) in August 2019 (Fig. 20).

Hammerhead sharks

The tagged scalloped hammerhead shark was not detected after tagging. The great hammerhead shark provided data for ~4 months, which showed that the individual spent most of its time in the coastal areas of the Whitsunday Islands, but made three short (up to 1 week) trips to the outer reef, ~60 km away (Fig. 21). Four core use areas (indicated by separated 50% KDE regions), that show that the habitats most used were the western inlets of the Whitsunday and Hook Islands and around the Hook passage (Fig. 21).

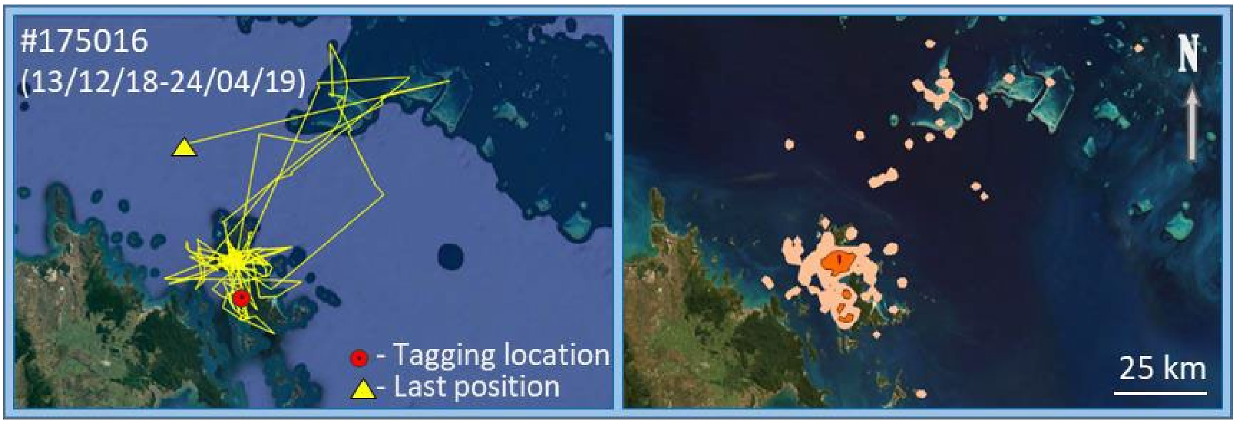

Figure 21. Movements of the satellite-tagged great hammerhead shark (a 241 cm female, ST #175016), showing the movements to the outer reef and the extent of the 10% (brown), 50% (orange) and 95% (light pink) fixed-kernel density estimates (KDEs). Map source: Google, Landsat/Copernicus.

Acoustic tracking

Of 101 sharks caught, 43 were tagged with acoustic transmitters (Table 6). Acoustic data were downloaded on the 30th of July 2020. Unfortunately, receivers Gate 1 and Hook 4 were damaged and no data could be recovered, and the receiver at the passage between Whitsunday Island and Haslewood Island (receiver 'Pass 2') could not be retrieved (see

Fig. 5 for receiver locations). Twenty-nine (67.5%) of the tagged sharks were detected by the Whitsundays receivers after tagging.

Use of Cid Harbour

Overall, residency in Cid Harbour (receivers C1-C6 and Gate 2-Gate 4 – see Fig. 5) was low for most individuals, with 79% of all sharks tagged visiting the harbour on less than 10% of days at liberty (Fig. 22). For tiger sharks, 13 (72.2%) out of the 18 individuals acoustically tagged were detected in Cid Harbour after tagging, with residency indices ranging from 1.0% to 15.5% of days (Fig. 22). Of these, 77% visited the area on <10% of the days at liberty (including 69% that visited the area on <5% of days at liberty) (Fig. 22). Most (72%) of the tiger shark visits to Cid Harbour were over a single day, and overall, tiger sharks were detected in the Cid Harbour area on average 1.5 ± 1.3 consecutive days (±SD). Individual AT #64003 visited the area the most, and was detected on 15.5% of days at liberty, when it visited on average 1.7 ± 1.1 days in a row (Fig. 22). That individual was also tagged with a satellite transmitter (ST #176411), with data confirming that it remained in the broader Whitsundays region over the tracking period (Fig. 18). Individual AT #28255 also visited Cid Harbour on >10% of days at liberty (13.5 %), and was regularly detected between the tagging date in December 2018 and mid-June 2019 (Fig. 22). Over that period, it was detected on up to 11 days in a row (average: 3.8 ± 2.8 days). However, after mid-June 2019, that animal was no longer detected in Cid Harbour (Fig. 22), with satellite data showing that it moved more offshore, ~70 km away (individual ST #175018; Fig. 17d). The other shark that was detected >10% of days at liberty was AT #64005, and satellite data showed it moved to various locations including the outer reef, the Coral Sea, and coastal areas north of Airlie Beach (ST #178943, Fig. 17h). Of the five tiger sharks that were not detected in Cid Harbour after tagging, three were also tagged with satellite transmitters, and data shows that one individual remained in the broader Whitsundays region (ST #178946; Fig. 17i), one moved to the Solomon Islands (ST #178942; Fig. 17g), and the third moved to the outer reef (ST #178947) (Fig. 18). Seasonality analysis of the use of Cid Harbour showed that tiger sharks were present more often in October/November (Fig. 23), although circular tests did not identify a significant effect of month on shark presence (Rayleigh test (Z) = 2.775, $p = 0.062$).

As with tiger sharks, different bull shark individuals were detected by Cid Harbour receivers for different amounts of time, and had different patterns of visitation (Fig. 22). Two of the tagged individuals were not detected after tagging. One of those was also tagged with a satellite transmitter (ST #178952), with data showing that it moved to the outer reef, and then to Torres Strait (Fig. 20). On the opposite end of the spectrum, individual AT #5021 had the highest residency index of 52.4%, with satellite data also showing that it remained in the area throughout the tracking period (ST #178955; Fig. 20). During the monitored time, it visited Cid Harbour 39 times, on average on 2.7 ± 2.4 consecutive days (range: 1-11 days). The third individual that was also tagged with a satellite tag was AT #12812 (ST #175012), which moved to Torres Strait immediately after tagging, to return to Cid Harbour two months later (see Fig. 20). Upon returning, it made 32 more visits to the harbour (Fig. 22), ranging from 1 to 7 days consecutive days (average: 1.8 ± 1.4). When considering all tagged bull shark individuals, data suggests that, when in the area, bull sharks visit Cid Harbour in average 2.7 (±3.4) consecutive days. Circular statistics detected a significant seasonality in the use of Cid Harbour by bull sharks ($Z = 23.38$, $p < 0.001$), with a peak in detections in September (Fig. 23). However that this analysis was based on only two individuals, so at this stage this pattern can not be generalised.

For spot-tail sharks, five of the eight tagged individuals (63%) were detected in Cid Harbour after tagging (Fig. 22). Individuals AT #6159 and AT #28254 had the highest residency indices of 47% and 43%, respectively. AT #6159 was regularly detected from the tagging date until the date receivers were downloaded (i.e. at the end of the present study), visiting the harbour on average 3.6 (±3.6) days in a row (maximum: 12 days). AT #28254 was regularly detected for one year after tagging (Fig. 22), when it visited the area up to 42 days in a row (average: 7.1 ± 7.7 days in a row), suggesting that it was resident in the area over that time period. However, it was not detected after mid-December 2019. Individual AT #12814 also had a relatively high residency index (32.5%), and visited the area up to 51 days in a row (average: 16.7 ± 18.7 days in a row), but data shows that it remained in the Cid Harbour area for three months after tagging, after which it left the area, to return seven months later (Fig. 22). Overall, spot-tail sharks visited Cid Harbour on more consecutive days than tigers and bull sharks (5.5 ± 8.2 days).

For the remaining species tagged, due to small sample sizes (≤3), it was not possible to conduct a meaningful investigation of the movement patterns. For example, the three *C. limbatus/tilsoni* tagged left the area immediately after tagging, one returning a month later after which it remained in the area for extended period (Fig. 22). Similarly, three blacktip reef sharks were tagged, with two leaving the area after tagging but one remaining in Cid Harbour, where it was detected on 98% of days after tagging (Fig. 22). The two great hammerhead sharks were detected over two weeks, after which they left the area, while the scalloped hammerhead and the whitecheek shark left the area immediately (scalloped hammerhead) or shortly (four days - whitecheek shark) after tagging (Fig. 22).

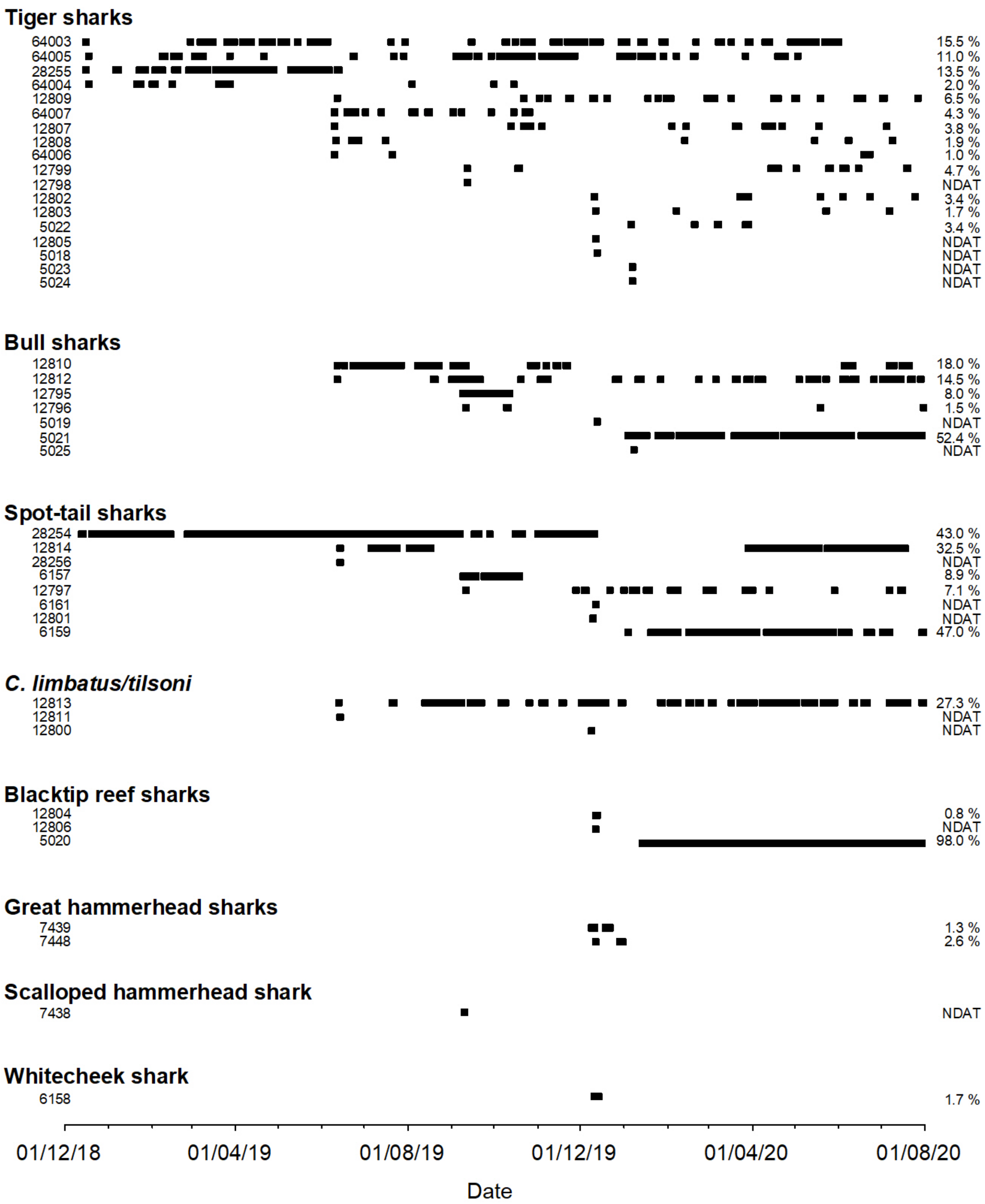

Figure 22. Timeline showing the days each acoustically tagged shark was detected by receivers deployed in the Cid Harbour area (receivers C1-C6 and Gate 2-Gate 4 – see Fig. 5). For each individual, the first day recorded on the timeline corresponds to the tagging day. Numbers to the right of each timeline are the residency index, representing the proportion of days each individual was detected over the period between the tagging date and date the receivers were downloaded (30/07/2020). NDAT = not detected after tagging.

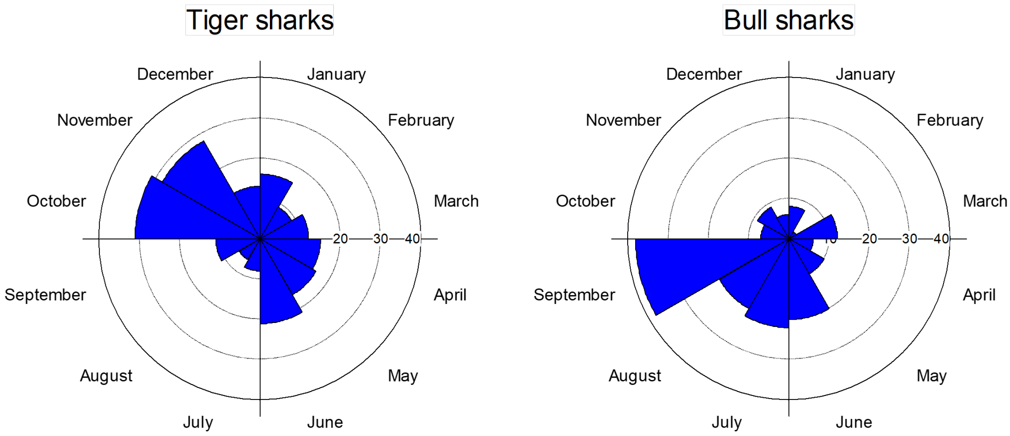

Figure 23. Seasonality in the use of Cid Harbour for tiger and bull sharks. Note: that this analysis was based on a limited number of individuals (nine tiger and two bull sharks), particularly for bull sharks, for which only two individuals provided a whole year of data, so these results are preliminary and can not be considered as indicative of the seasonal use of Cid Harbour by the overall bull shark population.

Use of the Sawmill Bay area. The use of Sawmill Bay area (i.e. of the area where the shark bite incidents took place, and where boats moor for the night) was mostly characterised by short visits (Figs. 24 & 25). Indeed, for tiger sharks, bull sharks and small whaler sharks, there was a clear peak in proportion of visits at visit duration <30 min, after which the proportion of visits decreased sharply (Fig. 24). This peak was particularly strong for tiger sharks, for which 64% of the visits lasted less than 30 min (including 20% of visits that lasted less than 1 min, suggesting the animal was just passing through the area).

No pattern in time of arrival at Sawmill Bay area was evident for tiger sharks ($Z = 1.938$, $p = 0.144$; Fig. 25). However, for bull sharks and for small whalers, arrival times were not uniformly distributed, and data indicates that these species enter the area more often at the end of the day: bull sharks on average around 15:50 h (median: 16:00 h; $Z = 32.653$, $p < 0.001$), and small whalers around 17:40 h (median: 17:00 h; $Z = 26.568$, $p < 0.001$) (Fig. 25). However, for small whalers, this distribution was driven by one spot-tail individual (AT #28254), which visited the area much more often between 17:00 and 19:00 (mean: 18:15 h), and when that individual was not included in the analyses, no pattern in time of arrival was present for this group.

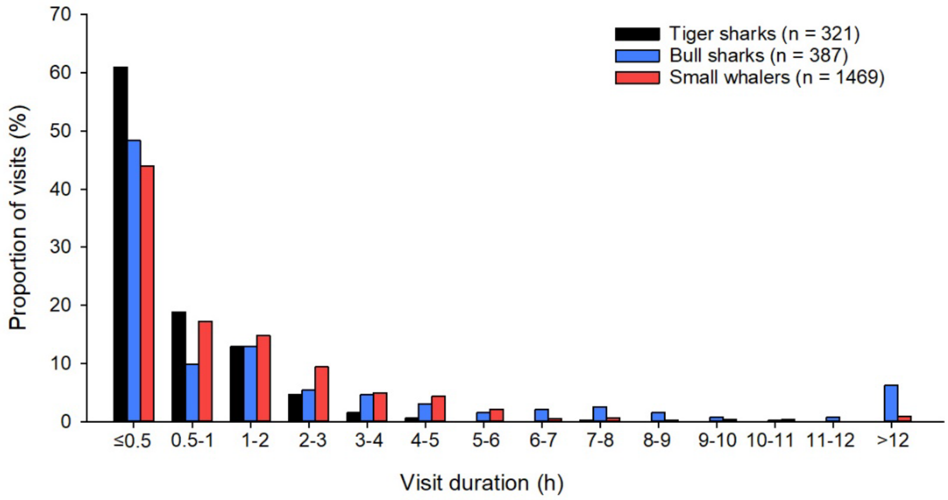

Figure 24. Distribution of visit durations to the Sawmill Bay area of Cid Harbour (Receivers C1-C6).

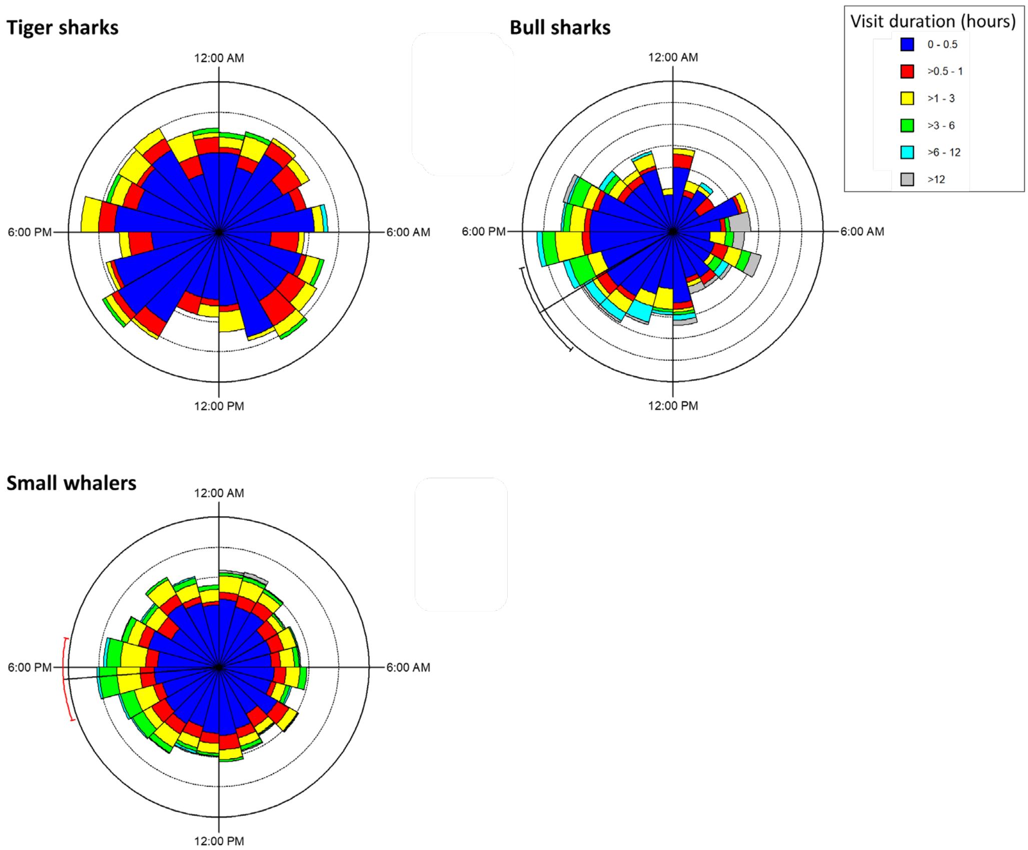

Figure 25. Circular plots showing the distribution of times of arrival at the Sawmill Bay area (receivers C1-C6) for tiger sharks (*n* = 317 visits), bull sharks (*n* = 387) and small whalers (*n* = 1460), and the time spent in the area at each visit. Colours indicate visit duration, in number of hours, with the frequency of each time interval represented by the area of the wedge. Mean visit duration and 99% confidence intervals (CI) are presented for bull sharks and small whaler sharks, the groups for which Rayleigh uniformity test identified a non-uniform distribution of arrival times ($p < 0.05$). Spot-tail shark's 99% CI is in red as it is driven by one only individual, and is therefore not representative of the arrival times/visit durations for the species.

For the three shark groups, the time between two consecutive visits (inter-visit time) varied widely, from just above 1 hour (the cut-off time with no detections for a new visit to be considered) to 162 days for tiger sharks, 294 days for bull sharks, and 225 days for small whalers (Fig. 26). In general, inter-visit times were longer for tiger sharks than for bull sharks and smaller whales, e.g. in 90% of the times, inter-visit times were 20 days or less for tiger sharks, 6 days or less for bull sharks, and only ~21.5 h or less for small whalers (see 90th percentiles in Fig. 26). For tiger and bull sharks, the median of inter-visitation times was slightly more than half a day (13 h for bull sharks and 15.5 h for bull sharks), whereas small whaler sharks visits were separated by much shorter time periods, with median inter-visit times of ~3 h (Fig. 26). This means that, when in the general area, tiger and bull sharks come in and out of the Sawmill Bay area several times separated by hours-days, sometimes moving out to return weeks or even months later, whereas small whalers make more regular visits. There was no relationship between the time spent in the area and inter-visit time for any of these species.

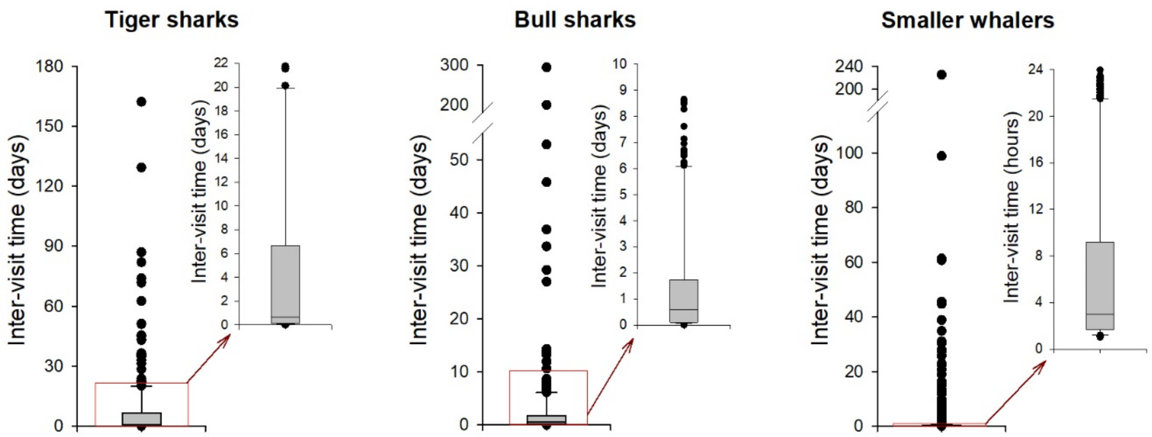

Figure 26. Box and whisker plots showing the distribution of inter-visit times to the Sawmill Bay area of Cid Harbour (tiger sharks: *n* = 301; bull sharks: *n* = 314; small whalers: *n* = 1942). Plots show the upper and lower quartiles (boxes), medians (lines within boxes), 10th and 90th percentiles (whiskers) and outliers (circles).

Use of other Whitsundays locations

Most acoustically tagged animals were detected by at least one of the receivers placed at other locations around the Whitsunday Islands (Figs. 27-30). For the three main species (tiger, bull and spot-tail sharks), there was high intraspecific variability in the use of the different locations (Figs. 27-29), suggesting that individuals use the different areas differently. This was supported by satellite tracking data. For example, tiger shark #AT 12809 used all the monitored locations (and in particular Tongue Bay, which was used much more than the other individuals), whereas tiger shark AT #28255 was detected in Cid Harbour but not in any of the other locations (Fig. 27); bull shark AT #5021 used the monitored area around Hook Island, regularly moving between Cid Harbour and Hook Island, whereas bull sharks AT #12795 and AT #12796 never used that area (Fig. 28); spot-tail AT #12797 used almost all monitored locations, while spot-tails AT #6157 and AT #6159 were only detected by Cid Harbour receivers (Fig. 29).

For tiger sharks, besides Cid Harbour, Tongue Bay was the other monitored location most used (Figs. 27, 31 & 32): 72% of the tagged individuals used that location over a total of 353 visits (Fig. 31) of 17 min average duration (median: 6.4 min (Fig. 32)). Whitehaven Beach was the least visited location, with only 43 shorter visits (Fig. 31 & 32). For bull sharks, the southern part of Hook Island (receivers Hook 1-3) was the area most visited (Figs. 28 & 31), and although bull sharks made relatively few visits to Whitehaven Beach (only 20), those visits tended to be longer than visits to the other areas (Figs. 31 & 32). As with bull sharks, the other area most used by the tagged spot-tail sharks was the southern coast of Hook Island, which was used by 38% of the tagged individuals, over 56 visits (Figs. 29, 31 & 32).

In some cases, although a significant proportion of the tagged sharks were detected at a location (Fig. 31), sharks did not remain at that location for long periods, suggesting that those locations are only used for transit. For example, the channel between the Whitsunday and Hamilton Islands (Pass 3/4) was used by 85% of the tagged bull sharks over 56 visits, but visit durations were short (75% <3 min) (Figs. 31 & 32).

For the other species, due to the small number of individuals tagged (≤3), it is not possible to conduct a meaningful analysis of the movement data. Nevertheless, for *C. limbatus/tilsoni* and for blacktip reef sharks, it was possible to identify a wide variability in movement behaviour between individuals. Among the three *C. limbatus/tilsoni* tagged, two individuals (AT #12800 and AT #12811) were detected by receivers at the Entrance to Cid Harbour for 1 h after tagging, after which they left the area and were not detected again. In contrast, the third individual (AT #12813), was detected for 98% of the time at liberty, with data showing it moving regularly between Cid Harbour and Hook Island to the north and Pass 3/4 to the south, and even moving to Tongue Bay (Fig. 30), on the opposite side of Whitsunday Island. As with *C. limbatus/tilsoni*, only three blacktip reef sharks were tagged, and those provided very different movement data. One individual (AT #2806) was not detected after tagging, another (AT #12804) moved from

Sawmill Bay to the Entrance to Cid Harbour after tagging and was not detected again, and the third (AT #5020) remained in the Sawmill Bay area for ca. 7.5 months, and only moved to the Entrance to Cid Harbour once, and for a short period of time (<1 h), before returning to Sawmill Bay (Fig. 30). Interestingly, the blacktip reef sharks and the whitecheek shark were not detected by any of the receivers placed in the broader Whitsundays area. The two great hammerheads were only detected for two weeks after tagging, during which time they were detected at Hook Island (Hook receivers 1-3) and the channel between the Whitsunday and Hamilton Island (P3/4), while the one scalloped hammerhead tagged remained in the Bay for 30 min after tagging, and then left to not return (Fig. 30).

When connectivity plots were constructed, it was possible to visualise the flow of movements between the pairs of receiver locations (Figs. 33-35). There were clear differences in movement patterns between tiger, bull and spot-tail sharks. Of the three species, tiger sharks moved the most between the different monitored locations (Fig. 33), with 65% of the movements detected between Cid Harbour and other locations around the area, and only 35% between the entrance to Cid Harbour and the Sawmill Bay area. This agrees with the relatively shorter times spent at the Sawmill bay area (typically <30 min; Figs. 24 & 25), and longer inter-visit times (Fig. 26) when compared to the other two species. Besides the two areas of Cid Harbour (Sawmill Bay and entrance to the harbour), Tongue Bay also had a significant tiger shark movement flow, in agreement with other analyses that show Tongue Bay as the monitored location most visited by tiger sharks (Figs. 31 & 32). This was followed by Hook Island receivers (Hook 1-3) and the passage between the Whitsunday and Hook Islands (P1). Interestingly, when moving out of Cid Harbour, in a large proportion of cases sharks were subsequently detected at Tongue Bay, meaning they did not use the monitored channels (P1 and P3/4) to get there. It is possible that they swam around Hook or Hamilton Islands instead. Note also that although most movements from Sawmill Bay were to the Entrance to Cid Harbour, in 22% of the cases sharks were detected in Sawmill Bay and subsequently detected by other receivers (Fig. 32), indicating that in those occasions animals moved through receiver 'Gate 4' (see Fig. 5 for receiver location), which was damaged and could not provide data.

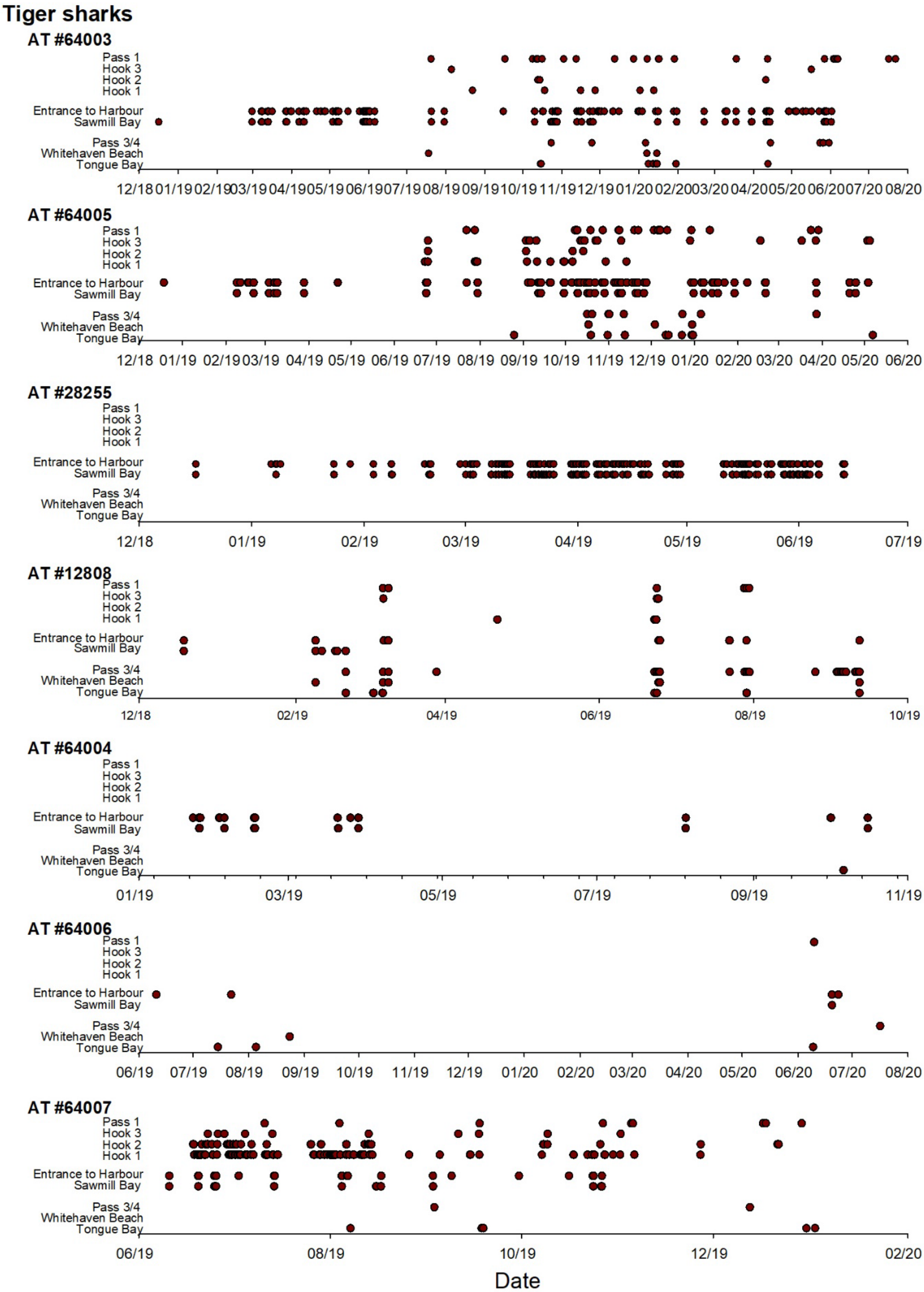

Figure 27. Timeline of detections of acoustically tagged tiger sharks by receivers placed around the Whitsundays Islands. ‘Entrance to Harbour’ includes detections by receivers Gate 2, Gate 3 and Gate 4; ‘Sawmill Bay’ includes detections by receivers C1-C6. See Fig. 5 for receiver locations.

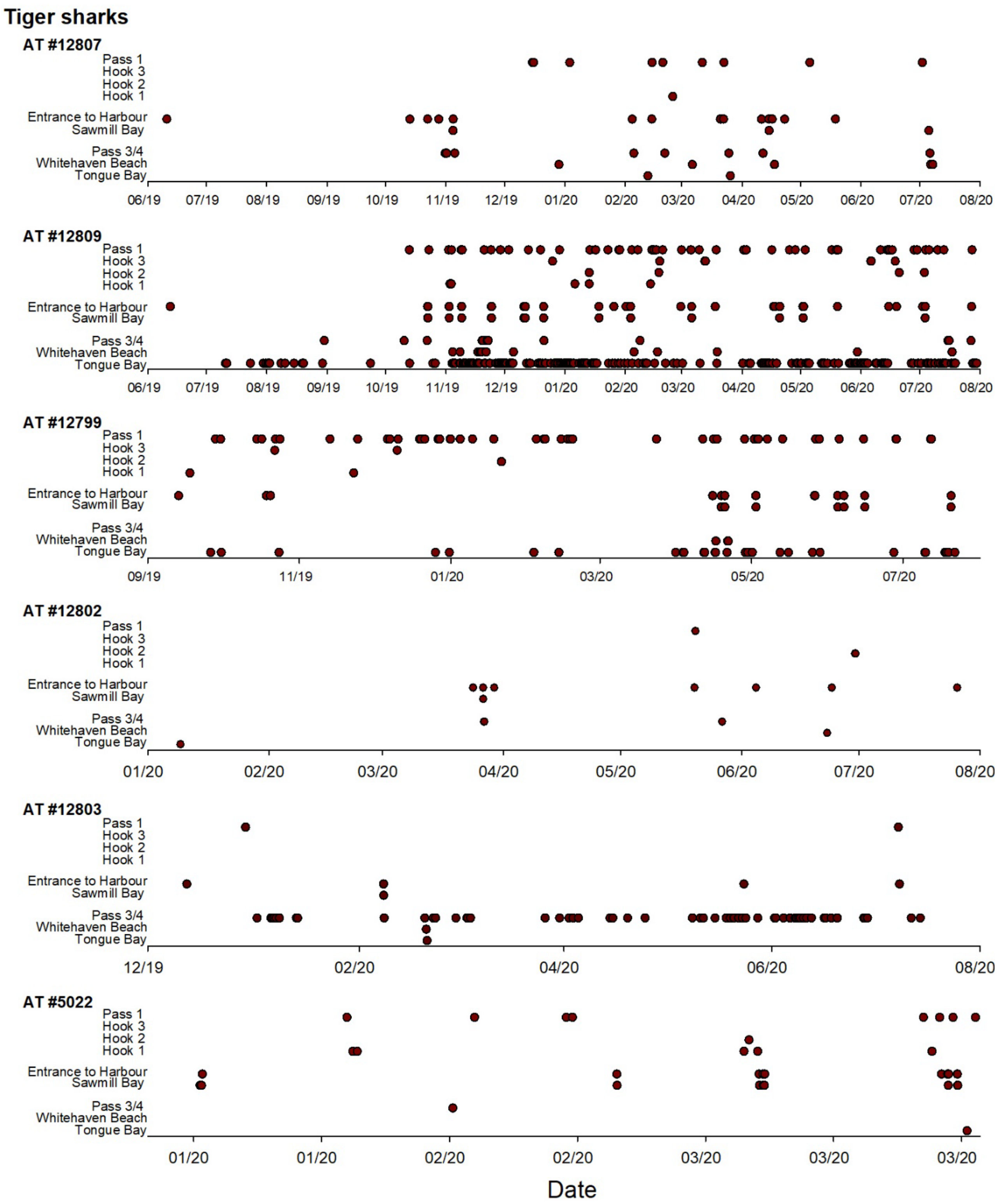

Figure 27 (cont.) Timeline of detections of acoustically tagged tiger sharks by receivers placed around the Whitsundays Islands. 'Entrance to Harbour' includes detections by receivers Gate 2, Gate 3 and Gate 4; 'Sawmill Bay' includes detections by receivers C1-C6. See Fig. 5 for receiver locations.

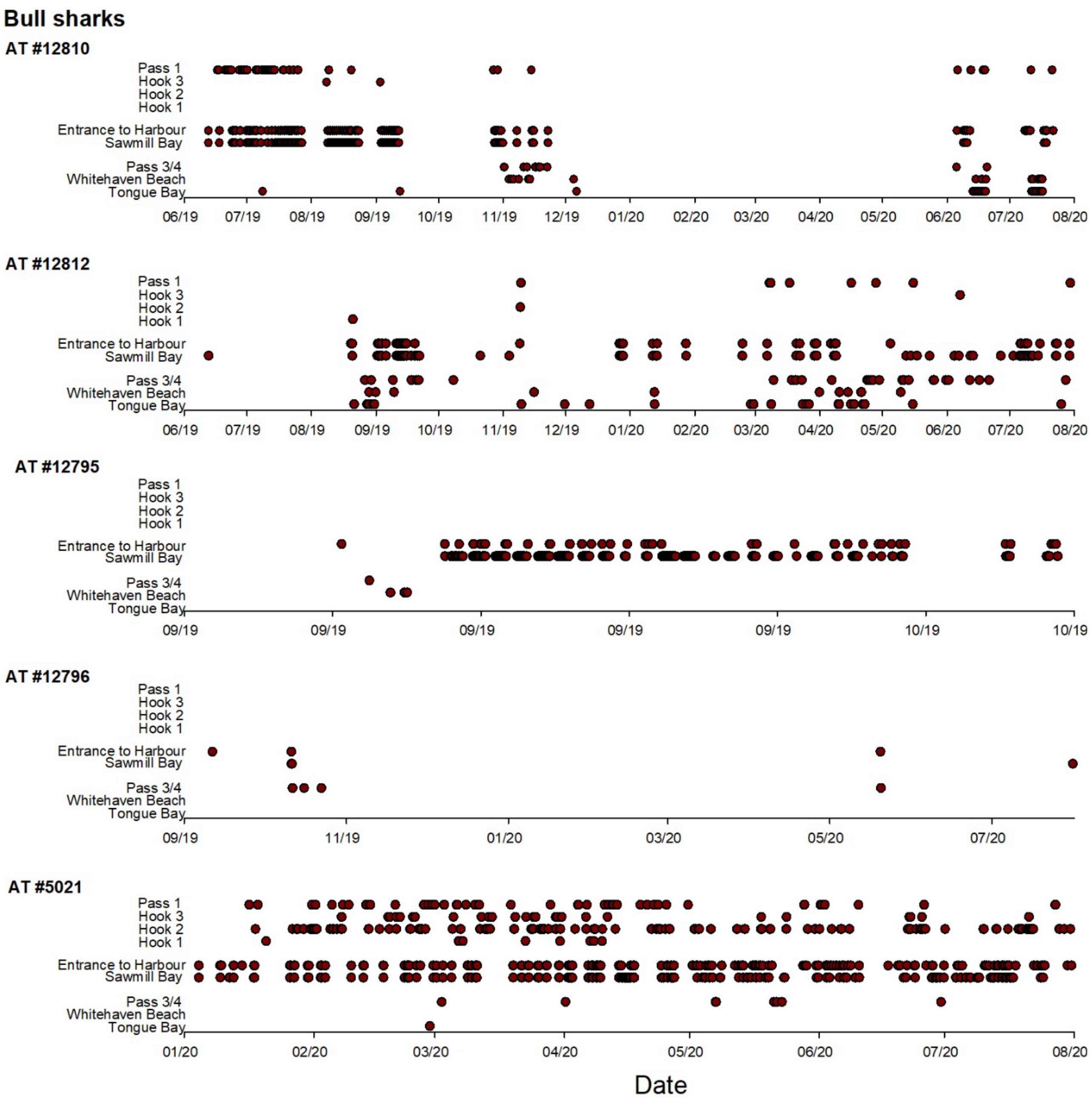

Figure 28. Timeline of detections of acoustically tagged bull sharks by receivers placed around the Whitsundays Islands. 'Entrance to Harbour' includes detections by receivers Gate 2, Gate 3 and Gate 4; 'Sawmill Bay' includes detections by receivers C1-C6. See Fig. 5 for receiver locations.

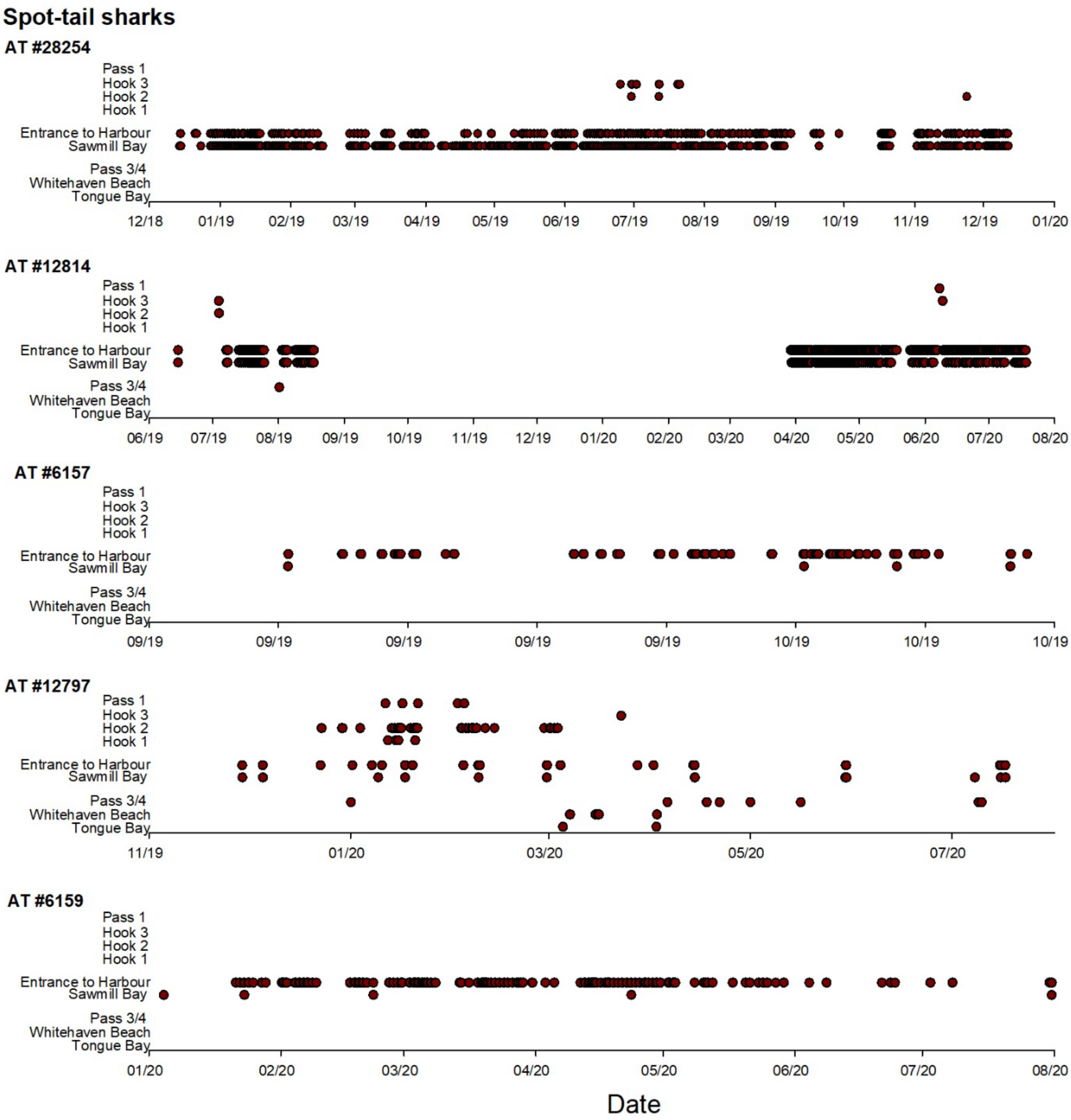

Figure 29. Timeline of detections of acoustically tagged spot-tail sharks by receivers placed around the Whitsundays Islands. 'Entrance to Harbour' includes detections by receivers Gate 2, Gate 3 and Gate 4; 'Sawmill Bay' includes detections by receivers C1-C6. See Fig. 5 for receiver locations.

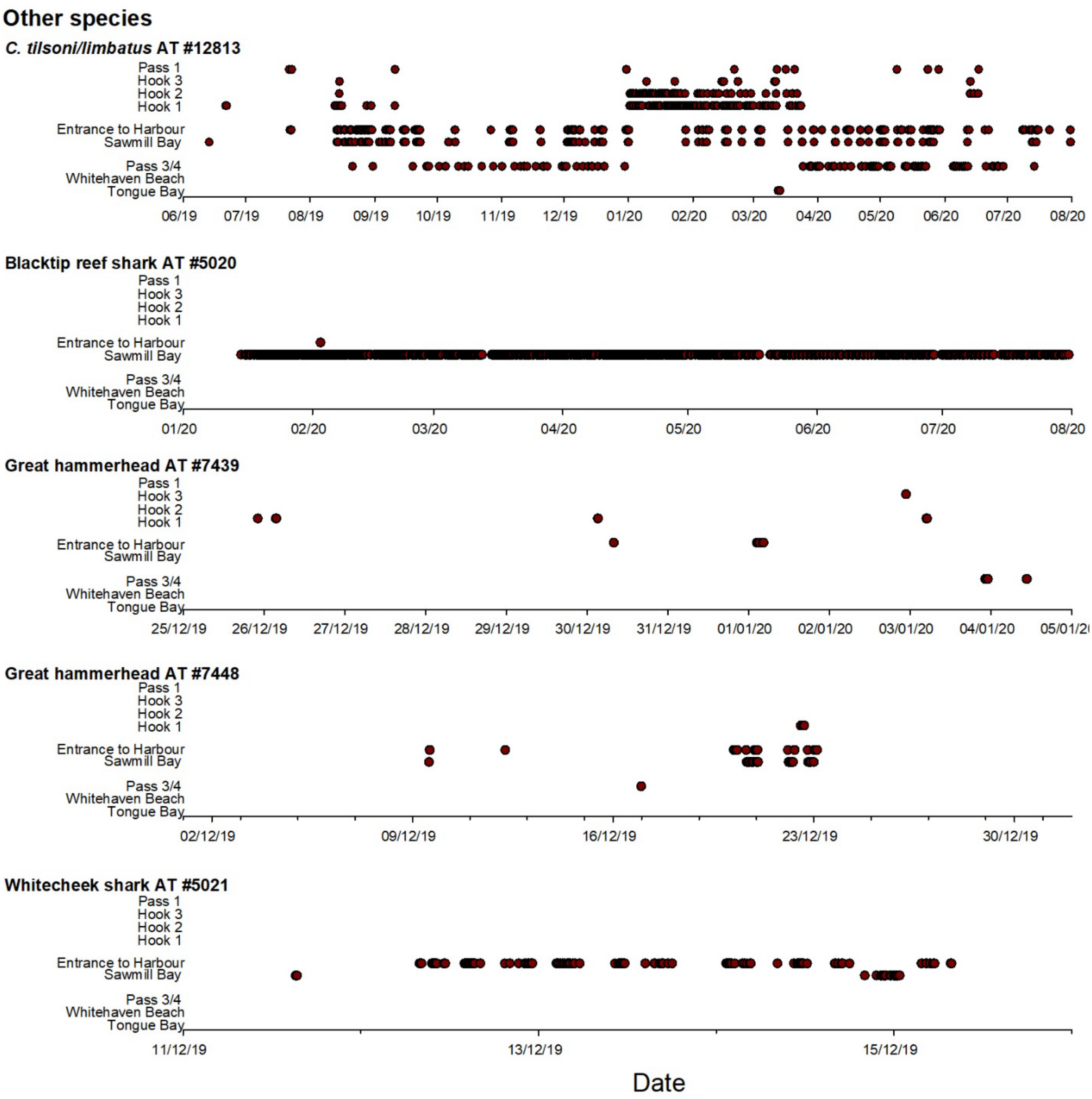

Figure 30. Timeline of detections of acoustically tagged sharks of the other species by receivers placed around the Whitsundays Islands. ‘Entrance to Harbour’ includes detections by receivers Gate 2, Gate 3 and Gate 4; ‘Sawmill Bay’ includes detections by receivers C1-C6. See Fig. 5 for receiver locations.

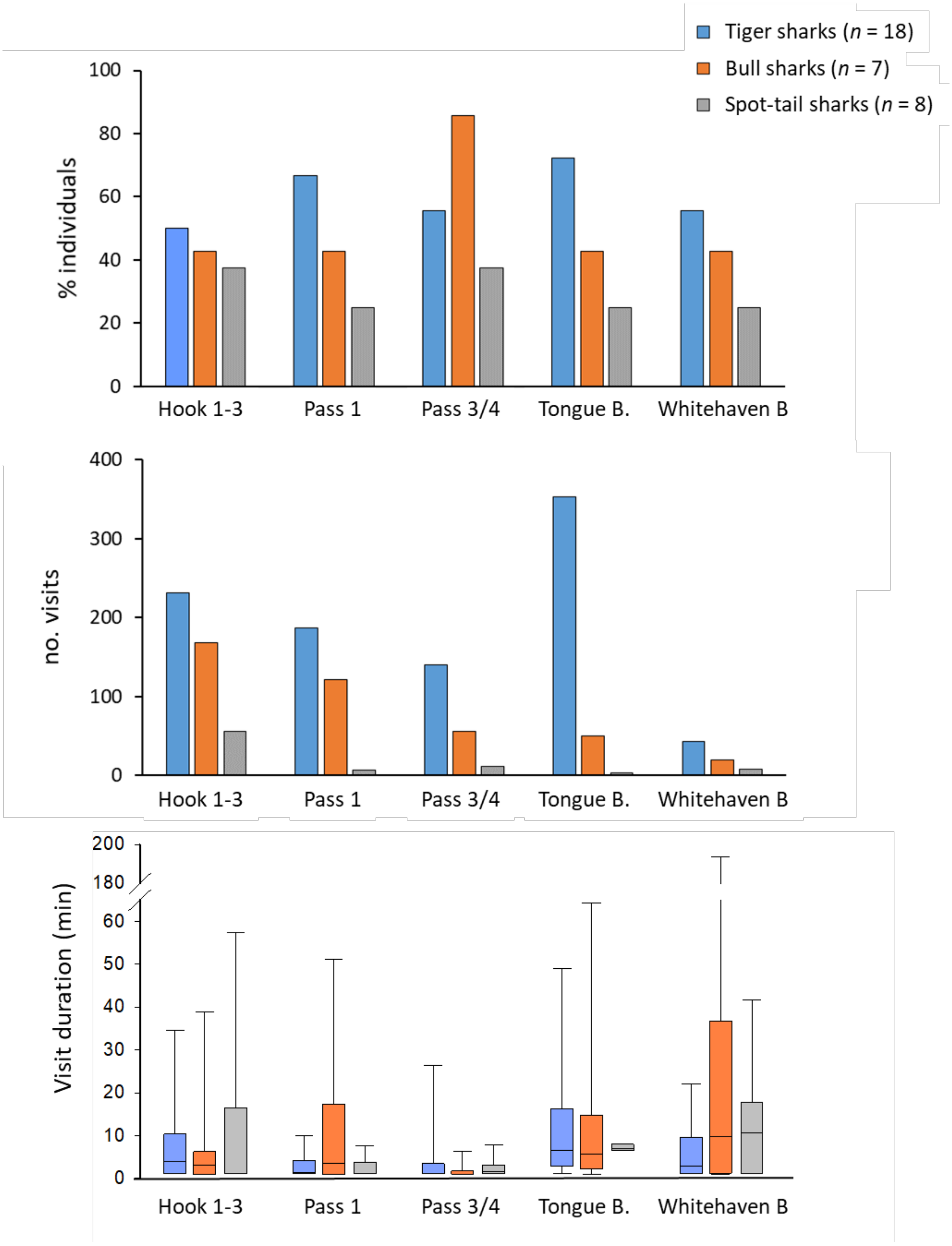

Figure 31. Proportion of tiger, bull and spot-tail shark individuals that visited each of the acoustically monitored locations (top graph), total number of visits those individuals made to each location (middle graph), and box and whisker plots showing the distribution of visit durations (bottom). In box and whisker plots, boxes indicate the upper and lower quartiles, lines within the boxes indicate the medians, and whiskers the 10^{th} and 90^{th} percentiles.

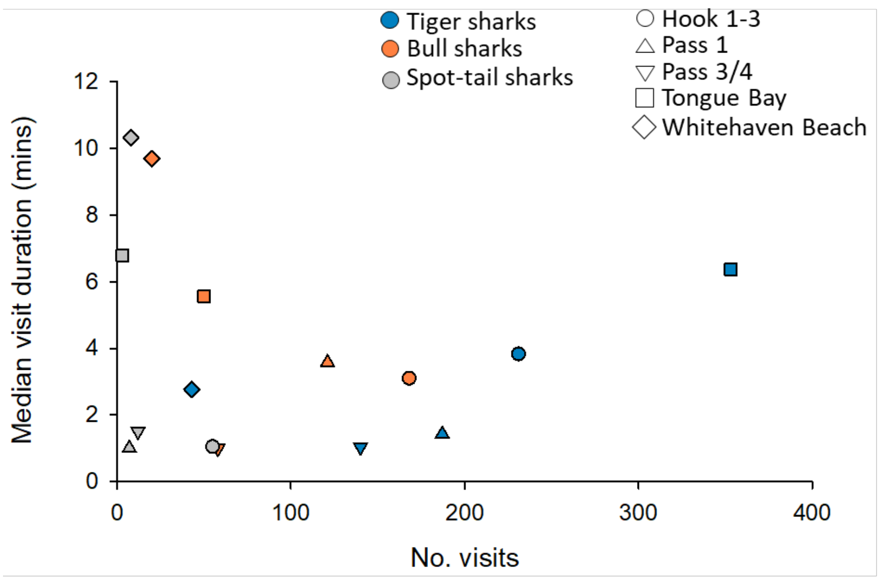

Figure 32. Relationship between number of visits and visit duration (median) for tiger, bull and spot-tail sharks.

As with tiger sharks, bull sharks also moved between the different locations, but to a lesser extent than tiger sharks (Fig. 34), with about half (49%) of their trajectories being between Cid Harbour and receivers located at other Whitsundays sites, and the other half between the Sawmill Bay area and the entrance to the harbour. This indicates that, when entering the Harbour, bull sharks remain in the area for longer than tiger sharks and/or that, bull sharks use the other Whitsundays sites to a lesser extent than tiger sharks. As with tiger sharks, the presence of direct links between Sawmill Bay and receivers at locations around the Whitsunday Islands provide evidence of bull sharks entering/exiting Cid Harbour through its southern entrance (Gate 4). Despite the lack of data from receiver Gate 4, the comparison of the relative proportion of movements between the two tracked areas of Cid Harbour (Sawmill Bay and entrance to the harbour) and between Cid Harbour and the other receivers provides an indication of the scale of movements of the different species throughout the Whitsundays region. For spot-tail sharks, the majority (94%) of the detected movements were between Sawmill Bay and the entrance to the harbour (Fig. 35) showing that, when in the area, this species has more localised movements, and makes limited use of the other monitored locations, in agreement with previous analyses.

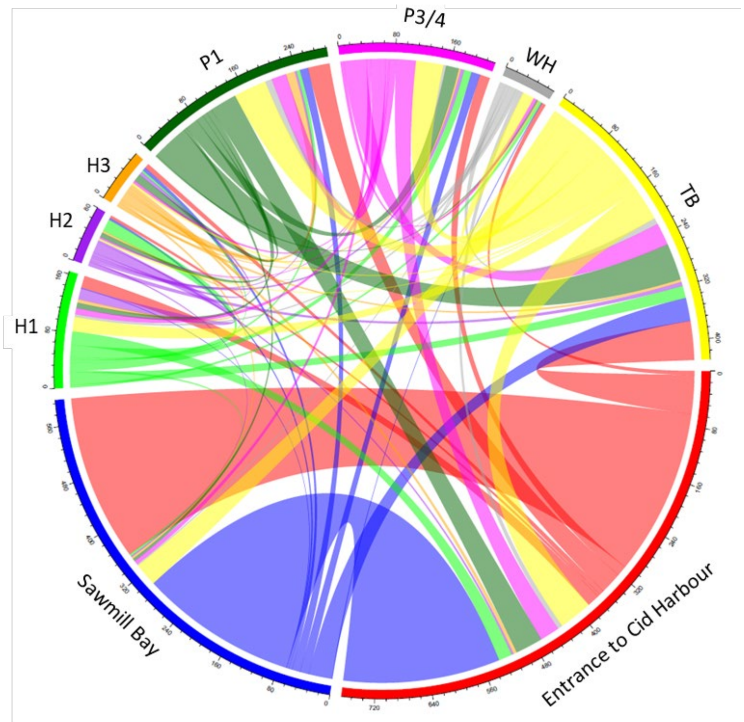

Figure 33. Connectivity plot representing the movement flows of tiger sharks between the receivers placed around the Whitsunday Island. The number of movements between receivers is represented by the thickness of lines. Self-links are not represented. Entrance to Cid Harbour = receiver Gate 2 - Gate 4; H1-H4 = Hook 1 - Hook 4; P1 = Pass 1; P3/4 = Pass 3/4; Sawmill Bay = receivers C1-C6; TB = Tongue Bay, WH = Whitehaven Beach.

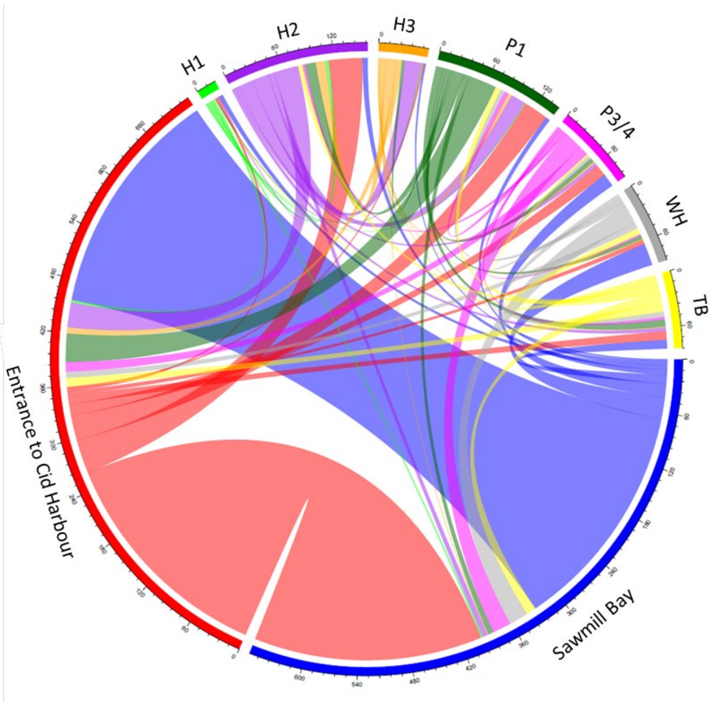

Figure 34. Connectivity plot representing the movement flows of bull sharks between the receivers placed around the Whitsunday Island. The number of movements between receivers is represented by the thickness of lines. Self-links are not represented. Entrance to Cid Harbour = receiver Gate 2 - Gate 4; H1-H4 = Hook 1 - Hook 4; P1 = Pass 1; P3/4 = Pass 3/4; Sawmill Bay = receivers C1-C6; TB = Tongue Bay, WH = Whitehaven Beach.

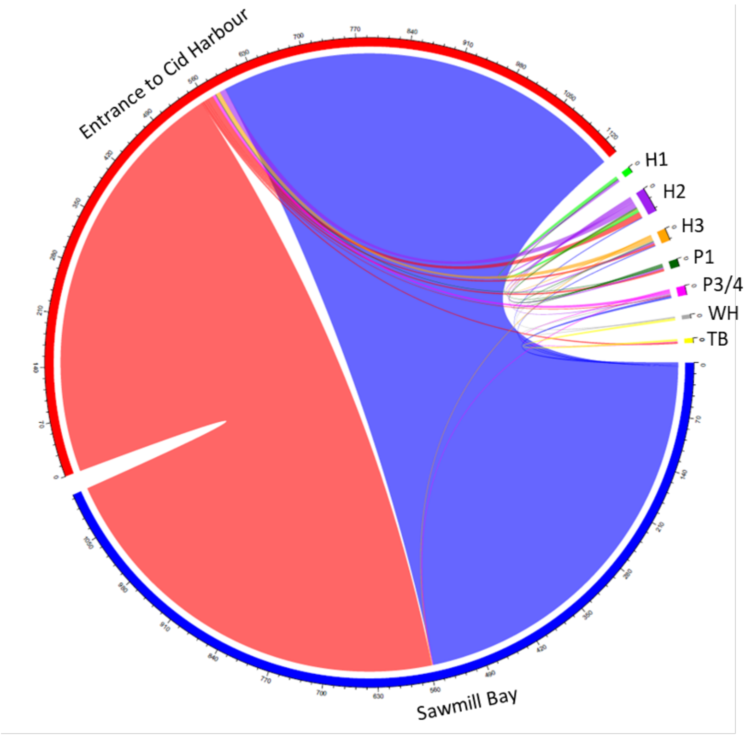

Figure 35. Connectivity plot representing the movement flows of spot-tail sharks between the receivers placed around the Whitsunday Island. The number of movements between receivers is represented by the thickness of lines. Self-links are not represented. Entrance to Cid Harbour = receiver Gate 2 - Gate 4; H1-H4 = Hook 1 - Hook 4; P1 = Pass 1; P3/4 = Pass 3/4; Sawmill Bay = receivers C1-C6; TB = Tongue Bay, WH = Whitehaven Beach.

When the temporal (daily) pattern of area use was examined, it was possible to determine that tiger sharks tend to use Cid Harbour throughout the day, with a small peak in mid-morning (Fig. 36). Tongue Bay and the passage between the Whitsunday and Hamilton Island were mostly used during the day, but for other locations no particular pattern was present (Fig. 36). Bull sharks, on the other hand, seemed to have a more pronounced daily cycle of habitat use, as Cid Harbour was mostly between 18:00 h and 20:00 h (Fig. 37), Hook Island (Hook 1-3) mostly used between 00:00 h and 06:00 h, the passage between the Hook and Whitsunday Islands (P1) mid-morning, and Whitehaven Beach in the afternoon (Fig. 37). Overall, spot-tails used Cid Harbour mostly in the evening, between 18:00 h and 20:00 h (Fig. 38), but this was driven by one only individual (AT #28254), as seen previously for Sawmill Bay (Fig. 25). The other individuals had very different patterns of Cid Harbour use: one (AT # 12814) was equally present throughout the daily cycle, another (AT #6159) had a peak mid-morning, while two (AT #6157 and AT #12797) had a strong peak around mid-day. No daily pattern or area use was present for the other locations (Fig. 38).

Tiger sharks

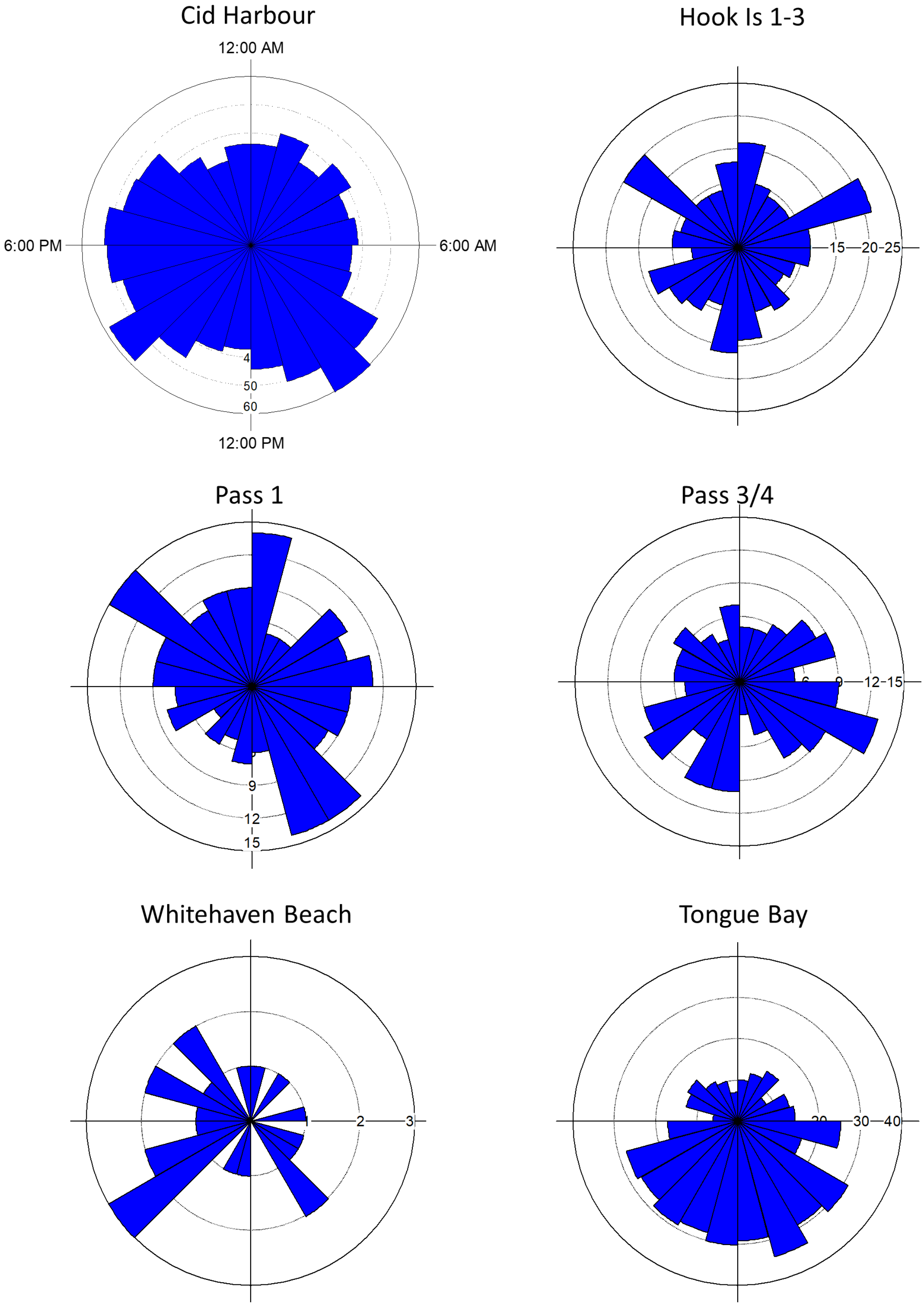

Figure 36. Circular plots showing the distribution and frequency of the hours tiger sharks were detected by the acoustic receivers placed around the Whitsunday Island. Input data was the number of days tiger sharks were detected in each of the 24 h of the day, pooled across individuals. Cid Harbour includes receivers C1-C6 and Gate 2-Gate 4.

Bull sharks

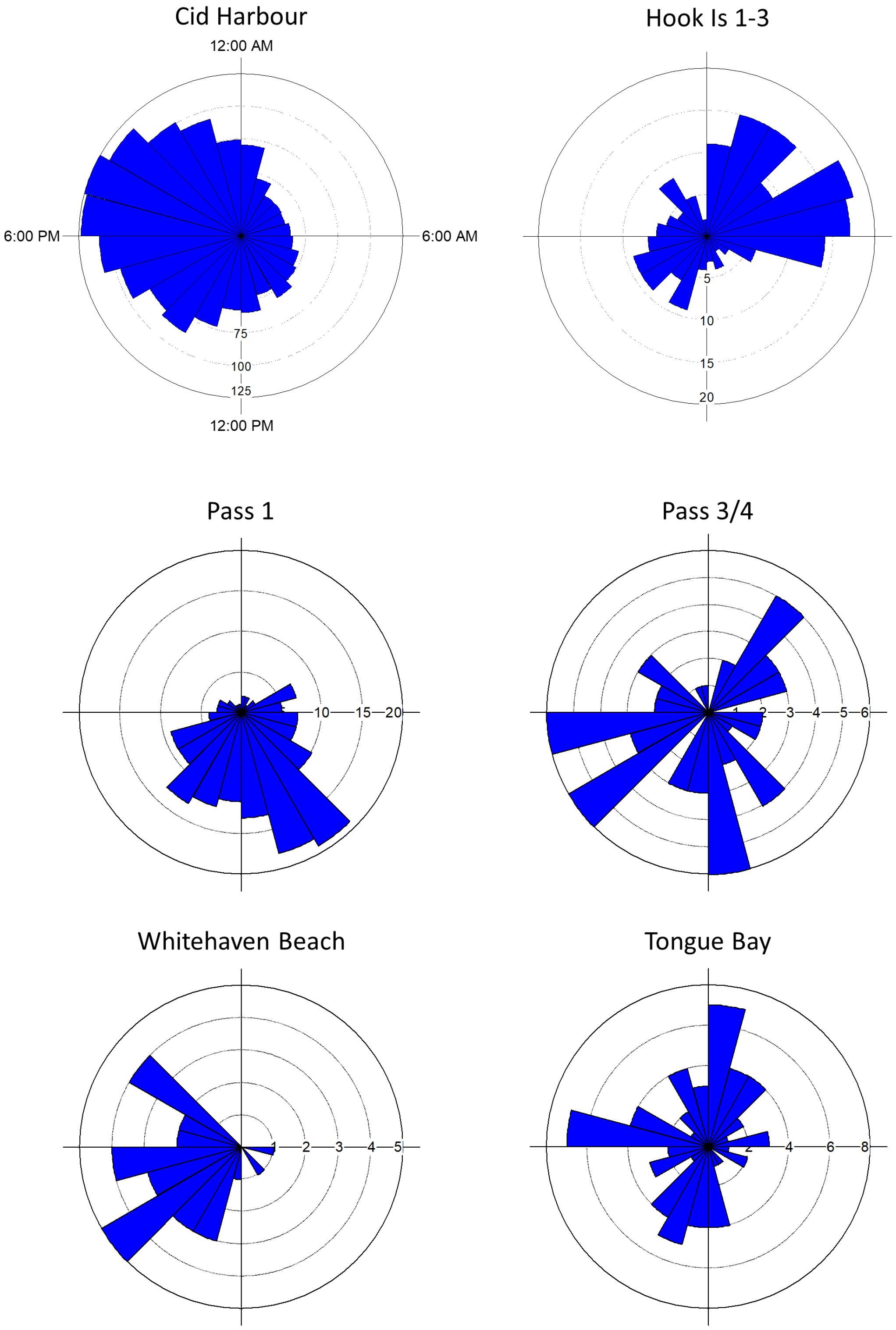

Figure 37. Circular plots showing the distribution and frequency of the hours bull sharks were detected by the acoustic receivers placed around the Whitsunday Island. Input data was the number of days bull sharks were detected in each of the 24 h of the day, pooled across individuals. Cid Harbour includes receivers C1-C6 and Gate 2-Gate 4.

Spot-tail sharks

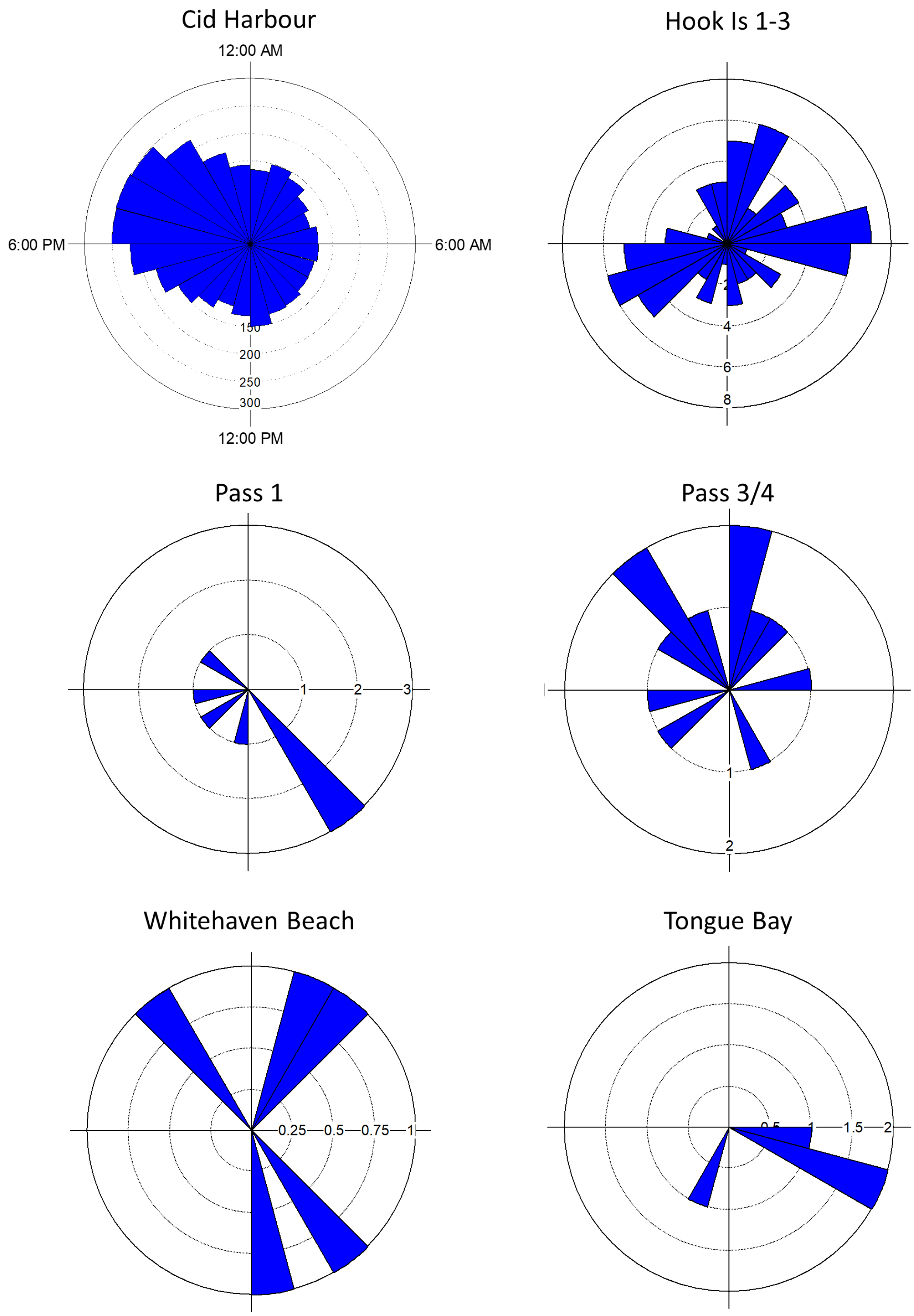

Figure 38. Circular plots showing the distribution and frequency of the hours spot-tail sharks were detected by the acoustic receivers placed around the Whitsunday Island. Input data was the number of days spot-tail sharks were detected in each of the 24 h of the day, pooled across individuals. Cid Harbour includes receivers C1-C6 and Gate 2-Gate 4.

Discussion

This study is the first to examine shark occurrence and behaviour in the Whitsundays region. Eleven shark species were documented, including the potentially dangerous (West 2011) tiger sharks and bull sharks, which together comprised 20% of the species caught/sighted over five field trips. Hammerhead sharks and, particularly, small whalers are also capable of biting humans (West 2011) and comprised 62% of sharks caught/sighted (hammerhead sharks: 12%; small whalers: 54%). In Australia, species in the small whaler group have been implicated in approximately 20% of shark bite incidents (West 2011).

Despite intensive fishing and BRUV effort throughout the study, shark catches and sightings in BRUVs were not high in comparison to previous projects the authors have worked on and published literature (e.g. Wirsing et al. 2006, Heupel et al. 2009, Barnett et al. 2010, Goetze and Fullwood 2013, Espinoza et al. 2014, Yates et al. 2015, Goetze et al. 2018). Indeed, Cid Harbour catch/sightings rates were not higher than in previous studies that used similar methodologies to estimate shark abundance. For example, BRUV sampling demonstrated consistently higher shark relative abundances in various habitats throughout the Great Barrier Reef, with mean values of 4.2 and 2.2 $MaxN.hr^{-1}$ in closed and open fishing sites, respectively (Espinoza et al. 2014). This is higher than this study's overall mean shark relative abundance of 0.11 $MaxN.hr^{-1}$. Much higher abundances were also reported for other locations such as Fiji (0.2–0.7 $ind.hr^{-1}$) (Goetze and Fullwood 2013) and the Solomon islands (0.9–1.7 $ind.hr^{-1}$) (Goetze et al. 2018). Dropline catches were also not higher than those reported in other studies, e.g. tiger shark CPUE values in this study (0.008 $ind.hook^{-1}.hr^{-1}$) were lower than those found for tiger sharks in Shark Bay (Western Australia) (0.06 $ind.hr^{-1}$ in diurnal sets; Heithaus et al. 2001), and close to tiger shark CPUE in Reunion Island (0.006 $ind.hook^{-1}.h^{-1}$; Blaison et al. 2015). For bull sharks, dropline catches in this study (0.002 $ind.hook^{-1}.hr^{-1}$) were only slightly lower than those of bull sharks in Florida (average 0.004 $ind.hook^{-1}.hr^{-1}$; Hammerschlag et al. 2012) and the Reunion Island (average 0.003 $ind.hook^{-1}.hr^{-1}$; Blaison et al. 2015).

Relatively low catches, coupled with the lack of empty hooks after fishing, suggest that there is not an unusually high abundance of sharks using Cid Harbour. Noting that some shark species can be more active at night, the lack of captures during night fishing (both by the shark control contractor and on research sampling trips in this study) was somewhat surprising, but further shows that sharks are not unusually abundant in Cid Harbour.

This study found no effect of water temperature or number of boats present in the harbour on shark relative abundance. Although there was some evidence of seasonality in tiger and bull shark occurrence in Cid Harbour, with tiger sharks more often present between October and November and bull sharks around September, it is important to note that these results were based on few individuals (particularly of bull sharks, for which only two individuals provided a whole year of data), and sampling period was only one year. Sampling of more individuals over multiple years would be required for a more rigorous analysis of seasonal patterns and possible effects of factors such as temperature, prey availability or boat presence (Barnett and Semmens 2012).

Bull sharks and tiger sharks

Bull sharks and tiger sharks are two of the three species commonly implicated in shark bite incidents worldwide (McPhee 2014), and for this reason it has been speculated that these species may have been responsible for one or more of the Cid Harbour bites. Bull sharks, however, only occur in low numbers in Cid Harbour. No bull sharks were caught by the contractor that fished directly after the bite incidents in September 2018, or on the first sampling trip in the current study (December 2018), and bull shark catches were low in the last four trips (maximum two individuals in a trip). Furthermore, bull sharks were not recorded by the BRUVs.

The low bull shark catch and, therefore, low number of acoustically tagged individuals prevents a robust analysis of the movement of the species in the Whitsundays region. Nevertheless, currently available data suggests that, in general, bull sharks have low residency in Cid Harbour. Satellite tracking complemented acoustic tracking data, showing that bull sharks had highly variable movements, with two tracked individuals making large-scale coastal movements north, another south, and the fourth individual remaining in the broader Whitsundays region. Similar intraspecific variability in residency and movements was previously documented for bull sharks both in Australia (Heupel et al. 2015, Espinoza et al. 2016) and overseas (e.g. Hammerschlag et al. 2012, Brunnschweiler and Barnett 2013, Daly et al. 2014). For example, on the east coast of Australia, some bull sharks conduct large-scale movements, including migrations of >1700 km, e.g. between the Sydney and Townsville regions (Heupel et al. 2015; Espinoza et al. 2016,), and others remain within the tagging regions, while still moving between different locations (e.g. reefs) within the regions (e.g. Espinoza et al. 2016). This variability is at least partially influenced by sex and life stage (Heupel et al. 2015, Espinoza et al. 2016, Lee et al. 2019), e.g. larger bull sharks tend to show greater movements (Heupel et al. 2015), with many of the larger migrations made by mature females (Espinoza et al. 2016). Studies in Australia and overseas also show that females have philopatry to natal areas (e.g. Karl et al. 2011, Tillet et al. 2012), and philopatry to habitats such as particular coastal areas (Brunnschweiler et al. 2010, Brunnschweiler and Barnett 2013, Lee et al. 2019) and offshore reefs (Heupel et al. 2015, Espinoza et al. 2016) has also been demonstrated for the species.

In New South Wales (east coast of Australia), bull shark residency was found to be related to seawater temperature, with higher probabilities of encounter at temperatures between 20 and 26 °C (Lee et al. 2019). However, in areas such as Reunion Island, where bull sharks occur year-round, turbidity is the main environmental parameter affecting the chances of shark bites, with increased chances of incidents in turbid conditions (Taglioni et al. 2019). In the context of the Whitsundays, average monthly seawater temperature ranges from 21 °C to 28 °C, and particular areas such as Cid Harbour are highly turbid, suggesting favourable bull shark habitats. In terms of likelihood of human-bull shark interactions, however, movement information available to date suggests that bull sharks are not a continual risk to humans in Cid Harbour as their occurrence and residency is typically not high and visits to most monitored areas were short. Cid Harbour is however part of the broader movement paths of some individuals, and acoustic data suggests that there might be a seasonality in the use of Cid Harbour, as bull sharks were detected on more days in September. This analysis was however based on only two individuals and over only one year, so results are indicative and should be interpreted with caution. A greater sample size would be required for a more rigorous analysis.

Satellite tracking showed some interesting large-scale movement for bull sharks. However, it led to few and highly separated (in time and space) location positions, suggesting satellite methods may have limited value in tracking bull sharks. Similar results are reported in the only other study to use SPOT tags on bull sharks, where Graham et al. (2016) found that tagged bull sharks in general provided much less data than tiger sharks or great hammerhead sharks. However, for individuals tagged with both satellite and acoustic transmitters, the few data provided by satellite tracking gave important complementary information. For example, the combined use of the two tracking methods identified the return movement of Bull shark AT #12812/ST #175012 from Cid Harbour to Torres Strait and back. This movement corresponded to a direct path swim of >2500 km (and is therefore a highly conservative estimate) within three months, fitting movement patterns previously suggested for some bull sharks on the east coast, where they were found to move in a directed manner between specific sites at discrete times (Heupel et al. 2015).

Tiger sharks were one of the species initially speculated to be associated with the bite incidents in Cid Harbour, as five tiger sharks were caught and euthanised directly after the two bite incidents in September 2018. In the present study, tiger sharks showed individual differences in habitat use and movement patterns, but as a group, their movement patterns include latitudinal movements between Townsville and south of Mackay, with forays out into the Coral Sea. In terms of shark behaviour and potential for human interactions, satellite and acoustic tracking data shows that tiger sharks move widely over the Whitsundays region, passing through areas of high human use (such as Cid Harbour), but do not reside in particular locations for extended periods. This suggests that the risk of shark bites from tiger sharks is not constant. In Hawaii, tiger sharks commonly occur in areas of high human use, including large sharks that visit highly used recreational areas almost daily (Meyer et al. 2018), yet the risk of shark bites remains extremely low, suggesting that tiger sharks are generally not 'interested' in people (Meyer et al. 2018).

Tiger sharks' optimal water temperature is 22–24 °C (Payne et al. 2018), which suggests that May to October would be the peak in tiger shark activity in the Whitsundays. However, tiger sharks occur over a wide temperature range (13 °C to >30 °C; Fitzpatrick et al. 2012; Payne et al. 2017), and given that the average monthly seawater temperature in the Whitsundays ranges between 21 °C and 28 °C, it is not surprising that tiger sharks occur year-round, and that acoustic data did not detect a seasonality in the use of the Whitsundays region.

Prey abundance in Cid Harbour

Observations from all field trips suggest that Cid Harbour has abundant marine life that could be shark prey. Numerous turtles were observed surfacing, along with mackerels leaping out of the water, dolphins moving around the bay, and shoals of baitfish observed around the boat at night. BRUVs also recorded turtles, teleosts (bony fish) and stingrays, groups known to be shark prey (e.g. Simpfendorfer et al. 2001, Tillet et al. 2014, Trystram et al. 2017). Despite the clear abundance of potential prey, few potential prey items were caught on hook and line methods, despite the range of hook sizes used. The smaller sharks caught could be important prey for larger sharks such as tiger, bull and hammerhead sharks (Cliff and Dudley 1991, Cliff 1995, Trystram et al. 2017).

Side-scan sonar results show that this method is a viable and valuable option for obtaining broad estimates of prey availability. Together with BRUV data, side-scan sonar suggests a seasonal variability in prey availability. However, for an adequate assessment of prey composition and relative abundance, much higher replication is needed. Furthermore, more than one year of data would be needed to confirm trends in seasonality. We suggest that future assessment of prey availability includes recording the occurrence and behaviour of animals at the surface (turtles, mammals, birds, fish jumping out of the water, etc.) during sonar transects, as in Heithaus (2001).

Regarding spatial variability in prey availability, preliminary side-scan sonar results suggest that less prey is available in the inner-bay area, i.e. closer to shoreline. Note however that the limited sample size and the wide range of prey detections seen in the different transects (see the wide interquartile intervals in the box plots of Figure 14) make meaningful comparisons problematic. Over the five trips, most boats moored for the night in the area between the inner- and mid-bay transects, and this is also where the three shark bite incidents took place. Long-term data on prey distribution and boat activity could potentially be useful to help assess the likelihood of sharks-human overlap and negative shark-human interactions. A combination of BRUVs, side-scan sonar and structured surface observations (of both prey and boat numbers) would be an effective approach obtain such data. Also, a standard side-scan sonar device was used in the present study, but the identification of prey types could be improved by using more a sophisticated device that producers clearer images.

Conclusion

Understanding the biological and environmental variables that drive shark abundance, residency and movement behaviour can help identify the species most likely to pose a risk to humans, and where and when this risk is higher (Payne et al. 2017, Myer et al. 2018, Lee et al. 2019). For example, in the Reunion Island, studies on the spatial patterns of shark presence and human uses identified the areas of higher risk for shark interactions and the conditions (e.g. turbid waters) that influence the chances of shark bites, information that was used to develop mitigation policies (Lemahieu et al. 2017, Lagabrielle et al. 2018, Soria et al. 2019). Based on the currently available information for Cid Harbour, sea surface temperature and turbidity may be favourable for bull sharks and tiger sharks year-round. Also, although the short time frame of the present study prevents an in-depth analysis of shark behaviour in relation to prey availability, preliminary results suggest that abundant prey are available year-round. Overall, the majority of tagged sharks did not use Cid Harbour for long periods of time. Even for the smaller carcharhinids (small whalers), the most commonly caught/sighted in this study (54% of all sharks), tracking data does not suggest a high residency in Cid Harbour.

This study did not identify anything unusual about shark relative abundance or movements in Cid Harbour that may have contributed to the cluster of shark bite incidents in 2018. The results indicate that the area is similar to other inshore, turbid, locations along the Great Barrier Reef. However, the number of boats using Cid Harbour can exceed 100 per day, and many throw food scraps overboard, some intentionally attracting sharks with food (Smith et al. 2020). Many shark species are opportunistic scavengers (e.g. Fallows et al. 2013, Hammerschlag et al. 2016), and such activities can attract sharks to an area (Trave et al. 2017) and possibly to boats, and may have contributed to an increased risk of shark bite incidents. Furthermore, the context of the Cid Harbour shark bite cases, i.e. the three incidents involved people getting bitten almost instantly after jumping into the water, was unusual, suggesting that the regular feeding/dumping food scraps from boats could have played a role in those shark bites. The education of water users about the effects of shark attracting/feeding and eradication of activities that attract sharks to anchored boats (including intentional shark feeding and disposal of food waste overboard) may therefore reduce the risk of future shark bite incidents. A social science study conducted concurrently to the present project (Smith et al. 2020) showed that most users of the Whitsundays area (mostly recreational boaters) believe that shark provisioning/attracting sharks is a key contributor to the increased risk of shark bites, and stakeholders are currently working together to improve waste disposal practices in the region.

Although the context of the 2018 Cid Harbour shark bite incidents and the occurrence and behaviour information from the present study do not provide evidence to identify the species responsible, regular feeding would suggest that any species capable of biting humans, or even multiple species, could have been responsible. Identifying the species responsible for shark bites is difficult, unless witnesses are able to reliably identify or describe the shark, or forensic examination of e.g. shark teeth or tooth fragments is possible.

Our short-term study demonstrates that the methods and analyses used were effective tools for studying shark movements and residency, including time spent at each location and visit frequency. The approaches used, if applied to a larger number of individuals of each species, would increase confidence in the interpretation of area use patterns. Therefore, continued tagging and monitoring of the shark community (including abundance, spatial behaviour and movements in relation to the Whitsundays regions) would enable more rigorous analysis to be conducted. Future work should also include areas of high tourism use (anchorages, swimming/snorkelling, and fishing areas) across the wider Whitsundays region and the simultaneous monitoring of environmental conditions (e.g. turbidity, rainfall, water temperature). A comprehensive acoustic array with strategically placed receivers (e.g. at areas most used by swimmers), coupled with greater numbers of tagged individuals, may enable the times of the day and the areas least/most used by the different species to be determined (e.g. as seen in Fig. 32). That information could be used to measure the probability of shark encounters in different areas, which could be incorporated into management measures for the region. In addition, since the overlap in site use by different stakeholders (e.g. snorkelers and fishers) has been proposed as a contributing factor to negative shark interactions, information on both shark and human behaviours could also be used in the development of localised shark bite mitigation strategies. A longer-term shark behavioural study also has the potential to contribute information for the science behind the current shark safety (SharkSmart) guidelines.

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