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RESEARCH ARTICLE

# Scientific response to a cluster of shark bites

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## Abstract

1. Shark bites are of high public concern globally. Information on shark occurrence and behaviour, and of the effects of human behaviours, can help understand the drivers of shark-human interactions. In Australia, a number of shark bite clusters occurred over the last decade. One of these took place in Cid Harbour the Whitsundays, Queensland, a region for which little was known about the shark community. Here, we describe and evaluate the research in response to that shark bite cluster.
2. Fishing methods, acoustic and satellite tracking, and baited remote underwater video cameras (BRUVs) were used to identify the shark species using Cid Harbour, estimate relative abundance, and describe habitat use and residency. Side-scan sonar and BRUVs were also used to assess prey availability. Recreational users were surveyed to understand human behaviour and their awareness and perceptions of 'Shark Smart' behaviours. This allowed shark occurrence and behaviour to be interpreted in the context of human behaviours in the Harbour.
3. Eleven shark species were identified. Relative abundance was not unusually high, and residency in Cid Harbour was typically low. For example, 79% of acoustically tagged sharks visited the harbour on <10% days at liberty. Shark prey was available year-round. Notably, anchored boats regularly conduct activities that can attract sharks (dumping food scraps, provisioning and cleaning fish).
4. Alone, the methods used in this study had variable success, but combined they provided a large amount of complementary information. Including a social science component in the research response to the shark bite incidents allowed for a more holistic understanding of the Cid Harbour bite incidents.

5. This study did not identify anything unusual about the shark community that could have contributed to the Cid Harbour shark bite cluster. However, the three incidents involved people bitten almost instantly after entering the water, which is unusual and suggests that feeding/attracting sharks to boats could have been a contributor and also that any species capable of biting humans could have been responsible.
6. The eradication of activities that attract sharks to areas where people enter the water may reduce shark bite risk.

**KEYWORDS**
acoustic tracking, human-wildlife conflict, satellite tracking, shark bite, shark provisioning, tourism

## 1 | INTRODUCTION

Human-wildlife conflicts occur in a wide range of settings globally, often leading to negative outcomes for both humans and wildlife (Dickman, 2010). Conflict that involves megafauna species that cause human fatalities or severe injuries are particularly complex issues and often evoke strong human responses (Dickman, 2010). Sharks are a prime example of such species. Although the probability of a shark biting a human is extremely low (Midway et al., 2019), the frequency of shark bites has increased in some locations over the last three decades (Chapman & McPhee, 2016). Any increase in shark-human incidents leads to disproportionate media coverage, drawing public interest and often escalating public concerns (Chapman & McPhee, 2016; Hardiman et al., 2020; Ryan et al., 2019). In Australia, a number of shark bite clusters occurred in the last decade, where more than one person was bitten over a relatively short period in a given area. For example, in southern Western Australia (March–May 2018), northern New South Wales (NSW; 2014–2015) and, more recently, in the Whitsundays, Central Queensland (2018; see Supplementary Information 3 for a space–time permutation model that confirmed the clustered nature of the Cid Harbour shark bites). The rise in shark bite incidents and, in particular, what drives these clusters has been a topic of considerable debate. In part, this is attributed to human population growth and the concomitant increase in the number of people participating in water-based activities (Chapman & McPhee, 2016). It is predictable that the more people in the water, the greater the chance of negative shark-human interactions, but an increase of on-water activities such as fishing and live-aboard boating can also increase the chances of attracting sharks to areas heavily used by humans (Mitchell et al., 2020). Other factors implicated in the increase of shark bite incidents include changes in prey availability, environmental conditions (e.g. water temperature, habitat degradation), sharks' behavioural patterns (e.g. movements and distributions, including changes due to human activities) and increased shark occurrence/abundance (Afonso et al., 2017; Chapman & McPhee, 2016; Lagabrielle et al., 2018).

Despite growing understanding that the occurrence and behaviour of marine animals is usually context specific (Bradley et al., 2020), there is often limited knowledge about the shark community in locations where shark bite clusters have occurred. Basic information such as which species occur in the area, their relative abundance and behaviour is often lacking, hindering interpretation of the possible reasons behind shark bite clusters. Understanding shark occurrence and behaviour is critical if we hope to predict the areas, times or conditions that could lead to increased shark bite risk. A predictive ability could form the basis of appropriate, site-specific measures to mitigate the risks of negative shark-human interactions. For example, in Réunion, 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 shark mitigation policies (Lagabrielle et al., 2018; Taglioni et al., 2019).

Recent studies used long time series and/or historical data to improve the understanding of shark occurrence, relative abundance and behaviour, providing information for future management of shark-human interactions. For example, in eastern Australia, white shark *Carcharodon carcharias* numbers have been estimated and their movement paths and habitat use are well understood, along with the fine-scale behaviour at beaches (Bruce et al., 2018; Colefax et al., 2020; Davenport et al., 2020; Spaet et al., 2020). Combined, this information improves our understanding of the risks posed by white sharks in different areas/times, which in turn provides information to develop and refine management approaches aimed at minimising the risks of shark bites (Colefax et al., 2020). Knowledge about other potentially dangerous species is also available for the east coast of Australia. For example, optimal temperatures for tiger sharks *Galeocerdo cuvier* and bull sharks *Carcharhinus leucas* can be used to predict when/where those species are more abundant/more active (Lee et al., 2019; Niella et al., 2020; Payne et al., 2018; Smoothey et al., 2019). In particular, a rise in temperature within Australian waters will likely lead to southerly range expansions of those species, leading to an increase in numbers and residency times within the southern end of their distributions (central-southern

NSW; Niella et al., 2020; Niella et al., 2022; Payne et al., 2018; Smoothey et al., 2019). Such changes potentially increase the risks of shark-human interactions, as the adjacent mainland area supports large human populations that display a high level of on- and in-water activity (Chapman & McPhee, 2016; West, 2011). Modelling predicts that bull, tiger and white shark occurrence is influenced by environmental variables such as water temperature, rainfall, boundary currents, upwellings and proximity to river mouths (Niella et al., 2020; Niella et al., 2022; Ryan et al., 2019). Although modelling approaches aimed at identifying the drivers of shark abundance and/or movement behaviour show promise for estimating the likelihood of a shark encounter (e.g. Payne et al., 2018; Lee et al., 2019), more detailed empirical data would strengthen predictive power (Ryan et al., 2019).

The Whitsundays region of Central Queensland is one of the two largest tourism hubs in the Great Barrier Reef Marine Park (GBRMPA, 2019). Most visitors and locals engage in in-water (e.g. snorkelling, diving and spearfishing) and on-water (e.g. fishing and boating) activities. Despite being heavily used for human activities, prior to 2018, the region did not have a noticeable history of negative shark interactions, with only four non-fatal shark bites recorded in the region between 1977 and 2000 (International Shark Attack File). In late 2018, however, a cluster of three shark bite incidents took place in Cid Harbour, a popular anchorage for boats, which involved people being bitten almost instantly after entering the water. In late 2019, there was another shark bite incident in close proximity to the harbour.

The objective of this paper is to evaluate a range of research tools used to gather information to support management decisions following a cluster of shark bite incidents in Cid Harbour, a region for which little data on shark species composition, relative abundance or behaviour were available. To better understand the prevalence and behaviour of sharks, environmental parameters, prey availability and human behaviours were also considered. The methods used and trialled are discussed in the context of developing solutions to mitigate shark bite risk in the Whitsundays and similar regions in the future. The specific aims therefore were to (1) identify and estimate the relative abundance of the shark species that occur in Cid Harbour, with a particular focus on potentially dangerous species; (2) describe the sharks' movement behaviour, including habitat use and residency within Cid Harbour and in the broader Whitsundays region; (3) test methods that could be used to assess prey availability in Cid Harbour; and (4) investigate how recreational users are using Cid Harbour and their awareness and perceptions of 'Shark Smart' behaviours. This final aim allowed for shark occurrence and behaviour to be interpreted in the context of human perceptions and behaviours in the Harbour.

## 1.1 | Case background

Located in Central Queensland, the Whitsundays region is internationally renowned for charter and recreational boat-based tourism that explores the region's many islands. Cid Harbour, the location of the three shark bite incidents, is one of the main anchorages, as it affords protection from inclement weather. Over 60 boats (~100 in peak seasons—pers. com. from tourism operators) can overnight in Cid Harbour, and many spend several days in the harbour undertaking boat-based, land-based and in-water activities.

The context of the three Cid Harbour shark bite incidents was extremely unusual. The first two bites led to severe injuries and occurred within 24 hours of each other, on the 19th and 20th September 2018. These were followed by a fatal bite on the 5th of November 2018 (three bites within 6 weeks). The three bites occurred in the afternoon (two in late afternoon) and in the same area, estimated to be the size of a football field (105 × 68 m; Figure 1b). Particularly unusual was that all three people were bitten almost instantly upon entering the water (the first two after jumping off a boat, and the third after entering the water from a paddleboard).

A cluster of shark bite incidents, especially when occurring within a very short time span, can be traumatic for local communities and may cause visitation rates to decline in tourism locations, leading to negative economic flow-on effects for local communities. These concerns often drive responses from authorities, which range from raising safety and awareness, to active measures to remove sharks that are considered dangerous (Neff, 2012). Directly after the two bite incidents (in September 2018), a Queensland Shark Control Program contractor deployed set lines in Cid Harbour to catch potentially dangerous sharks. Five tiger sharks, *G. cuvier*, and one common blacktip shark, *Carcharhinus limbatus*, were caught (and the tiger sharks killed) over seven days (216 fishing hours). In late October 2019, another shark bite incident occurred off Cairn Beach in Hook Passage (the channel between the Whitsunday and Hook islands), ca. 12 km from Cid Harbour. In that incident, two snorkelers were 'play fighting', and both were bitten.

After the fatal bite in November 2018, various stakeholders, including politicians, fisheries managers, tourism groups and scientists agreed that a number of actions should be set in place, and the Queensland Government implemented a five-point plan to improve safety. This included commissioning research into shark prevalence and behaviour in Cid Harbour, maintaining Cid Harbour as a no-swim zone until research was completed, supporting a high profile education program (committing funding to the 'Shark Smart' program), developing a broader 'Shark Smart' campaign (similar to the successful 'CrocWise' campaign), and continuing to meet with industry stakeholders and experts to develop adaptive responses. Consequently, the 'Whitsundays Working Group' was established. The culling of sharks was rejected by the vast majority of stakeholders, and it was agreed that increasing public education would be the best way forward. This resulted in increased funding into the already available 'Shark Smart' safety messaging, a program designed to provide a set of guidelines aimed at reducing the chances of negative encounters with sharks (www.daf.qld.gov.au/sharksmart).

As part of the commissioned research, a social science component explored the human dimensions surrounding the shark bite incidents and human safety in the Whitsundays. Recreational users,

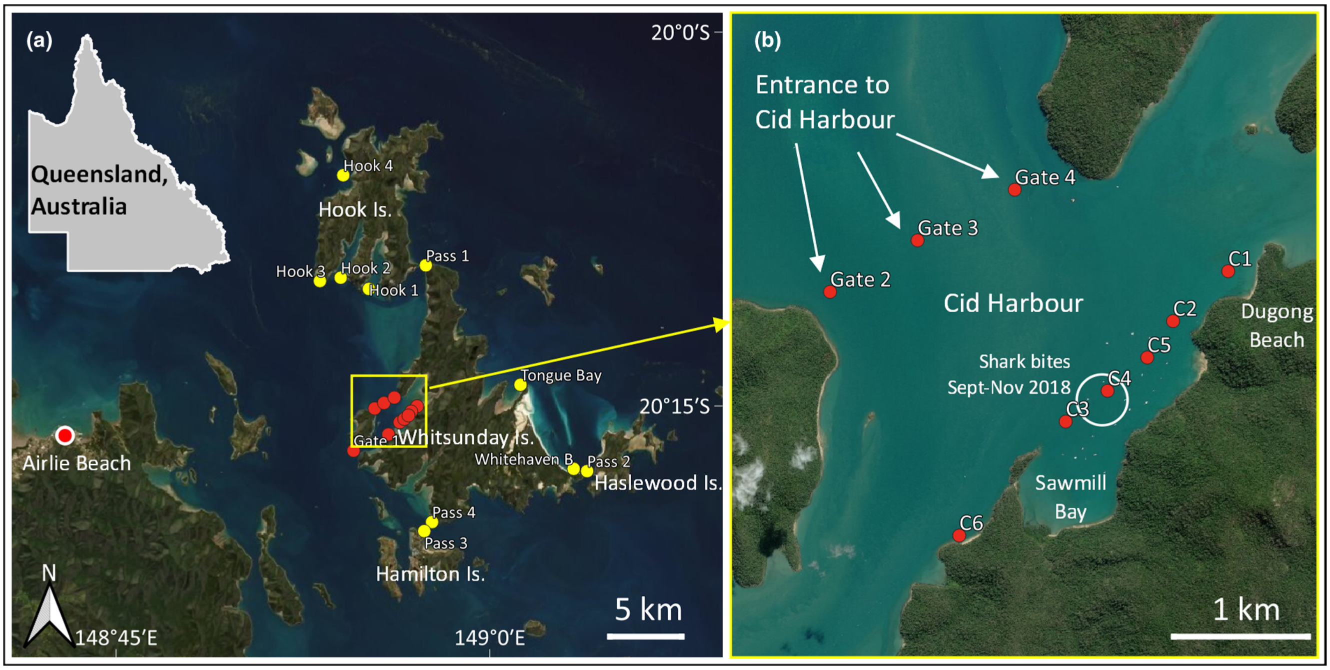


FIGURE 1 Study area, showing (a) the location of the Whitsundays in Queensland, and b) the locations of the acoustic receivers deployed in Cid Harbour (red) an the broader Whitsundays region (yellow). The site where the 2018 shark bite incidents took place is also indicated.

particularly boaters and charter operators that use harbours and anchorages in the Whitsundays, were surveyed to better understand their behaviours and awareness of shark safety messages, in order to inform actions to increase the safety of water users and to reduce the risk of further incidents. Pertinent results from the social science study (Smith et al., 2020) are presented in the current paper.

## 2 | MATERIALS AND METHODS

### 2.1 | Sampling methods

This study took place in the Whitsunday Islands, off the east coast of Queensland, Australia (Figure 1). Sampling was conducted over five weeklong field trips (12/18–01/20) and had a particular focus on Cid Harbour, and the area where the three shark bite incidents took place (Figure 1). A range of sampling and data analysis methods were used to investigate the species composition, occurrence and behaviour of the shark community using the harbour (see below).

### 2.2 | Fishing methods

To estimate the relative abundance and seasonality of shark species using Cid Harbour, 8–10 single-hook droplines were deployed between sunrise and sunset (~5:30 h to 18:30 h), at 2–20 m depth (Supplementary Information 4, Figure S4a). Deployments focused mainly on the area between the Sawmill Bay and Dugong Beach (Supplementary Information 4, Figure S4a), where most boats anchor. Bottom-set longlines were also used, mainly close to where the bites occurred (Supplementary Information 4, Figure S4a). See Supporting Information 4 for details. Sharks were also targeted late afternoon and at night among the boats anchored for the night using surface lines, rod and reel, and droplines (see Supplementary Information 5).

### 2.3 | Baited remote underwater video cameras (BRUVs)

BRUVs are stationary cameras placed on the sea floor and baited to attract and record the animals that move into the field of view. Cameras were Garmin VIRB XE, with a field of view of 70° vertical and 130° horizontal. BRUVs were deployed (20 cm above substrate) at the full range of available depths and habitats, on each of the five trips (Supplementary Information 6, Figure S6a,b). Bait was ~1 kg of pilchards, which were placed in a baitbox 1 m from the camera. Videos were reviewed and data on the identified species used to complement catch data in describing the shark community and species' relative abundance (see Supplementary Information 6 for details), and to obtain information on the occurrence of potential shark prey (see Supplementary Information 7).

### 2.4 | Acoustic and satellite tracking

Acoustic and satellite tracking were used to study the movement behaviour of species that could potentially be responsible for the shark bite incidents: tiger sharks, bull sharks, smaller carcharhinids (spot-tail shark *Carcharhinus sorrah*, blacktip shark *C. limbatus*, Australian blacktip shark *C. tilsoni*, blacktip reef shark *C. melanopterus* and whitecheek shark *C. coatesi*) and hammerhead sharks *Sphyrna* spp. (West, 2011).

In December 2018, 10 VR2W acoustic receivers (VEMCO, Nova Scotia, Canada) were deployed in Cid Harbour (Figure 1), including one at the southern entrance to the harbour (Gate 1) and three that gated the northern entrance (Gates 2–4). The other six receivers (Receivers 'C' in Figure 1) were deployed in the Sawmill Bay area, where the shark bites occurred. This array was designed to monitor shark movement behaviour in the area where the shark bites occurred and where boats anchor, and to provide information about the residency of tagged sharks in Cid Harbour. In June 2019, 10 additional receivers were deployed more widely around the Whitsunday Islands region to better understand broader shark movements. The additional locations were selected for being popular anchorages, tourist destinations, or channels between Islands that might act as potential shark transit routes.

For acoustic tagging, each shark captured on a dropline was brought to the side of the boat and a VEMCO V16 acoustic transmitter (VEMCO, Nova Scotia, Canada) was surgically implanted into the peritoneal cavity through a small incision, which was then closed with surgical sutures. Species of no potential threat to humans (e.g. tawny nurse sharks), and individuals too small to tag or not in good condition from capture were not tagged and were released as quickly as possible.

For larger species (tiger, bull and hammerhead sharks), smart position and temperature satellite transmitters (Wildlife computers SPOT6, Redmond, Washington, USA) were attached to the first dorsal fin to help determine how the Whitsundays and Cid Harbour fit into the broader movement space of those species. The satellite transmitter was attached to the dorsal fin by four 5 mm diameter threaded nylon rods that were passed through the fin and secured on the other side by washers and nuts. The position of the transmitter on the fin was such that the antenna extended out of the water when the fin broke the surface. Most individuals were double tagged with acoustic and satellite tags. All sharks tagged were also marked with external identification tags (Drovers, Australia).

## 2.5 | Side-scan sonar imagery

Side-scan sonar imagery was trialled and used together with BRUV data to assess if this approach is suitable for assessing prey availability in Cid Harbour. Briefly, a Humminbird 1199CI HD side-imaging device was used to conduct 10 km long transects parallel to the shore, through the inner-, mid- and outer- sections of the bay. Both side and down imaging were captured per transect. Sonar imaging recordings were visually interpreted to identify potential prey and analyse the spatial variability in prey composition and availability. See Supplementary Information 7 for details.

## 2.6 | Social science surveys and interviews

Social science data were collected using two methods: (1) an online survey distributed through industry and social networks, and (2) semi-structured interviews conducted face-to-face with individuals with relevant knowledge of the case study (e.g. tourism industry representatives, fishers, community groups and management agencies; see Supplementary Information 15). The self-complete online survey included questions addressing the participants' general awareness and understanding of the 'Shark Smart' practices, safety measures and vessel usage patterns in Cid Harbour (see Smith et al., 2020 for a complete reporting of results). An informed consent form was included on the first page of the survey (Supplementary Information 15). The semi-structured interviews explored some of the key themes arising from the online surveys of recreational users. These interviews took a flexible approach to allow researchers to explore emergent themes and interviewee perceptions and knowledge. The interviewees provided verbal consent prior to the interviews (see Supplementary Information 15).

## 2.7 | Data analysis

### 2.7.1 | Species composition and relative abundance

Dropline and longline catches, along with BRUV data, were used to identify the species that use Cid Harbour. To estimate relative abundance, catch data were used to calculate catch per unit effort (CPUE). The maximum number of individuals observed in a single BRUV frame (MaxN) was also determined for each species and, for each trip, the cumulative MaxN (i.e. the sum of all MaxNs from all BRUVS) was divided by the number of BRUV hours to calculate the mean MaxN per hour. See Supplementary Information 6 for details.

### 2.7.2 | Residency in Cid harbour

The dates each acoustically tagged shark was detected by Cid Harbour receivers (receivers C1-C6 and Gate 1–4 (Figure 1)) were plotted on a timeline to visually interpret the temporal pattern of area use. Residency indices (0%–100%) were calculated, as the proportion of days each individual was detected (days at liberty) in relation to the total number of days it was monitored.

### 2.7.3 | Seasonality in the use of Cid harbour

Acoustic data were used to determine if there was seasonality in the use of Cid Harbour by sharks. Data were analysed with the circular statistics software package Oriana v.4.02 (Kovach Computing Services, Pentraeth, UK). Input data were the day of the year (DOY, 1–365) each individual shark was detected by Cid Harbour receivers. This analysis was done for tiger sharks, and only for the nine individuals for which a whole year of data were available. Data from 01/06/19 to 31/05/20 were used. Since the distribution seemed to be bimodal (visually), Rao's Spacing Test (*U*) was used to determine if the data were uniformly distributed throughout the annual cycle. The relationship between sea water temperature (from a logger placed at Hook Island by the Australian Institute of Marine Science [AIMS, 2020]) and the total number of days tiger sharks were detected by Cid Harbour receivers in each month was also investigated with quadratic regression. Since several individuals were tracked, if more than one individual was detected in a given day, each individual was included as an extra day for that month. For the other species, a whole year of acoustic data were only available for ≤2 individuals, a number too small for a meaningful analysis. For tiger, bull and spot-tail sharks, the number of consecutive days each individual was detected in Cid Harbour was also calculated.

#### 2.7.4 | Daily pattern of Sawmill Bay use

To investigate the use of the area where the shark bite incidents occurred in more detail, the time of arrival at the Sawmill Bay area (receivers C1–C6) and visit durations were investigated with circular statistics (Oriana v.4.02). A new visit was recorded when a shark reappeared in the array after not being detected for more than 1 h, and visit durations were calculated as the time difference between the last and first detections (within each visit). When only one detection was recorded, visit duration was considered to be 1 min. Rayleigh's uniformity test (z) was used to test for homogeneity in data distribution.

The times between consecutive visits (inter-visit times) were also calculated for a random subset of visits. These analyses were done separately for tiger sharks, for bull sharks, and for smaller carcharhinids (hereafter referred to as 'small whalers', a group that includes the blacktip group of sharks (*Carcharhinus sorrah*, *C. limbatus*, *C. tilsoni*, *C. melanopterus*) and whitecheek sharks (*C. coatesi*) as a group. These analyses aimed to identify usage patterns in this area, for example, if sharks use this area at particular times of the day and, when occurring in the area, how long they stay.

#### 2.7.5 | Use of broader Whitsundays area

To analyse how sharks used the other monitored locations around the Whitsundays, timelines were constructed where acoustic detections at each location were plotted for each individual. For tiger, bull and spot-tail sharks, the daily (hourly) use patterns were also investigated using circular statistics. Input data were the number of days an individual was present (detected) for each of the 24 h of the day. The number of visits and visit durations (for a random subset of visits) were also calculated. In addition, the density of movement flow between all pairs of receivers was also analysed with connectivity plots—see Supplementary Information 8 for methodological details.

#### 2.7.6 | Broad scale movements

Before analyses, locations of class Z 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; Shimada et al., 2012) was also used to remove locations indicative of unrealistic swimming speeds of >5 m s$^{-1}$.

To determine how the Whitsundays area fits into the sharks broader habitat use, satellite location positions of individual sharks with more than 100 detections and of all tiger sharks combined were used to estimate core area use and home ranges. Kernel density estimates (KDEs) were computed using the R (R Core Team, 2019) package adehabitatHR (Calenge, 2019), to identify the core use areas used (50% KDE) and overall home ranges (95% KDE). 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 using the Free and Open Source QGIS v. 3.16.1.

### 2.8 | Ethics statement

This work was conducted with approval of the James Cook University Animal Ethics Committee (A2320 and A2648). The tiger shark tagged in NSW was done so through the New South Wales Department of Primary Industries, as part of the NSW Government's Shark Management Strategy, under the 'scientific' (Ref. P01/0059[A]), 'Marine Parks' (Ref. P16/0145-1.1) and 'Animal Care and Ethics' (ACEC Ref. 07/08) permits. In accordance with JCU Human Research Ethics Permit (H7689), this paper does not contain any personal or confidential information, and all responses are 'de-identified' so that none of the responses herein are identifiable or attributable to any specific person or persons.

## 3 | RESULTS

### 3.1 | Fishing methods

Across the five trips, single hook droplines were deployed over 30 days, totalling 2844 hr fished. Eighty-two sharks of nine species were caught, giving an overall CPUE of 0.03 ind.h$^{-1}$, which was similar for the five trips (Table 1). Small whalers had the highest dropline CPUE of 0.013 ind.hook$^{-1}$.h$^{-1}$, followed by 0.008 ind.hook$^{-1}$.h$^{-1}$ for tiger sharks, and 0.002 ind.hook$^{-1}$.h$^{-1}$ for both bull and hammerhead sharks. Longlines were set for a total of 91 hours, with 17 sharks caught (Table 1), corresponding to a CPUE of 0.2 ind.longline$^{-1}$.h$^{-1}$, or 0.0005 ind.hook$^{-1}$.h$^{-1}$ (Table 1).

Spot-tail sharks were the most commonly caught species, followed by tiger sharks (Table 2). Most baits on both droplines (Supplementary Information 2, Table S2a) and longlines were retrieved intact, that is, did not catch any animal and the bait was not removed from the hook. There was no bycatch on longlines, and the only other animals caught on a dropline were five catfish *Netuma thalassinus*, one grouper *Epinephelus* sp. and one black marlin

**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. of days fished | No. of hours fished | No. of 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[a] | 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 | |

[a]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.

| Species | Scientific name | Size range (cm) | *n* | No. tagged | |
|---|---|---|---|---|---|
| | | | | AT | ST |
| Spot-tail shark | *Carcharhinus sorrah* | 50–173 | 36 | 8 | – |
| Tiger shark | *Galeocerdo cuvier* | 230–386 | 22[a] | 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 |

[a]Four of the tiger shark captures were recaptures, as two individuals were recaptured twice.

*Istiompax indica*. Additional sampling also led to low shark catches (see Supplementary Information 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 at night. Average seawater temperature during the field trips ranged from 22 to 28°C (AIMS, 2020; Supplementary Information 1, Figure S1a), 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).

### 3.2 | Baited remote underwater video cameras (BRUVs)

A total of 551 BRUV deployments provided 664 hours of video, returning 48 shark observations, from five families (Supplementary Information 6, Table S6). Detailed results can be found in Supplementary Information 6. Overall, total shark observations were relatively low and consistent between sampling periods. The whitecheek shark was the most commonly encountered species, followed by blacktip sharks *Carcharhinus limbatus/tilstoni*, both of which were encountered in all five field trips (Supplementary Information 6, Table S6).

## 3.3 | Prey availability

Detailed prey availability results can be found in Supporting Information 7. Briefly, BRUV and side-scan sonar data show that a range of potential prey were available in Cid Harbour on all sampling trips. Both techniques suggest a seasonality in prey species composition and, for some prey, seasonality in relative abundance (Supplementary Information 7, Table S7a, Figure S7e). However, when considering broad prey groups (large bodied fish, schooling baitfish, marine megafauna, including sharks, rays, dolphins, turtles and dugongs), those were present in similar frequencies on all sampling trips. Side-scan sonar data also suggests a spatial variability in prey distribution, with large fish most commonly encountered in the outer-bay and schooling baitfish in the mid-bay, while marine megafauna were encountered in the three sections of the bay in similar frequencies (Figure S7d).

## 3.4 | Shark movements and residency behaviour

Movement and residency behaviour was assessed for 43 sharks tagged with acoustic transmitters (AT) and 19 of the 20 sharks tagged with satellite transmitters (ST; Table 2; one scalloped hammerhead *Sphyrna lewini*, was not detected), including 18 individuals that were tagged with both types of tags (Supplementary Information 2, Table S2b).

## 3.5 | Acoustic tracking—use of Cid harbour and the Whitsundays area

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 receiver 'Pass 2' could not be retrieved. Of the 43 animals tagged, 29 (67.5%) were detected by the Whitsundays receivers after tagging.

### 3.5.1 | Use of Cid Harbour

Residency in Cid Harbour was low for most individuals: 79% of acoustically tagged sharks visited the harbour on <10% of days at liberty (i.e. residency index <10%; Figure 2). Of the 18 tiger sharks tagged, five were not subsequently detected within the harbour, and the 13 individuals that were detected had residency indexes between 1.0% and 15.5%, with only three with residency index >10% (Figure 2). Most (72%) of the tiger shark visits to Cid Harbour were over a single day and, on average, tiger sharks were detected in the Cid Harbour area on 1.5 ± 1.3 consecutive days (±*SD*). Seasonality analysis suggests that tiger sharks were more often present in October/November (Rao's Spacing Test ($U$) = 265.161, $p < 0.01$; Figure 3). Despite tiger shark catch rates not being related to temperature, acoustic data showed a significant quadratic relationship ($R^2 = 0.56$; $p = 0.008$) between the monthly average sea water temperature and total number of days tiger sharks were detected by Cid Harbour receivers, with sharks being detected more often at 24–26°C (Figure 3).

Bull and spot-tail shark individuals had different patterns of Cid Harbour use (Figure 2). For example, two bull sharks were not detected after tagging while one was detected for 52.4% of days at liberty, and three of the eight spot-tail sharks tagged were not detected in Cid Harbour after tagging, while two others had residency indices >40%. When in the area, bull sharks visited Cid Harbour on average on 2.7 (±3.4) consecutive days, and spot-tail sharks on 5.5 (±8.2) consecutive days. For the remaining species tagged, due to small sample sizes (≤3), it was not possible to conduct a meaningful analysis of movement patterns. See Supplementary Information 9 for further details on the use of Cid Harbour by the different species.

The use of Sawmill Bay was characterised by short visits (Figure 4). For tiger sharks, bull sharks and small whalers, there was a clear peak in proportion of visits of <30 min duration, after which the proportion of visits decreased sharply (Supplementary Information 1, Figure S1b). This peak was particularly strong for tiger sharks, for which 61% of the visits lasted <30 min.

No pattern in time of arrival at Sawmill Bay area was evident for tiger sharks ($z = 1.938$, $p = 0.144$), but bull sharks ($z = 32.653$, $p < 0.001$) and small whalers ($z = 26.568$, $p < 0.001$) enter the area more often at the end of the day (Figure 4). However, for small whalers, this distribution was driven by spot-tail individual AT #28254, and when that individual was not included in the analyses no pattern in time of arrival was present for small whalers.

For the three shark groups, the time between two consecutive visits (inter-visit time) varied widely, from just above 1 hr (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 (Figure 5). Inter-visit times were longer for tiger sharks than for bull sharks and smaller whalers. For example, in 90% of the times inter-visit times were 20 days or less for tiger sharks, 6 days or less for bull sharks, and ~21.5 h or less for small whalers (Figure 5). This means that, when they are in the general area, tiger and bull sharks come in and out of the Sawmill Bay area several times separated by hours-days, and sometimes move out to return weeks or even months later, whereas small whalers make more regular visits (Figure 5). There was no relationship between the time spent in the area and inter-visit time for any species (regression analysis, $p > 0.05$).

### 3.5.2 | Use of other Whitsundays locations

Most acoustically tagged animals were detected by receivers placed at the other locations around the Whitsundays (Figure S1c–f). For the three main species (tiger, bull and spot-tail sharks), there was high intraspecific variability in the use of the different locations (Figure S1c–f).

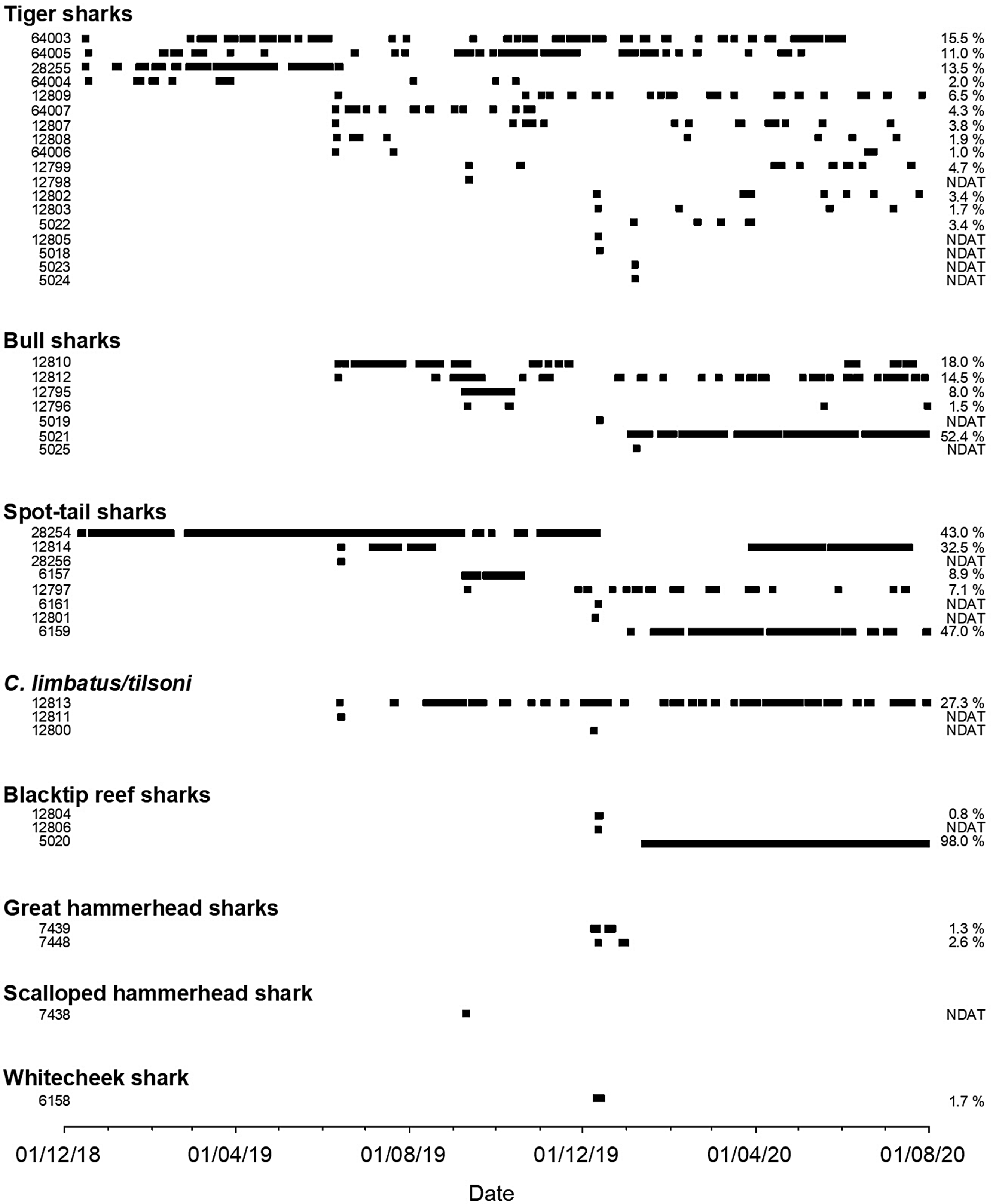


FIGURE 2 Timeline showing the days each acoustically tagged shark was detected by receivers deployed in Cid Harbour (receivers C1–C6 and Gate 2-Gate 4—see Figure 1). For each individual, the first day recorded corresponds to the tagging day. Numbers to the right are the residency indices. NDAT, not detected after tagging.

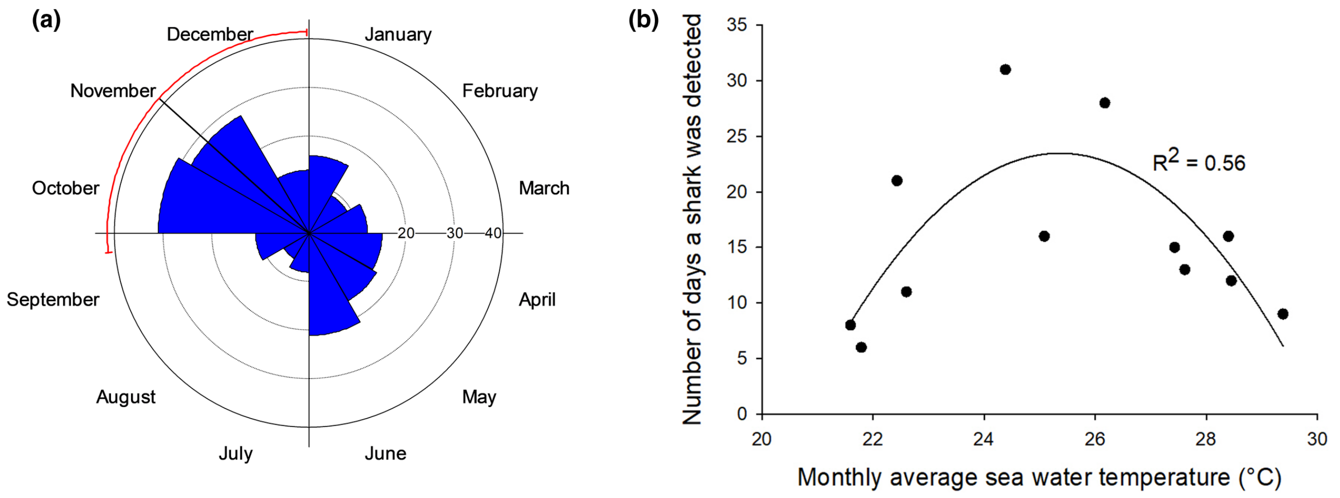


FIGURE 3 Seasonality in the use of Cid Harbour by tiger sharks, based on acoustic data of nine individuals tracked over 1 year (01/06/19–31/05/20). (a) Cumulative number of sharks detected per day for each month, including mean month of visit and 95% confidence interval [Rao's Spacing Test ($U$) = 265.161, $p < 0.01$]. (b) Relationship between sea water temperature and use of Cid Harbour by tiger sharks (quadratic regression, $p < 0.01$). Response variables were the total number of days tiger sharks were detected by Cid Harbour receivers in each month. If more than one individual was detected in a given day, each individual was added as a separate day for that month.

For tiger sharks, besides Cid Harbour, Tongue Bay was the other monitored location most used, with 72% of the tagged individuals using that location (Figure 6) over 353 visits of 17 min average duration (median: 6.4 min; Figure S1c–f). Whitehaven Beach was the least used location, with only 43 shorter visits (Figures 6 and S1g). For bull and spot-tail sharks, the southern part of Hook Island (receivers Hook 1–3) was the area most visited (Figure 6, Figure S1d,e). Although both species made few visits to Whitehaven Beach, those visits tended to be longer than visits to the other areas (Figure 6; Figure S1g). In some cases, although a significant proportion of the tagged sharks were detected at a location, 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 (Figure 6) over 56 visits, but visit durations were short (75% <3 min; Supplementary Information 1, Figure S1g). See Supplementary Information 10 for a description of the other species' movements.

When connectivity plots were constructed, it was possible to visualise the flow of movements between pairs of receiver locations. There were differences in area use between the three species. Tiger sharks moved the most between the monitored locations, with 38% of the movements out of the Cid Harbour northern entrance (Gates 2–4) being towards the more distant Whitsundays locations, and 62% towards the adjacent Sawmill Bay area (receivers C1-C6). For bull sharks, 28% of the trajectories out of the entrance to the harbour were towards the more distant locations (and 72% towards Sawmill Bay), while spot-tail sharks made more localised movements, with 94% of the movements out of the harbour entrance being towards the Sawmill Bay area. See Supplementary Information 8 for details.

The analysis of the temporal (daily) pattern of area use showed the main times of the day tiger, bull and spot-tail sharks were detected for each location. Detailed results can be seen in Supplementary Information 11.

### 3.5.3 | Large scale movements and home ranges

Large scale movement information was mainly obtained from satellite tracking. In general, the 15 tagged tiger sharks had large home ranges and spent most of their time in the broader Whitsundays region, moving between the mainland coast, nearshore islands and offshore reefs (Figure 7, Supplementary Information 1, Figure S1h). Most individuals did not move much further north than Townsville or further south than Mackay (Figure 7). One exception was shark ST #178942 (321 cm total length [TL] female, tagged in December 2019), that moved out of the Whitsundays area soon after tagging and in two months swam >3700 km to the Solomon Islands (Figure 7, Supplementary Information 1, Figure S1h). The second exception was shark ST #41821 (316 cm TL male, tagged July 2019), that moved ~800 km southeast to a seamount 220 km east of Fraser Island (Figure 7; Supplementary Information 1, Figure S1h).

Even among the 13 tiger sharks with more localised movements, there were clear differences in movement patterns. Some individuals made movements out to the Coral Sea and back, others remained close to the coast throughout the tracking period, and others moved between reefs offshore from Townsville to well south of Mackay, ~400 km away (see Supplementary Information 1, Figure S1h). Accordingly, the tagged individuals had highly variable home range and core area sizes (Table 3, Supplementary Information 1, Figure S1i). Eight out of the nine sharks for which these metrics were calculated (i.e. sharks with >100 detections) had home ranges <1,715,000 ha and core areas <327,000 ha, whereas the individual that moved to

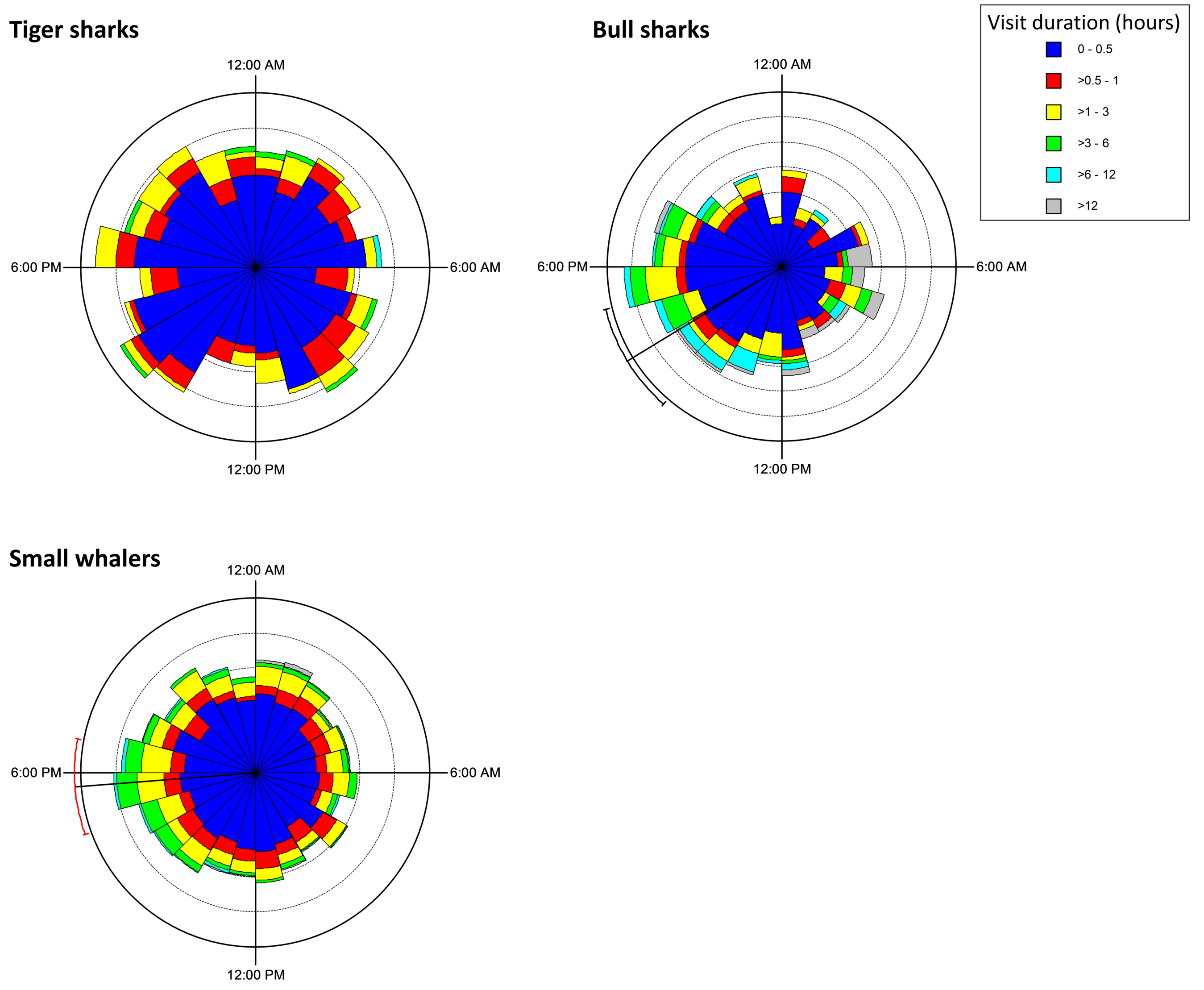


**FIGURE 4** Circular plots showing the distribution of times of arrival at the Sawmill Bay area (receivers C1–C6) for tiger sharks ($n = 317$ visits), bull sharks ($n = 387$) and small whalers ($n = 1460$), along with the time spent in the area at each visit. Colours indicate visit duration, in number 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 whalers, the groups for which Rayleigh uniformity test identified a non-uniform distribution of arrival times ($p < 0.05$). Small whalers' 99% CI is in red as it is driven by one only spot-tail shark individual, and is therefore not representative of the arrival times/visit durations for the species.

the Solomon Islands (#178942) had a much larger home range size of >14,230,000 ha, and a 2,095,647 ha core area (Table 3).

Although the core areas of all individuals were large (Table 3), for most individuals these overlapped with the region around the Whitsunday/Hook Islands (Supplementary Information 1, Figure S1i). The only exceptions were individual ST#178942, which moved to the Solomon Islands, and individual ST#178946, for which the core area was just south of the Whitsunday Island, but still in the Whitsundays region (Supplementary Information 1, Figure S1i). All tiger sharks used a number of spatially separated areas as core area, as indicated by several well separated 50% KDE regions (Supplementary Information 1, Figure S1i), meaning they moved to different areas that they used for considerable amounts of time, and did not remain in only one area only throughout the tracking period.

Large-scale information was also obtained through an acoustically tracked female tiger shark, that was tagged (at 375 cm TL) in Kiama, NSW, in December 2017 by the NSW Department of Primary Industries, and detected by the Tongue Bay acoustic receiver, >1800 km from the tagging site, on 31/08/19. It remained in the Whitsundays area for two days, after which it left to return to the Whitsundays in October 2019, when it was detected repeatedly over a two week period.

For the three tagged bull sharks, although satellite tracking produced little data, the data obtained, when combined with acoustic data shows that individual bull sharks have highly variable movement patterns and can move large distances. For example, two individuals moved ~1300 km north to the Torres Strait, one moved ~2000 south to Mollymook, NSW, while another remained in the Whitsundays

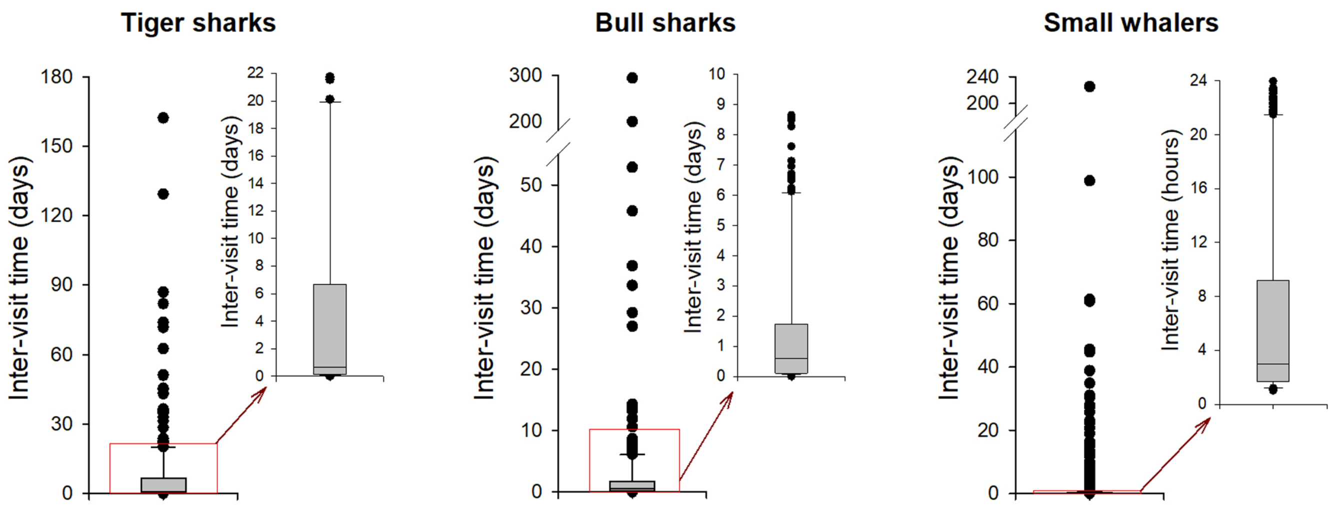


FIGURE 5 Box and whisker plots showing the distribution of inter-visit times to the Sawmill Bay area of Cid Harbour (tiger sharks: *N* = 301; bull sharks: *N* = 314; small whalers: *N* = 1942). Plots show the upper and lower quartiles (boxes), medians (lines within boxes), 10th and 90th percentiles (whiskers) and outliers (circles).

region throughout the tracking period (Figure 8). See Supplementary Information 12 for further details of bull shark and for hammerhead shark movements.

## 3.6 | Social science surveys and interviews

The survey returned 213 respondents representing residents (60%) and visitors (40%) to the Whitsundays (see Supplementary Information 13 for a summary of demographics). The majority (94%) of the surveyed individuals were residents or non-residents that own or work on boats birthed in the Whitsundays, and only 6% were guests on charter boats.

### 3.6.1 | Vessel usage patterns—Cid Harbour

About a third (36%) of the respondents have visited Cid Harbour more than 20 times, while for ~15% this was the first or second visit (Figure S12a). A number of respondents would not swim in Cid Harbour (37%; Table S13a). The harbour was recognised as a good location to anchor in inclement weather conditions (22%). The most popular activities include relaxing on the vessel (89%) and visiting the beach (82%). Forty percent of the respondents reported noticing an increase in boat numbers using the harbour over time (Table S13e), which was explained as resulting from an increase of tourist numbers in the region (Table S13g). On the other hand, 24% of the respondents reported a perceived decrease in boat numbers (Table S13e), which was explained as resulting from increased fear of sharks following the shark bite incidents (Table S13g). It is clear that these two respondent groups were considering different time frames: over the last few years vs. since the shark bite incidents (see Supplementary Information 13).

### 3.6.2 | 'Shark smart' practices

The respondent's knowledge of 'Shark Smart' practices was roughly split, with 37% claiming to know a great deal and 38% knowing only a little (Table S13h). The most important shark safety tip heard by the respondents was related to *'don't swim at dawn and dusk'* (mentioned by 79% of respondents) and '*Don't swim in murky water*' (48%; Table S13i). These were also regarded the most important 'Shark Smart' practices, with ~75.% of respondents classifying these as 'very important' messages (Table S13j). '*Don't throw food scraps overboard*' was mentioned by 24% of the respondents (Table S13i) and considered as a 'very important' safety message by 70% of respondents (Table S13j). However, only 4% of respondents believe that banning throwing food waste would be an effective response to the shark bites (Table S13l). '*Don't swim around fishers*' was mentioned as by 22% respondents and 'Don't swim near fish cleaning' by 9% (Table S13i), but this last measure was considered as 'somewhat unimportant' (Table S13j).

### 3.6.3 | Swim safe knowledge and shark safety measures

Most respondents (80.9%) had been informed of swim safe messages and were aware of where swimming is not advised (91.7%). This knowledge primarily came from media reports, and local knowledge (Table S13k). Most (59%) respondents did not believe there were additional safety message that need to be promoted. Those that did thought better public education was required (18%), along with an increase of emphasis on personal responsibility in and on the water (17%; Table S13l). Half of the respondents (49%) believe safety messages should be more widely publicised, and 56% that personal responsibility is crucial in reducing the risk of unwanted shark encounters.

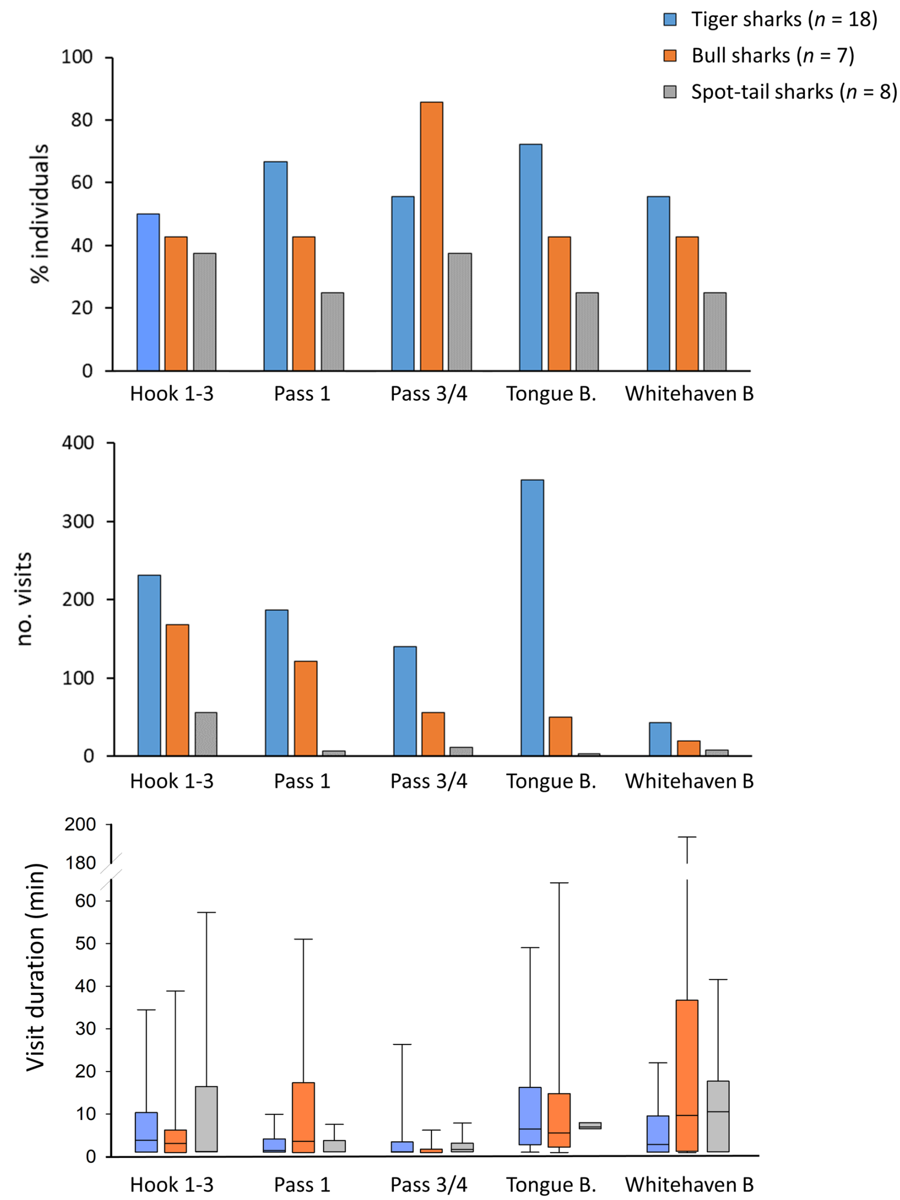


FIGURE 6 Proportion of sharks that visited each of the acoustically monitored locations (top graph), total number of visits those individuals made to each location (middle graph), and box and whisker plots showing the distribution of visit durations (bottom). In box and whisker plots, boxes indicate the upper and lower quartiles, lines within the boxes indicate the medians, and whiskers the 10th and 90th percentiles.

When asked about the perceived reasons for the occurrence of the Cid Harbour shark encounters, 30% of respondents believed it was related to the lack of awareness/ignoring shark safe practices, and 21% believed it was due to the practice of discarding food waste/fish remains off boats. Only 9% mentioned an increase in shark numbers as a potential reason (Table S13n). Respondents believed the most effective measure to reduce this risk was education on 'Shark Smart' practices (41%). Shark control measures including drumlines (28%) and shark nets (27%) were considered as least effective (Table S13o). A number of respondents (41%) believe additional management measures should be implemented to reduce the risk to swimmers, with availability of 'Shark Smart' practice information being the most frequently proposed management measure (25%; Table S13p).

#### 3.6.4 | Results from key participant interviews

Seven key participants representing the tourism industry (four interviewees), fishers (one interviewee), and community groups/management agencies (two interviewees) were interviewed (Supplementary Information 13). The main themes to emerge from interviews included the impacts of unwanted shark encounters, perceptions and beliefs about why the encounters had occurred, and minimising future risks of unwanted shark encounters. There was a diversity of opinions and beliefs spread across these themes, with many unique opinions expressed. In many instances, views were only expressed by one person (Table S12q). This was not unexpected given the variety of stakeholders involved. However,

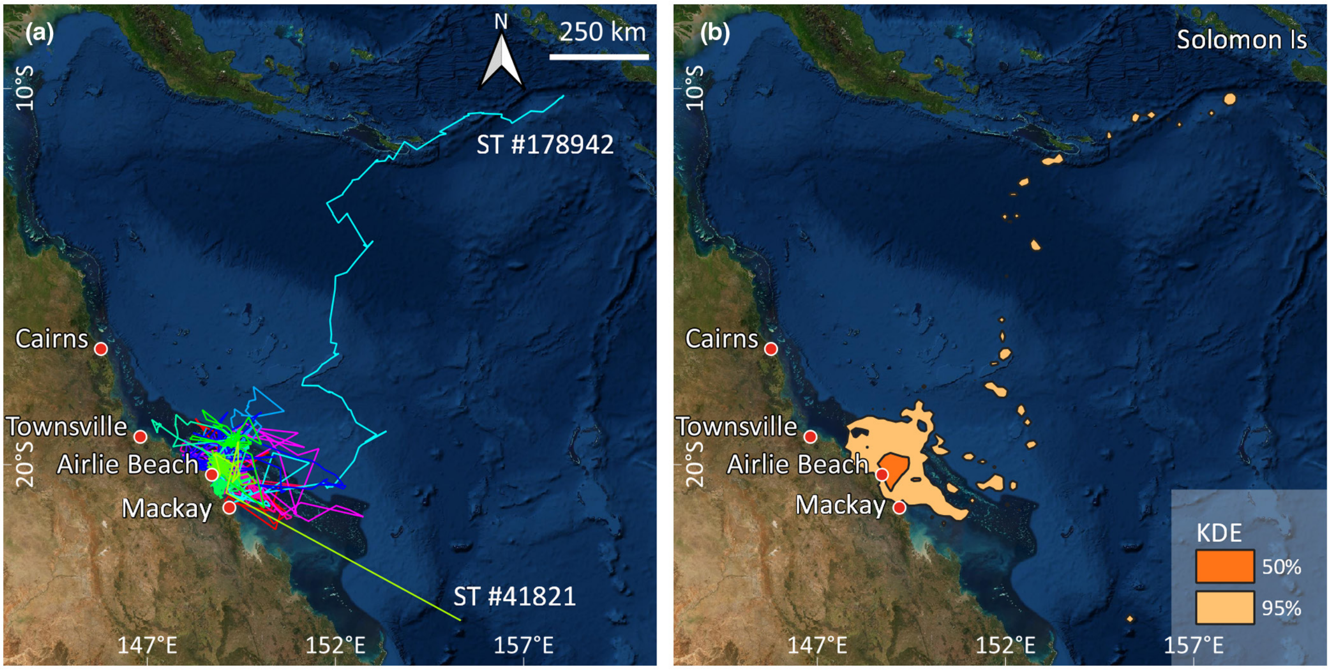


FIGURE 7 Satellite tracking data showing (a) the tracked movements of the 15 tiger sharks fitted with satellite transmitters, and (b) the extent of 50% and 95% kernel density estimates calculated from data from all tracked tiger sharks combined. The tracks of the two tiger sharks that made the most extreme movements are indicated (ST #178942 and ST #41821).

TABLE 3 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 | 5245 | 53,258 |

there were some points that were shared among three or more interviewees (Table S12q). This included the perception of a decline in tourism numbers, likely driven by a combination of factors including reef degradation and the occurrence of the shark bite incidents. Several participants believed a single shark was responsible for all bite incidents. A number of theories were proposed as the cause of the shark bites, including throwing fish/food scraps at anchorage, intentionally attracting sharks to boats, and increase in shark numbers. Some participants stated that since the shark bites, tourism briefings now had more information about sharks, but shark safety behaviours needed to be covered in safety briefings. There was strong consensus that people needed to be educated about shark behaviours.

## 4 | DISCUSSION

### 4.1 | Prevalence and behaviour of sharks in Cid harbour

Understanding species occurrence, residency and movement behaviour, along with the biological and environmental variables that drive shark abundance, can help identify the overlap between shark presence and human activities and, potentially, identify where and when the risk of negative interactions is higher (Payne et al., 2018, Meyer et al., 2018, Lee et al., 2019). Eleven shark species were documented for Cid Harbour, including bull sharks and tiger sharks, species known to be potentially dangerous to humans (West, 2011), which together comprised 20% of the sharks caught/sighted. Hammerhead sharks and smaller carcharhinids (whalers) are also capable of biting humans (West, 2011) and comprised 61% of sharks caught/sighted (hammerhead sharks: 8%; small whalers: 53%).

Despite intensive sampling effort, shark catches and sightings in BRUVs were not higher than those reported in other studies (see Supplementary Information 14 for details). This, coupled with the number of intact baits that remained on hooks after fishing and the lack of captures during night fishing, suggests that the abundance of

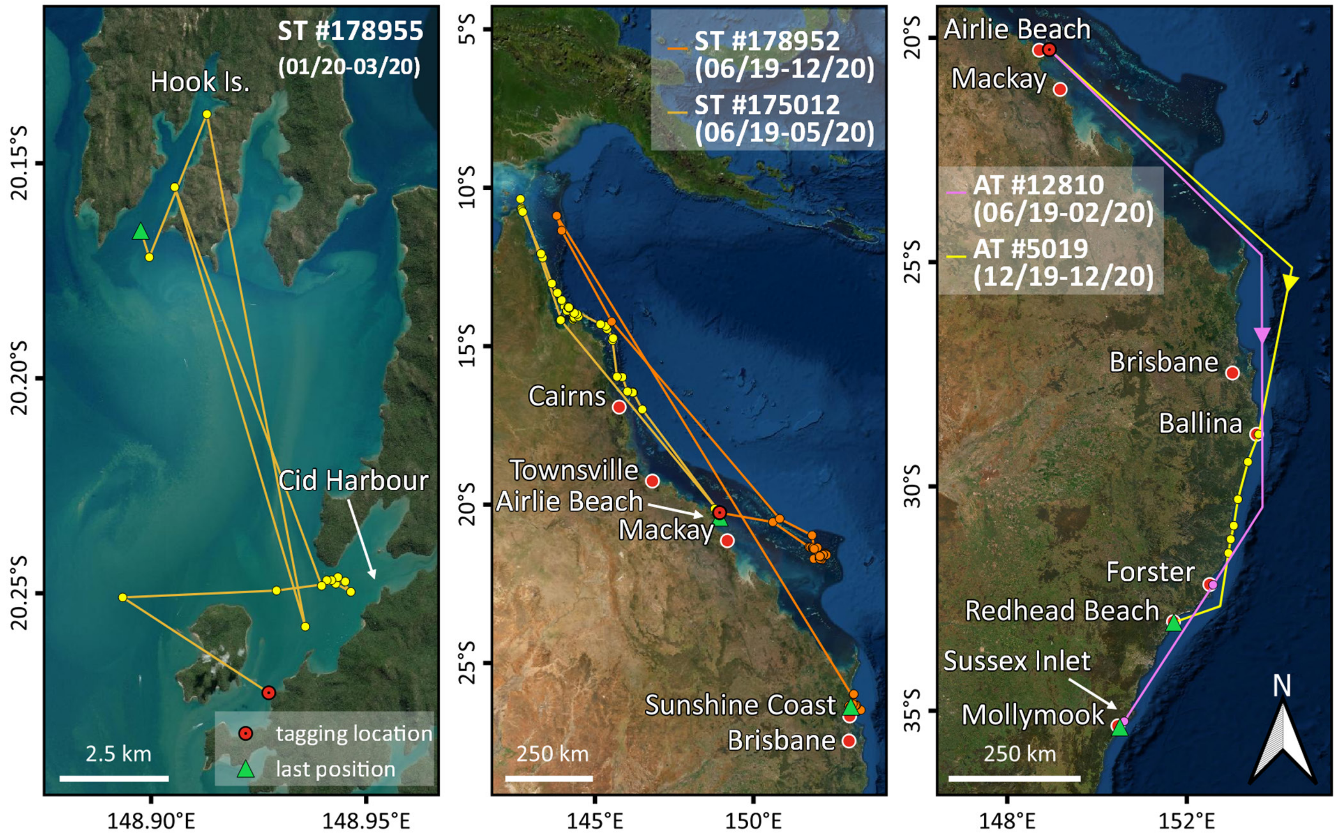


FIGURE 8 Movements of the three satellite tagged bull sharks, along with those of two acoustically tagged bull sharks that were detected by acoustic receivers from other studies.

sharks that use Cid Harbour is not unusually high. In addition, acoustic tracking shows that the majority of the tagged sharks do not use the harbour for extended periods of time.

Smaller carcharhinids (whalers) were the most commonly caught/sighted sharks. This group had more localised movements than tiger and bull sharks and used Cid Harbour the most, visiting the Sawmill Bay area more often and spending more time per visit than bull sharks and tiger sharks. Relatively restricted home ranges have been reported for small whaler species, including spot-tail and blacktip sharks, in other regions (e.g. Heupel et al., 2019; Munroe et al., 2016).

Since bull and tiger sharks are two of the three species commonly implicated in shark bite incidents (the third species being the white shark *Carcharodon carcharias*; West, 2011, McPhee, 2014), it was speculated that these species were the most likely to have been responsible for the Cid Harbour bites. Bull sharks, however, were found to occur in low numbers in Cid Harbour; none were caught by the Queensland Government contractor that fished directly after the bite incidents (September 2018) or on the first sampling trip of this study (December 2018); and bull shark catches were low in subsequent trips (maximum two individuals in a trip). Furthermore, bull sharks were not recorded on BRUVs.

The low bull shark catches limited the number of tagged individuals, preventing a robust analysis of the movement behaviour of the species. In addition, the three SPOT-tagged individuals returned few and highly separated (in both time and space) location positions, suggesting that SPOT-tags have limited value in tracking bull sharks. Similar results are reported in the only other study (to our knowledge) that used SPOT-tags on bull sharks (Graham et al., 2016), where bull sharks provided fewer position fixes than tiger and great hammerhead sharks, likely because they do not spend enough time at the surface for positioning information to be sent to satellites. Nevertheless, for individuals tagged with both satellite and acoustic transmitters, the limited satellite data provided important complementary information. For example, it identified the large-scale movement of a male bull shark from Cid Harbour to Torres Strait (~1300 km away) immediately after tagging, and its return to Cid Harbour two months later.

Bull sharks had highly variable large-scale movement patterns and, in general, low residency in Cid Harbour. Similar variability in movements was documented for bull sharks in Australia (Espinoza et al., 2016; Heupel et al., 2015) and overseas (e.g. Brunnschweiler & Barnett, 2013; Daly et al., 2014). For example, on the east coast of Australia, some individuals conduct large-scale movements, including migrations of >1700 km (Heupel et al., 2015; Espinoza et al., 2016), while others move among different locations (e.g. reefs) within their tagging regions (e.g. Espinoza et al., 2016).

In NSW, bull shark residency shows some correlation with seawater temperature, with the highest probability of encounter at 20–26°C (Lee et al., 2019). However, in Réunion, where this species is common year-round, turbidity is the main parameter affecting the chances of shark bites, with increased chance of an incident in turbid-water conditions (Taglioni et al., 2019). In the context of the Whitsundays, average monthly seawater temperatures of 21–29°C (AIMS, 2020) and highly turbid waters (Gruber et al., 2019) suggest favourable bull shark habitat year-round. In terms of likelihood of bull-shark human interactions, however, movement information suggests that bull sharks are not a continual risk to humans as their occurrence and residency are typically low and visits to most monitored areas brief. Cid Harbour is however part of the extremely broad east coast movement paths of some individuals, and the paths and timing of an individual's movement is, currently, unpredictable.

Five tiger sharks were caught by the Queensland Government contractor directly after the two incidents in September 2018, and therefore this species was initially considered likely responsible for the bites. In the present study, tiger sharks were the second most commonly caught species. Different individual sharks showed differences in habitat use and movement patterns but, as a group, their movements 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, tiger sharks move widely over the Whitsundays region, passing through areas of high human use (such as Cid Harbour), but do not stay in particular locations for extended periods. Here, it is important to note that shark presence is not directly equated to shark bite risk. In Hawaii, tiger sharks commonly occur in areas of high human use, including large sharks that visit highly used recreational areas almost daily, yet the risk of shark bites remains extremely low, leading Meyer et al. (2018) to suggest that tiger sharks are generally not 'interested' in people. Conversely, in some locations (e.g. Recife Brazil and Reunion) increases in abundance of potentially dangerous sharks have been suggested to lead to increased chances of shark bites (Afonso et al., 2017; Lagabrielle et al., 2018).

The peak in tiger shark occurrence at 24–26°C (in October/November) in Cid Harbour was slightly higher than the previously reported optimal temperatures for the species (22–24°C; Payne et al., 2018). However, our seasonal analysis was based on only nine individuals tracked over one year, and more data are needed for a more precise description of tiger shark seasonality and the possible influence of water temperature. Future work would also benefit from deploying temperature loggers in Cid Harbour and at other Whitsundays locations where acoustic receivers are deployed, to account for localised variations in water temperature. Nevertheless, tiger sharks occur over a wide temperature range (13 °C to >30 °C; Fitzpatrick et al., 2012; Payne et al., 2018), and since the average monthly seawater temperature in the Whitsundays ranges from 21 °C to 29 °C (AIMS, 2020), it is not surprising that tiger sharks occur throughout the year.

## 4.2 | Food resources

BRUVs, sidescan sonar and field observations suggest that there are seasonal shifts in relative abundance of different prey types but, overall, shark prey is abundant in Cid Harbour year-round. In all field trips, numerous turtles, teleosts, dolphins, stingrays and shoals of baitfish were observed, groups known to be shark prey (e.g. Simpfendorfer et al., 2001; Trystram et al., 2017). The smaller sharks caught could also be prey for larger sharks (Cliff, 1995; Cliff & Dudley, 1991; Trystram et al., 2017).

The natural food sources for sharks are likely to be supplemented through human activities within Cid Harbour. More than 60 boats can use the harbour per day, and most anchor for the night in Sawmill Bay, that is, in the area where the three 2018 shark bite incidents took place. During the social science study and in subsequent meetings with local stakeholders, one recurring discussion point frequently arose, related to the common practice of throwing food scraps overboard at anchorages, with accounts of some visitors intentionally attracting sharks with food or bait (pers. com.). Since quantifying dumping of food and fish scraps was not the objective of this study, this information can be considered as anecdotal. However, the frequent and repeatedly raised discussions on this topic suggests that this issue is widespread, and that it could have played a role in effecting shark behaviour in Cid Harbour. Fishing can also provide sharks with food through depredation (Mitchell et al., 2018), noting that 34% of the surveyed individuals reported using Cid Harbour for fishing (Table S13c). As many shark species are opportunistic scavengers (e.g. Fallows et al., 2013; Hammerschlag et al., 2016), these activities can attract sharks to an area and possibly to boats (Mitchell et al., 2020; Trave et al., 2017), contributing to an increased shark bite risk. For example, in French Polynesia, 45% of the shark bites that occurred between 1979 and 2001 were linked to people feeding sharks (Maillaud & Van Grevelynghe, 2005).

Where regular feeding/fishing occurs, sharks may anticipate feeding and associate boats with food (e.g. Fitzpatrick et al., 2011; Heinrich et al., 2021; Mitchell et al., 2020). Sharks can also associate a splash in the water with feeding (Martin et al., 2019), so could have mistakenly identified the splash of a person jumping into the water with food being thrown from a boat. Moreover, the presence of other sharks can increase competition and aggression (e.g. Clua et al., 2010) and in low visibility conditions (such as in Cid Harbour), sharks rely less on vision and more on other senses (electroreception, olfaction, lateral line, hearing) to detect prey (Gardiner et al., 2014). All these factors could have contributed to the Cid Harbour shark bites.

## 4.3 | Evaluation of the research methods

Alone, the methods used in this study had variable success, but combined they provided a large amount of complementary information. Fishing methods formed the basis for identifying the species that occur in the harbour, including relative abundance. Concentrating the fishing effort in the shark bite area allowed for intensive sampling, and the use of different hook sizes ensured that all shark sizes were targeted. BRUVs were useful to complement catch data, providing additional data on species occurrence over the broader harbour. Although cameras attached to drones (Butcher et al., 2020) or blimps (Adams et al., 2020) can also be useful to monitor shark occurrence, drones were trialled on the first field trip but were not successful due to the harbour's turbid waters. Drones/blimps with advanced sensors (e.g. multispectral or hyperspectral sensors) may have success at detecting sharks in turbid waters but these sensors' value is still being investigated (Butcher et al., 2021).

The trialled use of side-scan sonar led to promising results, showing that this is a viable and valuable method for obtaining broad estimates of prey availability, particularly if combined with BRUVs. Note however that a standard side-scan sonar, commonly used on recreational boats, was used, but identification of prey types could be improved by using more sophisticated devices that produce clearer images. Future assessment of prey availability could also include unbaited cameras and recording the occurrence and behaviour of animals (turtles, fish, birds) at the surface during sonar transects, as in Heithaus (2001), for example.

Acoustic and satellite tracking were particularly useful for this study, providing important information about movements, including patterns of visitation to Cid Harbour and home ranges. For bull sharks, although satellite tracking produced little data, it provided key information on large-scale movements, particularly when combined with acoustic tracking. Satellite data were also useful when bull sharks entered shallow coastal areas, for example, when a female bull shark used the Sunshine Coast River and lagoonal systems (Supplementary Information 9). Finally, including a social science component in the research response to the shark bite incidents allowed for opened discussions with local operators, which led to a more holistic understanding of the Cid Harbour bite incidents. This approach is therefore recommended for future studies. In particular, the concerns of dumping food and stakeholder overlap in area use (e.g. fishing, cleaning fish, dumping food, swimming and/or snorkelling in the same area) were raised multiple times not only in discussion with various stakeholders, but also in the survey of activities conducted in Cid Harbour (Table S13c). This allowed both surveyed and anecdotal information to be considered in the interpretation of the possible factors influencing the Cid Harbour shark bite incidents, therefore assisting in management planning.

## 4.4 | Future directions

Despite the relative short time frame of the present study, acoustic tracking was particularly informative for understanding how different shark species use Cid Harbour. A longer-term study, taking full advantage of the ~10 year acoustic tag battery life would allow for more rigorous analyses, that could contribute more comprehensive information to inform the management of shark-human interactions (Meyer et al., 2018; Spaet et al., 2020). This may provide information to refine the current shark safety ('Shark Smart') guidelines (www.daf.qld.gov.au/sharksmart), and potentially provide more location-specific and relevant advice to water users and tourism operators.

Since the overlap in site use by different stakeholders (in particular, swimmers/snorkelers overlapping with fishing and dumping food from liveaboard boats) was considered as one of the possible contributing factors to the Cid Harbour shark bites, the continued tagging and monitoring of the shark community, along with continued work to monitor visitor activities and identify risky behaviours and/or behaviour changes is recommended. Future work should focus on areas of particularly high tourism use (anchorages, swimming/snorkelling, and fishing areas) across the wider Whitsunday region, on the simultaneous monitoring of environmental conditions (turbidity, rainfall and water temperature) and visitor use and behaviour patterns. Such information may lead to the identification of times of the day and areas least/most used by the different species (as in, e.g. Figure S1g), and where this overlaps with the different human activities. Combined, this information can be used to assess the probability of shark encounter in different areas and to develop targeted management measures. For immediate public benefit, real time receivers (VR4G) could also be deployed at key locations such as high use tourism areas to instantly alert water users about the presence of tagged sharks at those locations (as in Spaet et al., 2020 and Colefax et al., 2020). Note however that it is important to keep in mind that not all sharks were tagged, and that threats from untagged sharks still need to be considered in shark mitigation planning. Moreover, in the broader context of mitigating shark risk, understanding human behaviours and drivers of behaviour change will be crucial in developing management responses to reduce shark bite risks.

The social science component of the study found that better public education and increased personal responsibility were considered more important in reducing the likelihood of shark bite incidents than shark control programmes, highlighting that managing people is preferred to trying to manage the animals. However, personal responsibility requires awareness and education of what 'responsible and safe' behaviours are. The Queensland government already had a 'Shark Smart' programme in place prior to the bite incidents. However, limited exposure or interest in the program was highlighted by individuals surveyed, with respondents ranking throwing food off boats as the second most important explanation for the increase in unwanted shark encounters (Figure S13n), and ranked as a very important shark safety practice (Figure S13j). Yet, only a quarter of respondents had heard of '*don't throw food scraps overboard*' as an important safety tip (Figure S13i), and only 4% believe that banning throwing food waste would be an effective response to shark bites (Figure S13l), again emphasising the need for better education. Information obtained through the present project increased engagement with the public and stakeholders through increased Government funding for the 'Shark Smart' program. This will hopefully contribute to better education outcomes. Indeed, some interviewees have already begun to implement/provide shark safety messaging within their tourism practices.

Identifying the species responsible for shark bites is difficult, unless witnesses are able to reliably identify or describe the shark, or the forensic examination of shark teeth (size/shape), tooth fragments and/or shark bite morphology, is possible. The genetic analysis of tooth fragments (Yang et al., 2019) or swabs taken from the bite site (Fotedar et al., 2019) can also lead to species identification. Therefore, future protocols following shark bite incidents should include obtaining as much information about the bite, including bite size/radius and, when possible, obtain a swab of the wound/s and collect teeth/tooth fragments for morphological and genetic analyses.

## 5 | CONCLUSION

This study did not identify anything unusual about the shark species composition, relative abundance or movement behaviour in Cid Harbour that could have contributed to the 2018 shark bite cluster. Although the occurrence of shark bite incidents can be random, several factors (e.g. location and environmental conditions such as prey distribution/abundance, temperature, rainfall, anomalous weather patterns, and water quality) can increase the probability of shark bites (Chapman & McPhee, 2016; Ryan et al., 2019), and the cumulative effect of different factors could lead to a cluster of bites. However, the context of the 2018 Cid Harbour shark bites, that is, the three incidents involved people bitten almost instantly after entering the water, was very unusual. Moreover, and a space–time permutation analysis based on the shark bite incidents recorded in Australia between February 2000 and February 2022 ($n = 438$), confirmed that the three incidents constitute a statistically significant cluster ($p = 0.024$; see Supporting Information 3). As indicated by the social science interviews, anchoring boats used to regularly feed/dump food scraps into the water, a behaviour that could have contributed to the shark bite incidents. Since, as suggested by West (2015), sharks can become more agitated, aggressive or reactive due to the regular food provisioning, sharks could have rapidly reacted to the water disturbance as the people jumped into the water, by biting. This also means that any species capable of biting humans (or even multiple species) could have been responsible. The spatial overlap of stakeholder activities such as fishing and swimming/snorkelling could also have contributed to increase the likelihood of shark bite incidents, along with other yet to identify factors, which likely operate in a cumulative way. Therefore, the eradication of activities that attract sharks into areas used for in-water activities (including food dumping and fishing) could reduce the risk of future shark bites.

## AUTHORS' CONTRIBUTIONS

A.B., R.F. and M.B.B. conceived the project; A.B., R.F., M.S., M.B. and C.M. designed the methodology; A.B., M.B., I.M., R.F., J.L.Y., N.L., K.C. and C.M. collected the data; K.A., A.B., M.B. and L.W. analysed the data; A.C., A.D. and B.S. designed, collected and analysed the social science component of the study; A.B. and K.A. led the writing of the manuscript, and all authors contributed to writing and provided critical feedback and gave final approval for publication.

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### CONFLICT OF INTEREST

The authors declare no conflict of interest.

### DATA AVAILABILITY STATEMENT

Acoustic tracking data is available from the IMOS Animal Tracking Facility (https://animaltracking.aodn.org.au/). Catch rates, satellite tracking, and BRUV data are available from the Dryad Digital Repository at https://doi.org/10.5061/dryad.fj6q573xc.

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## SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

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