# Residency and spatial use of sharks in relation to human activity at North West Island

A report for the Department of Environment, Tourism, Science and Innovation

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# Summary

In response to three shark bite incidents that occurred between December 2019 and April 2020 at North West Island (Capricorn Bunker Group), and amid ongoing concerns about the dumping of food and fish scraps in the area, the State of Queensland, acting through the Department of the Environment, Tourism, Science and Innovation (DETSI), commissioned a scientific study to investigate the prevalence, movements, and behaviour of potentially dangerous sharks around the Island, and to ascertain if certain human behaviours may increase the risk of negative shark-human interactions. Here, we report the findings of that project, which ran for two years (October 2022 – October 2024).

This study used multiple complementary approaches: acoustic and satellite tracking of shark movements, behavioural experiments, and aerial drone surveys. Underwater remotely operated vehicles were also trialled. The methods and sampling design were used to improve our understanding of the shark community, residency, and spatial use around North West Island, with a particular focus on a site where people had been dumping fish and food scraps for decades.

Thirteen shark and four ray species were documented, including the three species most associated with shark bites: bull sharks, tiger sharks, and white sharks. The white sharks were tagged in New South Wales through other projects and were likely on their migration to/from their winter habitats. Catch surveys revealed a relatively high shark abundance with an overall catch rate of 0.09 sharks.$hr^{-1}$. Tiger sharks dominated the catch, contributing to 45% of the total catch, and were followed by grey reef sharks (13%), bull sharks (10%) and sandbar and pigeye sharks (7% each). Seasonal variability in catch rates was evident for some species; for example, tiger shark catches declined in winter while sandbar shark catches increased.

The behavioural studies targeting the dumping of fish scraps and depredation resulted in few shark interactions (note: behavioural experiments used minimal bait). The interactions and DNA analysis of 26 depredated fish showed that grey reef sharks, bull sharks, and blacktip complex were the main species involved. We do note that despite behavioural interactions not being frequent in this study, there were three events where blacktip complex were attracted to our boat. On two occasions, this involved 4–5 individuals.

Despite being the most abundant species caught, tiger sharks showed low residency, but high visitation rates to North West Island. Satellite tracking showed that different individuals conducted very different movements, from individuals that remained in the Central Queensland region throughout their tracking period, to one that conducted a large-scale migration of ~13,200 km in one year. Tiger sharks also spent their time well distributed across the different island locations, showing a more even distribution of habitat use around the Island. Moreover, the species did not interact with any of the human activity experiments. Combined, these results suggest that tiger sharks are attracted to the island primarily by natural prey (turtles, seabirds) rather than by human activities. Like tiger sharks, great hammerheads used the overall island and did not spend a higher proportion of their time in

the dumping area, and did not occur in the behaviour experiments. As with tiger sharks, it is likely that great hammerheads use the island for feeding on abundant rays and are likely little influenced by human activities.

Bull sharks exhibited transient behaviour, suggesting they were passing through rather than residing at the Island. In contrast, their close relatives, pigeye sharks, showed higher residency to North West Island, spent more time in the dumping zone, and were less likely to conduct large-scale movements. This distinction is significant because pigeye sharks have recently been identified as one of the main species implicated in depredation, and could potentially be responsible for some negative interactions previously attributed to bull sharks.

Lemon sharks, the species implicated in negative human interactions near the beach at North West Island, were caught only in low numbers throughout the study and did not interact with behavioural experiments. However, drone surveys revealed a high prevalence in the shallow lagoon around the island. Limited tracking data suggest seasonal patterns in the use of North West Island, with lower occurrences in winter and higher summer-autumn presence, with February-March representing peak times — notably when the Island is closed to tourism, meaning human activities would not be attracting lemon sharks at that time.

Grey reef, lemon, sandbar sharks, and the blacktip complex showed fine-scale movement patterns that suggest some influence of human activities when the Island is open to campers: larger spatial use, habitat use closer to the island, the boat channel and main mooring site. In contrast, pigeye and bull sharks showed no difference in habitat use when the Island was open or closed, with core habitat use occurring in the deeper, more offshore, areas.

Overall, broad habitat use patterns around North West Island show that most species spend significant time in the dumping and mooring sites, and little time at sites farther along the Island's edge. This may indicate that decades of dumping scraps from boats have conditioned sharks to keep returning to these sites. High visitation rates to North West Island, coupled with short residency periods, match shark behaviour in Cid Harbour, Whitsundays, where human activities (including dumping of food/fish scraps) likely played a role in negative human-shark interactions.

The behavioural experiments, which resulted in very few shark interactions, do not strongly support the hypothesis that dumping drives shark habitat use at finer-spatial scales, suggesting that if sharks were previously associated with boats, the dumping ban implemented over a year before this study is working, at least to some extent. However, for most species, fine-scale movement data revealed higher occurrence and increased spatial use in and around the dumping zone when the Island was open. In particular, the blacktip complex and grey reef sharks showed behavioural changes indicative to being attracted to human activities. Furthermore, pigeye, grey reef, sandbar, and lemon sharks had some of the highest residency indices to North West Island, and recent information indicates that these species, along with the blacktip complex and bull sharks, are responsible for a significant proportion of negative human-shark interactions in Queensland and Western Australia.

# 1. Background

Only 75 kilometres from Gladstone, North West Island, the largest coral cay in the Capricornia Cays National Park, is a popular tourism destination that has hosted campers for decades. The campground caters to up to 150 people at a time, offering camping-only accommodation with limited facilities and no resort or hotel-style options available. The island can be accessed by a barge (which can take small boats/tinnies) or private vessels. Fishing is the most popular activity on the island, with many campers bringing their boats for this purpose. In the north of the island, there is a lagoon and a channel for smaller vessels to enter/leave the island, which is exposed at low tides. When not being used, vessels are beached or anchored in the lagoon. There are also two public moorings on this side of the island, one just outside the channel, the other ~2.1 km to the east. Prior to 23rd April 2021, visitors were required to either take all their waste back to the mainland, or they could dispose of fish and food scraps at sea, but away from the island, at least 500 m from land.

North West Island is one of the most significant green sea turtle nesting sites in the southern Great Barrier Reef and ranks with Raine Island as one of the most important seabird breeding islands on the Great Barrier Reef (Dyer et al. 2005). Historically, the Island supports ~70% of the breeding wedge-tailed shearwaters (*Puffinus pacificus*), and ~50% of the breeding black noddies (*Anous minutus*) on the east coast of Australia (Hulsman and Walker 1996). Coinciding with the high season for turtle hatching and seabird nesting and rearing of chicks, the island is closed to camping for ~2-months, between the day after the Australia Day weekend and the first day of the Queensland Easter school holidays.

Between December 2019 and April 2020, three shark bite incidents took place at North West Island. Those incidents raised concerns that human behaviour on and near North West Island may have increased the risk of shark bites. The dumping of fish scraps and other organic waste within 500 m of shore (with some people dumping from the beach) could have attracted sharks, and possibly conditioned sharks to boats within the dumping area. There were numerous anecdotal reports of sharks surrounding boats as people discarded fish scraps, with some people posting their footage online (e.g. see here). The Department of the Environment, Tourism, Science and Innovation (DETSI) also received reports of people using food to deliberately attract sharks. Stakeholder overlap was also a concern, with fishing, dumping of fish waste, and attracting sharks taking place from the beach where people swim, either concurrently or at other times. These initial reports of shark-human interactions are similar to what occurred in the Whitsundays, where decades of dumping scraps and cleaning fish at busy anchorages likely played a role in the cluster of shark bites that occurred in that area in 2018/19 (Barnett et al. 2022, 2024).

In March 2021, to address the possibility that human activities may be influencing shark behaviours, DETSI, with the help of Biopixel Oceans Foundation, undertook a pilot study to gather information about shark use of North West Island prior to the implementation of any management changes. Acoustic receivers were deployed at the two public moorings prior to

March 2021, and on 15 March 2021 five acoustic receivers were deployed ~800 m apart around the location where organic waste had been predominantly disposed of (i.e. 500 m off the reef edge, out from 'the channel'). Three additional receivers were deployed near the corners of the proposed Special Activity Area (SAA). Over three days of fishing, five female tiger sharks (*Galeocerdo cuvier*; 267 – 383 cm total length (TL) were captured and tagged with acoustic transmitters. The two largest sharks were also fitted with satellite 'SPOT' tags. No other sharks were caught.

In April 2021, a SAA was gazetted for the area surrounding North West Island (Figure 1), where any activities that attract sharks, including processing fish products, dumping of fish scraps, cleaning fish, and processing equipment, were prohibited. In October 2022, 18 months after implementing this management measure, DETSI commissioned research to assess the prevalence, movements, and behaviour of potentially dangerous sharks around the Island, and to determine if certain human behaviours may increase the risk of negative interactions with sharks. Here, we report the findings from this two-year project (October 2022 to October 2024).

***Timeline of events:***

- 29/12/2019 - A man suffered minor injuries after being bitten on the leg. The bite was originally reported to be from a shovelnose ray, but subsequent reports indicated he could have been bitten by a lemon shark while attracting and feeding sharks close to shore
- 08/01/2020 - A nine-year-old girl was bitten on the leg while paddling at the beach in the late afternoon, reportedly by a lemon shark
- 06/04/2020 - A man was fatally bitten while swimming at the back of a vessel moored off the island
- 15/03/2021 – DETSI pilot study
- 23/04/2021 - Special Activity Area gazetted (Figure 1)
- 10/2022 – Research project begins
- 10/2024 – Data collection complete

## 2. Objectives

1. Enhance our knowledge of the shark community using North West Island and spatio-temporal patterns of area use, with particular focus on species involved in negative shark-human interactions (shark bites, depredation)
2. Investigate whether human behaviours, including disposal of fish scraps/organic waste and fishing, influence the use of the waters around North West Island by sharks, and whether human activities may have increased the risk of negative (provoked or unprovoked) shark interactions

# 3. Study area

Research was conducted within the Special Activity Area surrounding North West Island (Figure 1), with a focus on the area off the reef edge adjacent to the campground, to include the area where fish scraps and other organic waste were historically dumped (i.e. ~500 m out from the channel), and the public moorings closest to the campground. Ten field trips were conducted between October 2022 and February 2024, including five liveaboard trips, three trips for behavioural experiments, and two trips to retrieve data from receivers.

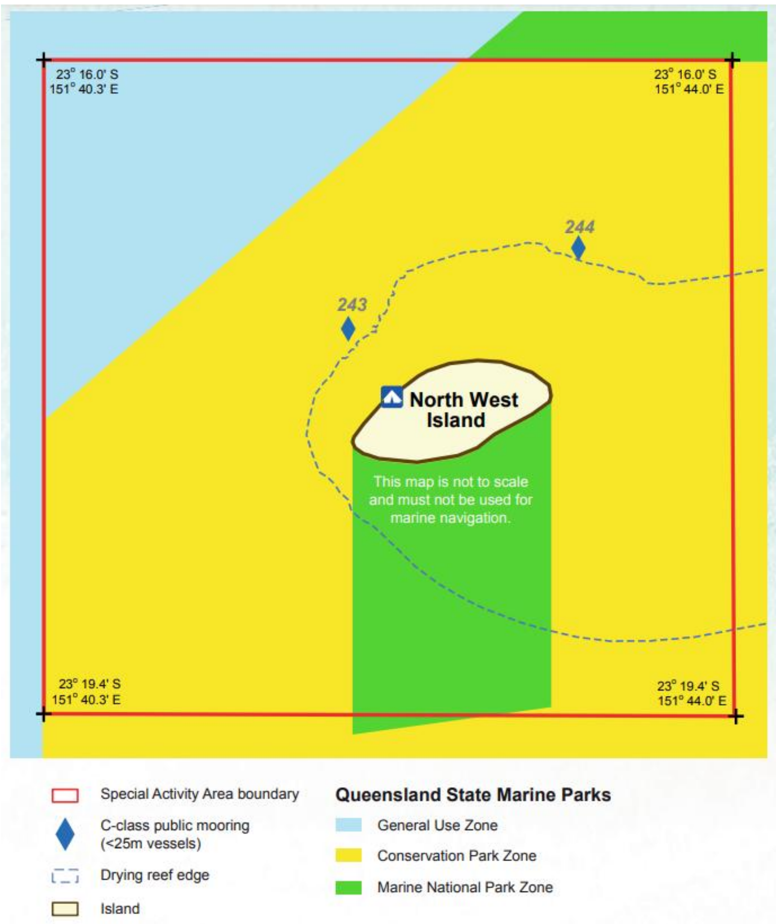


**Figure 1.** North West Island, showing the location of the camping ground, the two public moorings, the Special Activity Area boundary, and main study area (focus area) (map source: DETSI)

## 4. The North West Island shark community

To characterise the shark community utilising North West Island, five trips dedicated to fishing and tagging were conducted: in October 2022, February 2023, March 2023, August 2023 and February 2024.

### *4.1 Catch methods*

Single hook droplines were used, primarily around the channel/dumping area (Figure 2). The area to the south of the Island, just off the reef flat (within the Green Zone), and the southeast corner of North West Reef (within the Yellow Zone) were also sampled during two of the trips (Figure 2). On each sampling day, between 3 and 10 single hook droplines were deployed at depths of 7–34 m, during daylight hours. The number of droplines used depended on how busy the catch was. For instance, during the first field trip, only deployed five lines had been deployed before sharks started being consistently caught, resulting in 16 sharks being tagged in one afternoon. Hook sizes were predominantly 20/0, with some 18/0 and 16/0 also used. Bait consisted mainly of mullet, but tuna and frames of reef fish species were also used on some trips. See Table 1 for a summary of fishing effort.


**Figure 2.** Map showing the single hook dropline locations (red dots) around North West Island. The yellow square indicates the approximate location of the dumping zone; and ▲ indicates the camping ground (approximate location). Map source: Google, 2024 CNES/Airbus.

**Table 1.** Summary of dropline fishing effort, for the five shark tagging field trips. Between three and 10 droplines were used per day. Number of hours fished corresponds to the sum of the number of hours each dropline was deployed, for all days.

| Trip | Dates | No. days | No. hr fished |
|---|---|---|---|
| Trip 1 | 06–12 Oct 2022 | 4 | 150 |
| Trip 2 | 16–18 Feb 2023 | 3 | 353 |
| Trip 3 | 09–12 Mar 2023 | 4 | 431 |
| Trip 4 | 12–15 Aug 2023 | 4 | 236 |
| Trip 5* | 22–26 Feb 2024 | 5 | 417 |

*A 24-hook longline was also set in the shallower part of the dumping zone in an attempt to catch lemon sharks. Due to the chance of warmer than normal water temperature affecting the health of sharks caught, this was abandoned after two days. Seven reef sharks (four blacktip and three grey reef) were caught on the longline. Note the 417 hours are for droplines only.

In total, 145 sharks from 11 species were caught (Table 2), leading to an overall catch per unit effort (CPUE) of 0.09 ind.hr$^{-1}$. A whitespotted guitarfish (*Rhynchobatus australiae*; not included in the analyses) was also caught. Shark CPUE was highest on Trip 1, followed by Trip 2, while Trip 5 had the lowest CPUE of only 0.03 sharks.hr$^{-1}$ (Table 3). Low catches on Trip 5 were likely influenced by the warmer than average waters (surface waters >29 °C, at 15 m depth 28.5 °C). Additionally, drone surveys identified significant coral bleaching. For species with optimum temperature ranges <29 °C, the higher water temperatures may have caused some individuals to move to cooler water (e.g. tiger sharks' optimum water temperature is 22–24 °C; Payne et al. 2018).

**Table 2.** Species composition, sex ratio (M:F; when only one shark was caught, its sex is indicated) and size range of sharks caught on over the four field trips. *n* = number of sharks caught and, in brackets, the percentage of individuals that species contributes to the total number of sharks caught.

| Species | Scientific name | Sex ratio (M:F) | Size range (cm; TL) | *n* |
|---|---|---|---|---|
| Tiger shark | *Galeocerdo cuvier* | 1:60 | 97–420 | 65(45.0) |
| Grey reef shark | *Carcharhinus amblyrhynchos* | 1:5 | 117–180 | 19(13.1) |
| Bull shark | *Carcharhinus leucas* | 3:4 | 202–315 | 15(10.3) |
| Sandbar shark | *Carcharhinus plumbeus* | 0:10 | 179–208 | 10(6.9) |
| Pigeye shark | *Carcharhinus amboinensis* | 3:7 | 212–259 | 10(6.9) |
| Blacktip complex | *Carcharhinus limbatus/tilstoni* | 2:5 | 176–261 | 8(5.5) |
| Lemon shark | *Negaprion acutidens* | 3:2 | 225–268 | 5(3.4) |
| Great hammerhead | *Sphyrna mokarran* | 1:1 | 274–285 | 6(4.1) |
| Blacktip reef shark | *Carcharhinus melanopterus* | 1:4 | 134–156 | 5(3.4) |
| Silvertip shark | *Carcharhinus albimarginatus* | NA | NA | 1(0.7) |
| Spot-tail shark | *Carcharhinus sorrah* | 1F | 115 | 1(0.7) |

Note: two great hammerheads, two grey reef sharks, one silvertip shark, one tiger shark, and one sandbar shark were caught and identified, but escaped the line before sampling or sexing was possible. Those individuals are included in the overall sampling size (*n*), but not in the sex ratio or size range.

Tiger sharks were by far the most abundant species caught, contributing to 45.0% of the total catch (Table 2 and Table **3**; Figure 3). Grey reef sharks (13.1%), bull sharks (10.3%), pigeye sharks (6.9%), and sandbar sharks (6.9%) were also commonly caught. Tiger sharks dominated the catch in the four trips (Trip 1, 2, 3 and 5) that occurred in spring, summer and autumn periods, while sandbar sharks were the most commonly caught species in winter (Trip 4) (Figure 3). Spot-tail sharks and silvertip sharks were rarely caught (Table 2 and Table **3**; Figure 3). Catch included 11 recaptures (seven tiger sharks ,corresponding to 11% of tagged animals, one bull shark, and two grey reef sharks, one of which was recaptured twice), and eight individuals that escaped the line before being brought onto the boat for tagging (three great hammerhead sharks, two grey reef sharks, one silvertip shark, one tiger shark, and one sandbar shark). Note that the Australian blacktip shark (*Carcharhinus tilstoni*) and the common blacktip shark (*Carcharhinus limbatus*) are difficult to distinguish, so the two species were combined into the blacktip complex category throughout this report. Lemon sharks were only caught in Trips 2 (four individuals) and 5 (one individual), both in February. However, in February 2024, only one lemon shark was caught, which was lower than expected.

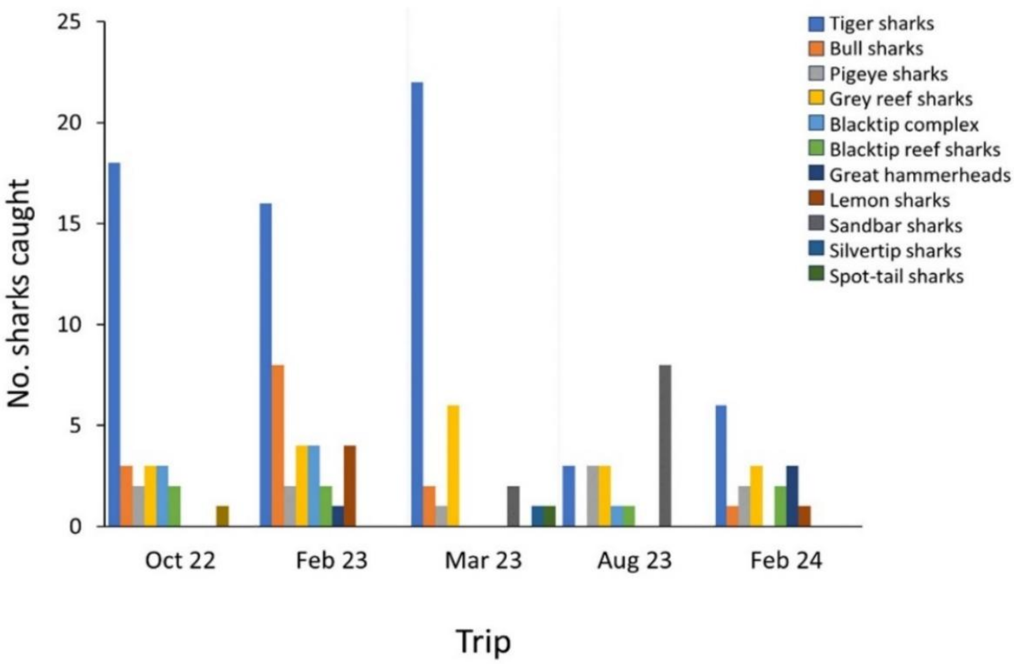


**Figure 3.** Number of sharks of each species caught on single hook set lines during the five field trips (Trip 1 to 5).

**Table 3.** Summary dropline shark catches per trip. Between three and 10 droplines were used per day. CPUE (catch per unit area) = number of sharks caught per hook hour.

| Species/Trip | No. sharks | CPUE | Species/Trip | No. sharks | CPUE |
|---|---|---|---|---|---|
| **All sharks** | | | **Grey reef sharks** | | |
| Trip 1 | 31 | 0.21 | Trip 1 | 3 | 0.02 |
| Trip 2 | 41 | 0.12 | Trip 2 | 4 | 0.01 |
| Trip 3 | 35 | 0.08 | Trip 3 | 6 | 0.01 |
| Trip 4 | 19 | 0.08 | Trip 4 | 3 | 0.01 |
| Trip 5 | 18 | 0.03 | Trip 5 | 3 | 0.01 |
| *Total* | *145* | *0.09* | *Total* | *19* | *0.01* |
| **Tiger sharks** | | | **Blacktip reef sharks** | | |
| Trip 1 | 18 | 0.12 | Trip 1 | 2 | 0.01 |
| Trip 2 | 16 | 0.05 | Trip 2 | 0 | 0.00 |
| Trip 3 | 22 | 0.05 | Trip 3 | 0 | 0.00 |
| Trip 4 | 3 | 0.01 | Trip 4 | 1 | <0.01 |
| Trip 5 | 6 | 0.01 | Trip 5 | 6 | 0.01 |
| *Total* | *65* | *0.04* | *Total* | *9* | *<0.01* |
| **Bull sharks** | | | **Lemon sharks** | | |
| Trip 1 | 3 | 0.02 | Trip 1 | 0 | 0.00 |
| Trip 2 | 8 | 0.02 | Trip 2 | 4 | 0.01 |
| Trip 3 | 2 | <0.01 | Trip 3 | 0 | 0.00 |
| Trip 4 | 0 | 0.00 | Trip 4 | 0 | 0.00 |
| Trip 5 | 1 | <0.01 | Trip 5 | 1 | <0.01 |
| *Total* | *15* | *0.01* | *Total* | *5* | *<0.01* |
| **Pigeye sharks** | | | **Spot-tail sharks** | | |
| Trip 1 | 2 | 0.01 | Trip 1 | 0 | 0.00 |
| Trip 2 | 2 | 0.01 | Trip 2 | 0 | 0.00 |
| Trip 3 | 1 | <0.01 | Trip 3 | 1 | <0.01 |
| Trip 4 | 3 | 0.01 | Trip 4 | 0 | 0.00 |
| Trip 5 | 2 | <0.01 | Trip 5 | 0 | 0.00 |
| *Total* | *10* | *<0.01* | *Total* | *1* | *<0.01* |
| **Great hammerheads** | | | **Sandbar sharks** | | |
| Trip 1 | 0 | 0.00 | Trip 1 | 0 | 0.00 |
| Trip 2 | 3 | 0.01 | Trip 2 | 0 | 0.00 |
| Trip 3 | 0 | 0.00 | Trip 3 | 2 | 0.01 |
| Trip 4 | 0 | 0.00 | Trip 4 | 8 | 0.03 |
| Trip 5 | 3 | 0.01 | Trip 5 | 0 | 0.00 |
| *Total* | *6* | <0.01 | *Total* | *10* | *0.01* |
| **Blacktip complex** | | | **Silvertip sharks** | | |
| Trip 1 | 3 | 0.02 | Trip 1 | 0 | 0.00 |
| Trip 2 | 4 | 0.01 | Trip 2 | 0 | 0.00 |
| Trip 3 | 0 | 0.00 | Trip 3 | 1 | <0.01 |
| Trip 4 | 1 | <0.01 | Trip 4 | 0 | 0.00 |
| Trip 5 | 0 | 0.00 | Trip 5 | 0 | 0.00 |
| *Total* | *8* | *<0.01* | *Total* | *1* | *<0.01* |

## *4.2 Drone surveys*

Aerial drone surveys were undertaken to identify the shark species using the shallow lagoonal habitat around North West Island. In addition, underwater drones were trialled on Trip 5 to compare the utility of the method against catch data.

### *4.2.1 Aerial drones*

The aerial drone surveying design used was developed in response to anecdotal reports of lemon sharks being common in the area and being fed by the public, an activity that could have contributed to the 29th of December 2019 incident. Furthermore, the large shallow lagoonal area is prime habitat for several species of rays (batoids) that are known prey for several large shark species such as great hammerheads, lemon sharks, and tiger sharks. Surveys focused on species/life-stages that could be involved in negative shark-human interactions (shark bites, depredation). Small juveniles were therefore not included in the quantitative analysis.

For each survey, a DJI Mavic 3 Cine drone was flown at a height of 70 m around the edge of the whole island when the tide was in the lagoon and the wind speed was not too strong to prevent flying (<25 knots). The height of flights resulted in a ~100 m wide transect from the edge of the island towards the sea. When an animal was sighted, one of the drone's three cameras zoomed in for species identification. For difficult identifications, the drone was dropped to 50 m before returning to 70 m and continuing the transect. Survey times varied between 13 and 20 min (mean: 17 ± 4 min) depending on the number/species of animals observed and wind speed.

***Results:***

**Trip 1.** October 2022: Thirty-two drone surveys were conducted on the first tip, with sharks observed on 12 surveys. Tiger sharks (always as one individual) were observed on three transects, and a juvenile grey reef shark on one, leading to a CPUE of 0.1 ± 0.3 (±SD) sharks per transect. No lemon or great hammerhead sharks were observed. Small blacktip reef shark juveniles were observed in the lagoonal habitat on 10 of the transects, once as a single individual, four times as a group of three, once as a group of five, and four times as a shiver of >5 individuals. Several rays (two transects) and turtles (one transect) were also observed utilising the lagoonal area.

Six additional drone flights were conducted at the southeast beach to investigate large groups of rays observed in the shallows. During this period of biological activity, one small (~40 cm) grey reef shark, three male green sea turtles, sea turtles mating, and reef manta ray courtship behaviour were also observed.

**Trip 2.** February 2023: Many more sharks were observed on Trip 2 when compared to Trip 1. Sharks were recorded on ten out of the 13 surveys, with lemon sharks occurring on all ten surveys, with a CPUE of 2.9 ± 1.7 individuals per transect. Four individuals were observed on eight out of the 10 surveys. One tiger shark, one great hammerhead shark, and one bull shark were also recorded, giving an overall CPUE of 3.2 ± 1.9 sharks that could be involved in negative shark-human interactions per transect. Juvenile blacktip sharks (not included in CPUE calculations) were abundant, with groups of >30 individuals recorded on five surveys. Groups of rays/stingrays were also observed.

**Trip 3.** March 2023: Multiple species were observed on 11 out of the 14 surveys. Lemon sharks occurred on eight surveys, with multiple individuals (up to 17) observed on eight. Bull sharks (as single individuals) occurred in three surveys, juvenile reef sharks in two, and a great hammerhead in one. One wedgefish was also recorded, and rays were common, with cowtail rays, eagle rays and/or shovelnose rays observed on ten surveys. A lemon shark attempting to capture a ray was also observed.

**Trip 4.** August 2023: Due to technical issues no drone surveys were completed during this trip.

**Trip 5.** February 2024: Sharks were observed on 12 out of the 19 drone surveys. Lemon sharks were the most sighted species, occurring on 10 surveys, with a CPUE of 1.4 ± 1.7 ind.transect$^{-1}$. A single individual was recorded in three surveys, and between two and five individuals in seven surveys. This included a lemon shark that was tagged with a satellite tag in February 2023. Tiger sharks were present in three surveys, and a great hammerhead shark in one. The CPUE of sharks that could be involved in negative shark-human interactions was 2.0 ± 1.9 ind.transect$^{-1}$. Groups of rays were observed in all surveys.

**Table 4.** Sharks that could be involved in negative shark-human interactions observed in drone transects. Transects involved flying at 70 m height around the whole island.

| Trip | No. drone transects | No. sharks | CPUE (no.transect$^{-1}$) | Lemon shark CPUE |
|---|---|---|---|---|
| Trip 1 - Oct 2022 | 32 | 4 | 0.1 ± 0.3 | 0.0 |
| Trip 2 - Feb 2023 | 12 | 38 | 3.2 ± 1.9 | 2.9 ± 1.7 |
| Trip 3 - Mar 2023 | 14 | 78 | 5.6 ± 5.4 | 5.5 ± 5.4 |
| Trip 5 - Feb 2024 | 19 | 30 | 1.6 ± 2.0 | 1.4 ± 1.7 |

***Summary of drone surveys:*** Lemon sharks were consistently observed using the shallows around North West Island, and were particularly abundant in March 2023 (Table 4). The use of this shallow habitat was expected, given anecdotal reports of lemon sharks being fed in the shallows.

*4.2.2 Underwater drones: Remote Operated Vehicles*

On Trip 5, Remote Operated Vehicles (ROV) surveys were undertaken to compare the relative abundance of sharks from ROVs with drop line catches. A BlueROV2 equipped with four GoPro cameras was mounted on the top frame to record ~360° video around the ROV. ROV surveys were conducted during daylight hours on the northern side of the island, in the dumping zone. Due to strong prevailing currents, a drift-diving protocol was used in all surveys, where the ROV was launched from a tender vessel, piloted to the seafloor, and maintained at an altitude of ~1–2 m above the substrate. Once positioned, the ROV was oriented to face forward into the current, allowing it to drift passively while the pilot made only minimal adjustments to depth and trim. At the surface, the tender followed the ROV's drift path, while the tether operator ensured sufficient slack to prevent tension that could restrict the ROV's movement or alter its orientation (Figure 4). This method minimised active manoeuvring, conserving battery power and enabling surveys of up to 40 minutes in duration. However, survey time was limited to 30 minutes to avoid overheating of the GoPro cameras during continuous recording. Visibility of ROV cameras was estimated to be ~10 m. However, varied among transects, from ~5–15 m.

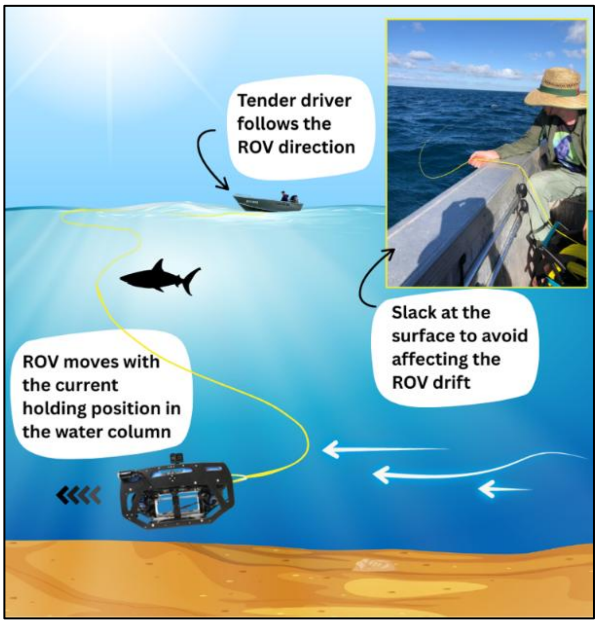


**Figure 4.** Drift diving protocol employed at Northwest Island. While the ROV drifts with the current, the tender follows the ROV, and the tether operator maintains sufficient slack to prevent movement restrictions of the ROV

Overall, 17 elasmobranchs were sighted during 13.3 ROV survey hours, resulting in a sightings per unit effort (SPUE) of 1.27 elasmobranchs per hour (Table 5). In comparison, during the same 5 days, drop lines caught 18 elasmobranchs over 417 hook hours, leading to a CPUE of 0.03 elasmobranchs per hour.

**Table 5.** Elasmobranchs sighted and caught from ROVs and droplines over the five sampling days. Mean SPUE and CPUE (with standard error) are also displayed as the mean values across all separate days of sampling.

| Method | No. sightings /catches | Effort (hrs) | Total SPUE/CPUE | Mean SPUE/CPUE |
|---|---|---|---|---|
| ROV surveys | 17 | 13.3 | 1.27 | $1.54 \pm 1.26$ |
| Dropline catches | 18 | 417 | 0.03 | $0.07 \pm 0.08$ |

Interestingly, the two methods recorded different species (Figure 5). Droplines caught mostly large roving species, such as tiger sharks, great hammerheads, grey reef sharks, and pigeye sharks. In contrast, ROVs sighted mostly ray species, including eagle rays (*Aetobatus narinari*) and Kuhl's maskray (*Neotrygon kuhlii*), along with whitetip reef sharks (*Trianodon obesus*). Grey reef and bull sharks were the only shark species recorded using both methods. These initial results suggest that incorporating both methods will result in a more complete understanding of the elasmobranch community in an area. While catch methods are likely better for quantifying relative abundance of the target species in the context of this project, further testing of ROV methods would be beneficial. Additional transects to increase ROV sample size are particularly warranted given that grey reef, hammerhead, and bull sharks were also sighted on ROV transects (Figure 5).

ROV surveys recorded comparable elasmobranch abundance to dropline methods (Table 5). However, when standardised by sampling effort (hook soak time vs. survey duration), ROVs appear more effective. These promising results, combined with the differential species diversity obtained from the two methods, indicate that integrating both sampling techniques could lead to the most accurate occurrence and abundance information.

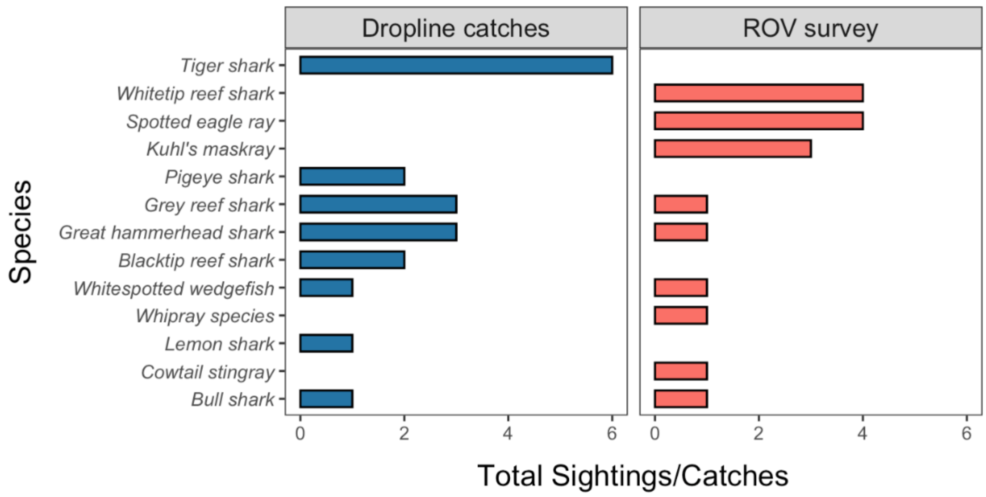


**Figure 5.** Number of elasmobranch catches/sightings in droplines and ROVs over the 5-day sampling period.

### 4.3 Acoustic tracking

#### 4.3.1 Acoustic receivers

Fifteen VR2AR acoustic receivers were deployed at North West Island between 6 and 9 October 2022 (Table 6; Figure 6) to track shark movements. Nine of those receivers were arranged in an 800 × 800 m grid VEMCO Positioning System (VPS) design to triangulate shark positions within the area adjacent to the campsite, which includes the site previously used as a dumping zone, and the main mooring site (Mooring 1). The remaining six were spread out around the North West reef to assess shark movements and residency in the general area. Receivers were strategically placed to cover the protected area (Green Zone), the second mooring site (Mooring 2), and two proposed depredation sites to the east of the island, with the remaining two receivers filling in gaps around the reef.


**Figure 6.** Positions of the 15 VR2AR receivers deployed around North West Island (NWI). The nine VPS receivers 1-9 are indicated in red, and the remaining receivers in yellow. Stars indicate receivers deployed along with the hydrophones. Map source: Google, 2022 CNES/Airbus.

Acoustic receivers were first downloaded on 7 and 8 October 2023. The receiver deployed at Halfway was missing, and the central VPS receiver (VPS-5) was moved ~50 m, suggesting it was dragged by an anchor, possibly from a trawler. The final download and gear retrieval took place on 17 October 2024. Two of the outer line of receivers in the VPS array (VPS-8 & VPS-9) were missing. VPS-9 was found ~300 m away from its deployment location, and VPS-8 could not be located (Table 6). Again, trawler anchors were the most likely reason for the disappearance of this receiver. Due to the loss of the VPS-8 receiver, and the movement of VPS-9, positional estimates of tagged animals in the second year of the study were calculated using seven of the original nine receivers. Due to the redundancy built into the design of the VPS array, the positional accuracy and precision of the array were not compromised.

**Table 6.** Details of the VR2AR receivers deployed around North West Island.

| Station | Receiver ID | Deployment date | Depth (m) | Latitude | Longitude | Sound trap no. |
|---|---|---|---|---|---|---|
| Green zone | 552734 | 6/10/2022 | 15 | -23.3152 | 151.7074 | |
| South side | 552739 | 6/10/2022 | 18 | -23.3166 | 151.7406 | |
| Fish tail - South | 552735 | 6/10/2022 | 10 | -23.3045 | 151.8113 | 6971 |
| Fish tail - North | 552736 | 7/10/2022 | 14 | -23.2690 | 151.8419 | 6959 |
| Halfway* | 552741 | 7/10/2022 | 14 | -23.2790 | 151.7516 | |
| Mooring | 552740 | 7/10/2022 | 10 | -23.2820 | 151.7192 | 6955 |
| VPS-1 | 552737 | 09/10/22 | 7 | -23.2939 | 151.6959 | |
| VPS-2 | 552738 | 09/10/22 | 7 | -23.2908 | 151.6984 | |
| VPS-3 | 552742 | 09/10/22 | 7 | -23.2880 | 151.7009 | |
| VPS-4 | 552743 | 09/10/22 | 11 | -23.2916 | 151.6929 | |
| VPS-5** | 552744 | 09/10/22 | 12 | -23.2886 | 151.6956 | 6970 |
| VPS-6 | 552745 | 09/10/22 | 13 | -23.2859 | 151.6979 | |
| VPS-7 | 552746 | 09/10/22 | 15 | -23.2894 | 151.6900 | |
| VPS-8*** | 552747 | 09/10/22 | 17 | -23.2864 | 151.6924 | |
| VPS-9**** | 552748 | 09/10/22 | 24 | -23.2838 | 151.6946 | |

*Receiver missing during first deployment period (Oct 22-Oct 23)
**Receiver moved 30-50m in first deployment period (Oct 22-Oct-23)
***Receiver missing during the second deployment period (Oct 23-Oct 24)
**** Receiver moved ~300m during second deployment period (Oct 2023).

### *4.3.2 Acoustic tagging*

Acoustic transmitters (VEMCO V16H with 10-year battery lives, set to emit a signal every 90-150 s) were surgically implanted into the peritoneal cavity of sharks (see Barnett 2022 for methods). Tagging focused on species involved in negative shark-human interactions (shark bites, depredation). In total, 128 sharks from 10 species were acoustically tagged over the five trips (Table 7). Of those, 117 were detected at North West Island on subsequent days (days detected per individual varied between 1 and 166). In addition, 51 sharks tagged in other projects were also detected at North West Island (Table 8), bringing the total to 168 sharks detected, from six projects. Over the same time period, 107 sharks were detected by receivers deployed at Heron and One Tree Islands, ~27 and ~45 km away, respectively (see Figure 7): 47 from our project, and 60 from other projects (Table 8).

**Table 7.** Species composition and size range of sharks tagged with acoustic transmitters throughout this project.

| Species | Size range (cm TL) | No. sharks tagged |
|---|---|---|
| Tiger sharks | 97–420 | 53 |
| Grey reef sharks | 117–180 | 16 |
| Bull sharks | 202–315 | 13 |
| Sandbar sharks | 179–208 | 10 |
| Blacktip reef sharks | 134–161 | 9 |
| Blacktip complex | 176–261 | 8 |
| Pigeye sharks | 212–247 | 10 |
| Lemon sharks | 225–271 | 5 |
| Great hammerheads | 274–300 | 3 |
| Spot-tail sharks | 115 | 1 |
| | **Total** | **128** |

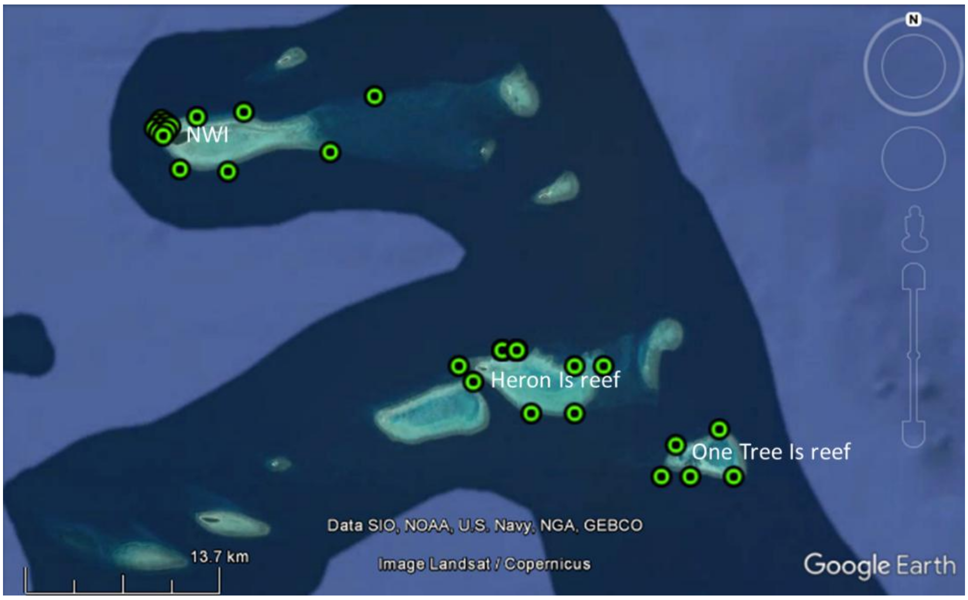


**Figure 7.** Map of the North West, Heron and One Tree Island acoustic arrays, showing the receivers (green dots) deployed for the duration of the present study. The Heron and One Tree Island arrays are managed by the Integrated Marine Observing System (IMOS).

**Table 8.** Number of sharks from different tagging projects detected by the North West Island (NWI) array and the Heron/One Tree Island array during this project (October 2022 to Oct 2024).

| Project/Species | NWI | Heron/One Tree Is |
|---|---|---|
| **NWI Shark Behaviour** | | |
| Tiger sharks | 49 | 34 |
| Bull sharks | 13 | 8 |
| Pigeye sharks | 10 | 0 |
| Sandbar sharks | 9 | 0 |
| Lemon sharks | 5 | 0 |
| Blacktip complex | 6 | 2 |
| Great hammerhead sharks | 3 | 3 |
| Grey reef sharks | 14 | 0 |
| Blacktip reef sharks | 8 | 0 |
| Spot-tail sharks | 0 | 0 |
| **Norfolk Island Project (Flinders University)** | | |
| Tiger sharks | 1 | 1 |
| **NSW DPI - Movements of Coastal Sharks** | | |
| Bull sharks | 7 | 3 |
| **NSW DPI - Whaler, White and Tiger Shark Program** | | |
| Bull sharks | 11 | 14 |
| Tiger sharks | 5 | 16 |
| White sharks | 10 | 8 |
| Sandbar sharks | 1 | 0 |
| **Sunshine Coast Bull Shark Program (UniSC)** | | |
| Bull sharks | 1 | 0 |
| **IMOS/AIMS Acoustic Telemetry Array Queensland** | | |
| Bull sharks | 8 | 9 |
| Tiger sharks | 4 | 4 |
| Pigeye sharks | 1 | 1 |
| Lemon sharks | 2 | 2 |
| Great hammerhead sharks | 0 | 1 |
| **Biopixel Oceans Foundation** | | |
| Bull sharks | 0 | 1 |
| **TOTAL** | **168** | **107** |

### *4.3.3 Use of North West Island*

For most species, the dumping zone (represented by VPS-5, the receiver at the centre of the VPS) was the most used site, followed by the Mooring site, with both sites often containing >50% of a species' detection days (Figure 8). The Green Zone was also significantly used (~20–25% of days) by all species. Tiger sharks and great hammerheads used the area more broadly, moving throughout the different sites. Pigeye sharks, grey reef sharks and sandbar sharks, however, seemed to remain mostly in the proximity of the dumping zone and the Mooring 2 site, moving less frequently to other areas (Figure 8).

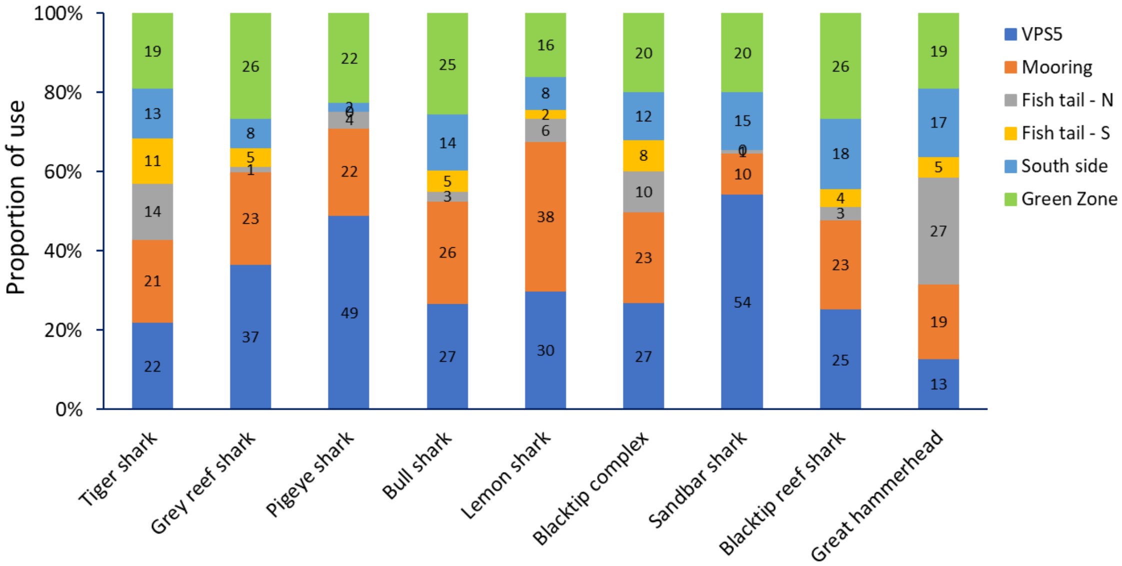


**Figure 8.** Proportion of days each species was detected at each site (based on the sum of the total days each individual shark was detected by a receiver, for each species). VPS-5, the receiver at the centre of the VPS, was considered representative of dumping site use. The 'Halfway' receiver was lost after the first year, so its data are not shown. Numbers within boxes show the proportion of use of the respective receiver.

Residency index (RI) to North West Island was calculated for each individual, as the proportion of days each individual was detected in the North West Island array, in relation to the number of days it was monitored (i.e. from the tagging date until 17 October 2024), so that a value of 100% means the shark was detected every day, and 0% means the shark was not detected after tagging. For each species, RI was calculated as the average RI from all individuals.

Mean RI values were low for all species (Table 9; Figure 9). Blacktip reef sharks had the highest mean RI (13.9 ± 8.9%), and the one spot-tail shark tagged the lowest, as it was only detected on the day it was tagged (up to 45 minutes after tagging). If we do not consider that spot-tail individual, data shows that bull sharks had the lowest mean RI of 2.7 ± 3.5%. Bull sharks also had the lowest maximum RI value, of only 12.2% (Table 9), suggesting individuals do not remain in the North West Island region for long periods of time. In contrast, the closely related pigeye sharks were one of the species with the highest residency (13.2 ± 7.3%), and were not detected at Heron Island (Table 9). There was substantial intra-specific variation in residency to North West Island for most species (Table 9; Figure 9).

Forty-seven sharks were also detected at Heron and One Tree Islands, mostly tiger sharks (34 individuals), but also bull sharks (8), great hammerheads (3) and blacktip complex (2) (Table 9). Residency indices were also calculated for receivers at Heron Island and One Tree Island,

and results show that sharks tagged at North West Island had low RIs, and did not spend much time at Heron/One Tree Islands (Table 9). With the exception of one pigeye shark individual, blacktip reef sharks, grey reef sharks, and pigeye sharks were not detected at Heron Island or at any other receivers along the Queensland coast (Figure 9; Figure S1), suggesting these species have smaller home ranges. This is somewhat in conflict with their relatively low RI values (Table 9), suggesting that the low RI values are because the animals move out of range of receiver coverage, but remain within the broader area around North West Island. Alternatively, larger movements could have been conducted to areas with no receiver coverage. The same could be assumed for lemon and sandbar sharks. However, satellite tracking shows that these species move considerable distances away from North West Island (see satellite tracking section below), and sandbar sharks are seasonal visitors to North West Island (Figure 11).

**Table 9.** Residency index (RI, in %) of sharks tagged at North West Island and at other sites (from other projects), to the North West Island and Heron/One Tree arrays.

| | North West Is | | | Heron/One Tree Is | | |
|---|---|---|---|---|---|---|
| **Species** | ***n*** | **mean ± SD** | **range** | ***n*** | **mean ± SD** | **range** |
| ***Sharks tagged at NWI*** | | | | | | |
| Tiger sharks | 53 | 7.9 ± 7.2 | 0.2 – 22.3 | 34 | 1.8 ± 2.4 | 0.1 – 10.4 |
| Bull sharks | 13 | 2.7 ± 3.5 | 0.2 – 12.2 | 8 | 2.0 ± 1.9 | 0.2 – 5.5 |
| Blacktip complex | 8 | 5.4 ± 4.8 | 0.1 – 13.0 | 2 | 0.4 ± 0.2 | 0.2 – 0.5 |
| Great hammerheads | 3 | 10.9 ± 5.4 | 6.8 – 17.0 | 3 | 5.5 ± 5.0 | 0.9 – 10.8 |
| Pigeye sharks | 10 | 13.2 ± 7.3 | 0.4 – 23.2 | | | |
| Lemon sharks | 5 | 11.7 ± 3.4 | 6.9 – 16.0 | | | |
| Grey reef sharks | 16 | 11.2 ± 9.6 | 0.2 – 23.7 | | | |
| Blacktip reef sharks | 9 | 13.9 ± 8.9 | 0.1 – 24.5 | | | |
| Sandbar sharks | 10 | 11.8 ± 6.5 | 0.2 – 20.7 | | | |
| Spot-tail sharks | 1 | 0.0 | 0.0 | | | |
| ***Sharks tagged at other sites*** | | | | | | |
| Bull sharks | 27 | 0.5 ± 1.4 | 0.1 – 7.6 | 27 | 0.2 ± 0.1 | 0.1 – 0.7 |
| Tiger sharks | 10 | 0.2 ± 0.1 | 0.1 – 0.5 | 21 | 0.3 ± 0.2 | 0.1 – 1.2 |
| White sharks | 10 | 0.2 ± 0.1 | 0.1 – 0.3 | 8 | 0.2 ± 0.0 | 0.1 – 0.3 |
| Lemon sharks | 2 | 0.1 ± 0.0 | 0.1 – 0.1 | 2 | 0.1 ± 0.0 | 0.1 |
| Pigeye sharks | 1 | 0.2 ± 0.1 | 0.1 – 0.3 | 1 | 0.3 | 0.3 |
| Sandbar sharks | 1 | 0.1 | 0.1 | | | |
| Great hammerhead | | | | 1 | 0.1 | 0.1 |


**Figure 9**. Timeline showing the days each acoustically tagged shark was detected by the North West Island array (all receivers combined) and by receivers from other projects. Numbers to the right of the figure are residency indices to North West Island, as the percentage of days an individual was detected, from its tagging date to the end of the study period (days at liberty). NDAT = not detected after tagging. Gray boxes indicate the periods when the island was closed to the public.

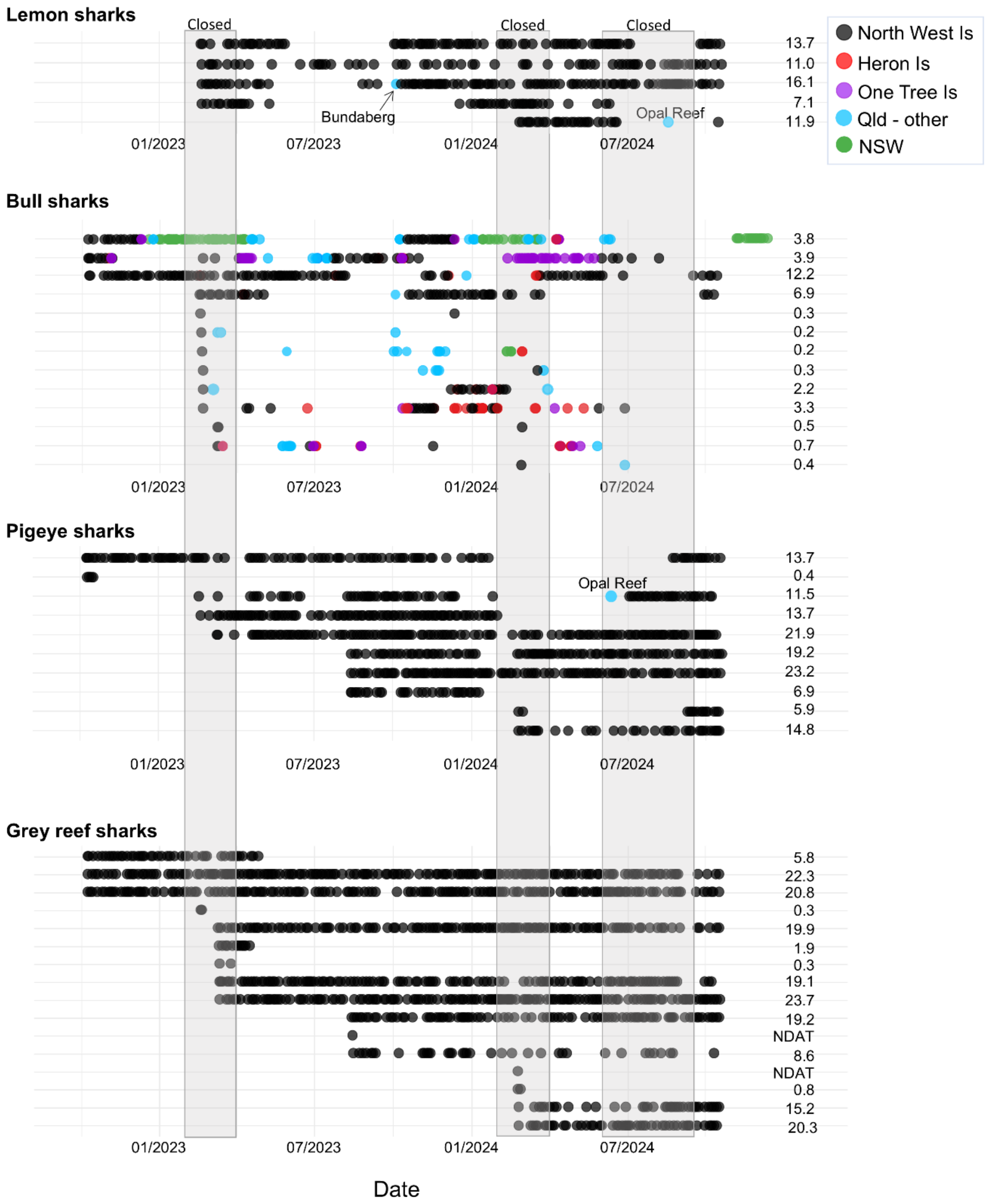


**Figure 9 (cont.)** Timeline showing the days each acoustically tagged shark was detected by the North West Island array (all receivers combined) and by receivers from other projects. Numbers to the right of the Figure are residency index to North West Island, as the percentage of days an individual was detected, from its tagging date to the end of the study period (days at liberty). NDAT = not detected after tagging. Gray boxes indicate the periods when the island was closed to the public.

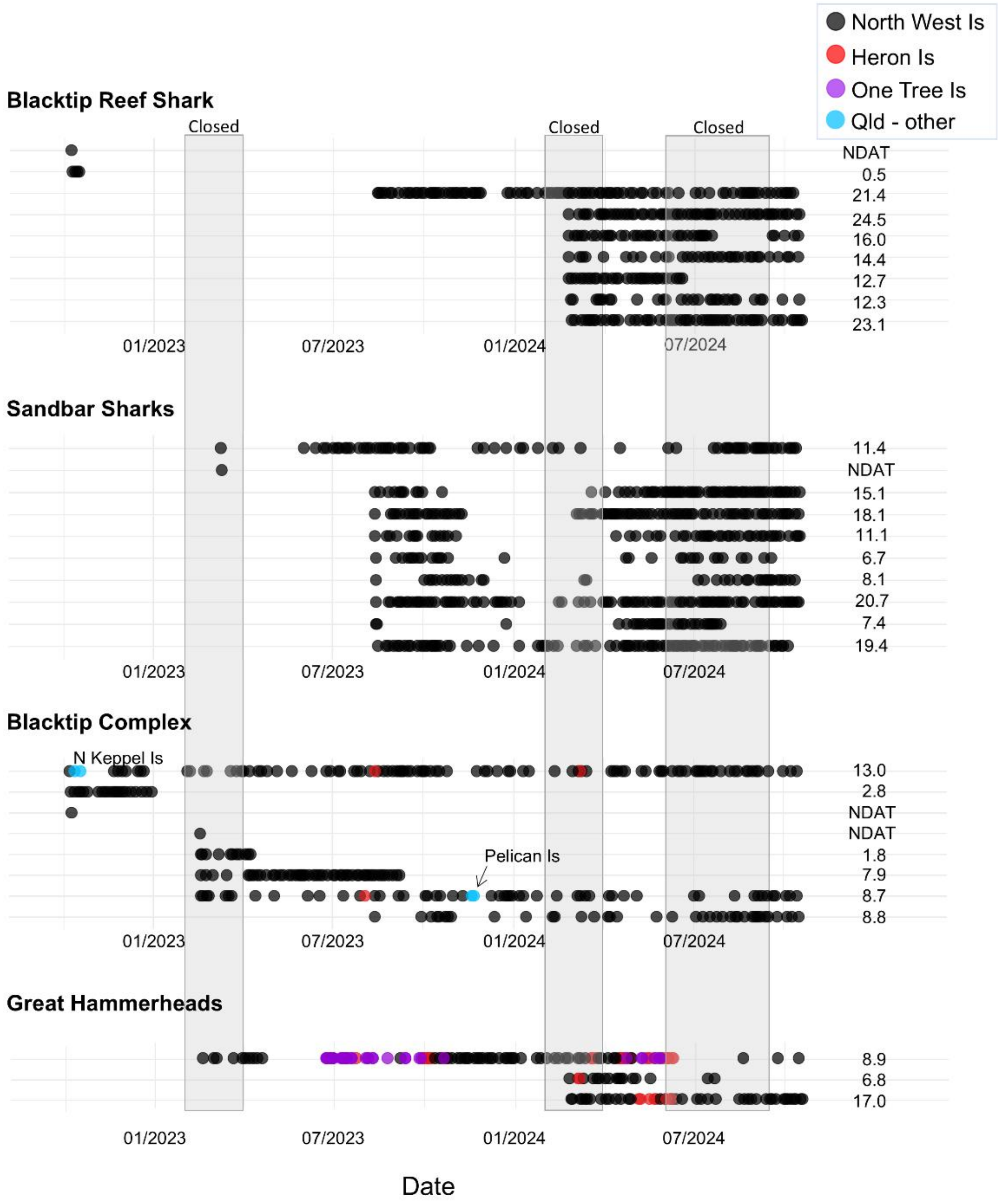


**Figure 9 (cont.)**. Timeline showing the days each acoustically tagged shark was detected by the North West Island array (all receivers combined) and by receivers from other projects. Numbers to the right of the Figure are residency index to North West Island, as the percentage of days an individual was detected, from its tagging date to the end of the study period (days at liberty). NDAT = not detected after tagging. Gray boxes indicate the periods when the island was closed to the public.

To analyse the seasonal use of North West Island, rose diagrams were constructed. These show the number of days per month a shark was present, as well as the number of individuals detected each day. This analysis was based on the 108 sharks that were tagged before 10 October 2023 (i.e. that could have been tracked for one whole year), while considering only their first year of data, to avoid pseudo-replication.

Results show that sharks use North West Island throughout the year, although numbers are slightly lower in the colder months, between June and September (Figure 10 and Figure **11**). The different species showed different seasonal patterns of area use (Figure 11 and Figure **S2**). Tiger sharks occurred throughout the year, but in lower numbers between June and August. Bull sharks were mostly detected between October and February, with very few animals detected per day between April and September. Sandbar sharks had the opposite pattern, with more detections between May and October, and very few in January–February. Grey reef sharks occurred throughout the year, with one peak in November–December, and another in March. Pigeye sharks also occurred throughout the year, but in higher numbers between August and December (Figure 11). This temporal analysis was not conducted for the remaining species as few individuals were monitored for at least one whole year.

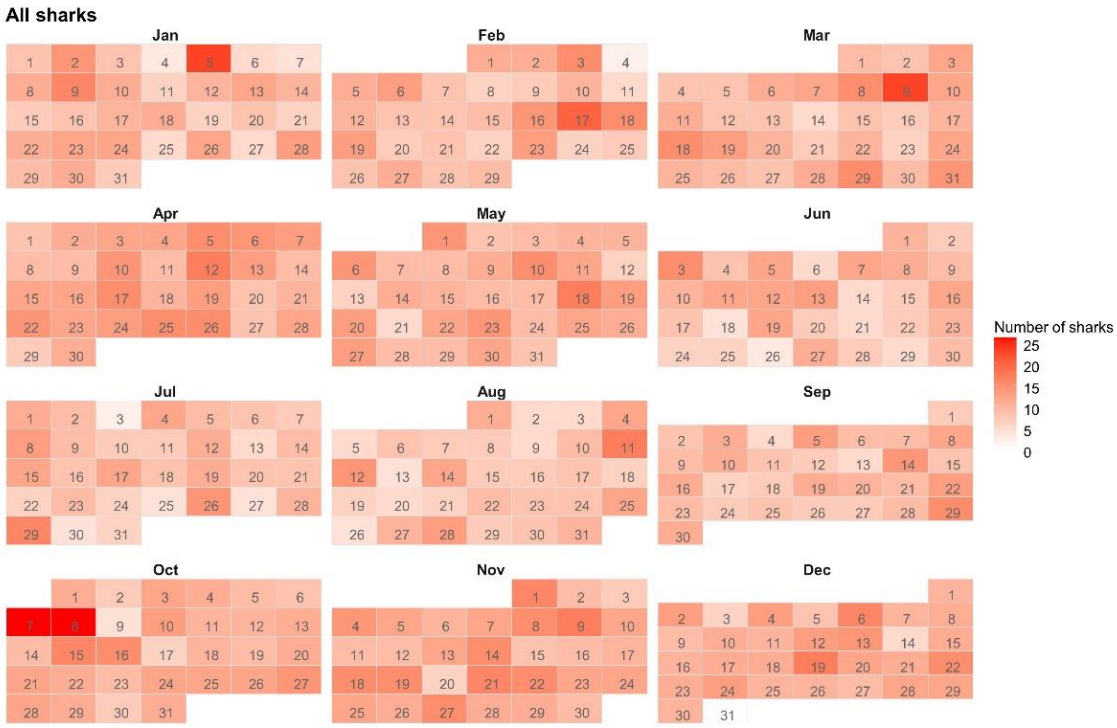


**Figure 10.** Number of tagged sharks detected per calendar day. Only sharks with at least one whole year of tracking data were included and, for each individual, only their first year of tracking data was considered to avoid pseudo-replication.

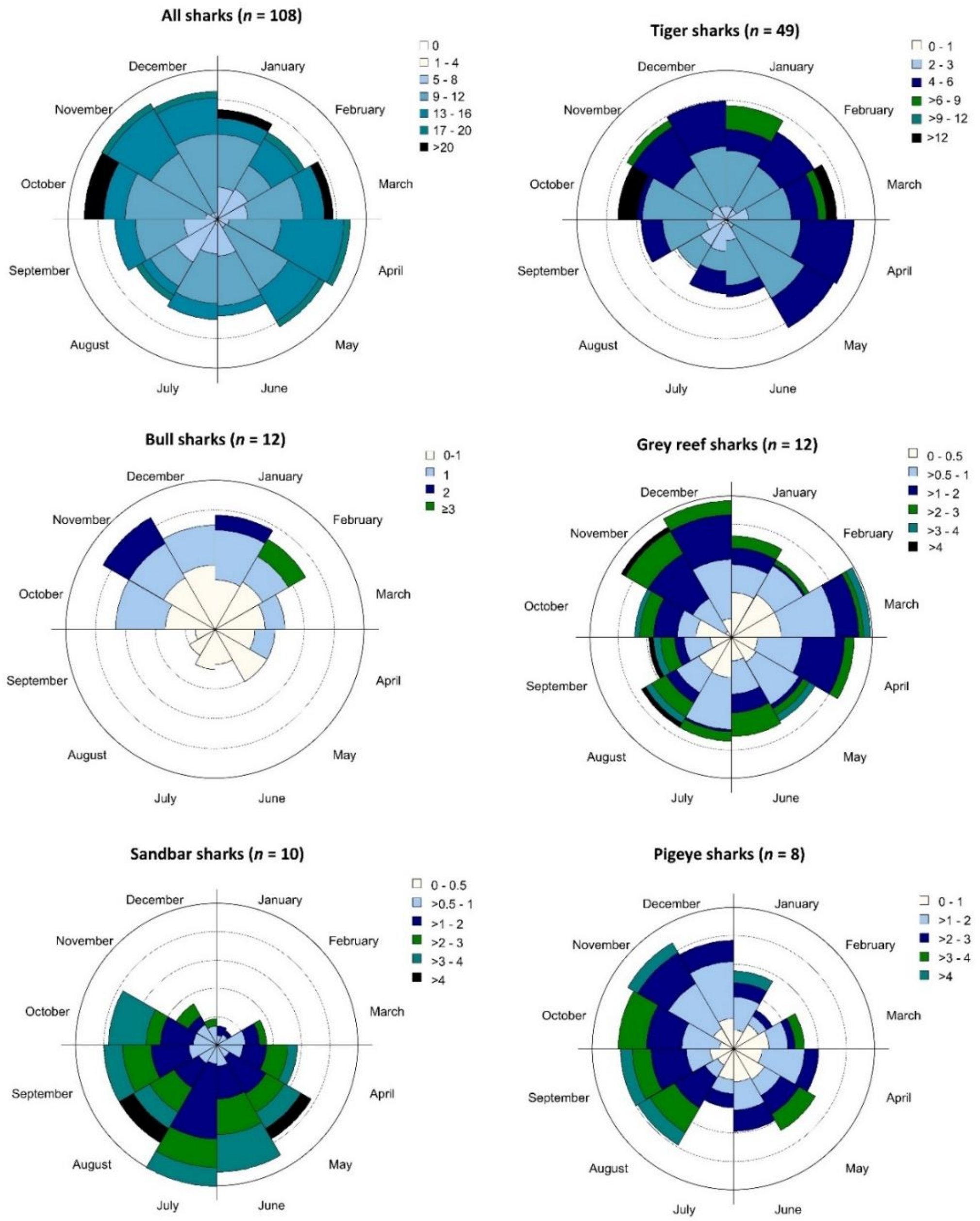


**Figure 11.** Rose diagrams showing the seasonal use of North West Island throughout the year by all sharks tagged and by species. Only sharks for which at least one whole year of tracking data were available were considered. For each individual, only their first year of tracking data was considered to avoid pseudo-replication.

### *4.3.4 Long distance movements*

Five of the species tagged at North West Island were also detected outside the Capricorn Bunker Region, by receivers from other projects, both in Queensland and New South Wales: tiger sharks, bull sharks, pigeye sharks, lemon sharks, and the blacktip complex (Figure 12) (see Figure S1 for receiver coverage in Queensland waters). Tiger sharks were mostly detected at locations south of North West Island, with two individuals detected as far south as

Narooma (NSW), >1,500 km away, and as far north as the Whitsundays, ~400 km away (Figure 12). Bull sharks moved south as far as Ballina, almost 700 km away, and ~1,300 km north to Davie Reef, off Cape Melville. One of the lemon sharks was detected off Bundaberg, and the other at a receiver in Opal Reef, ~1,000 km north. The pigeye shark was also detected at Opal Reef (Figure 12). The two blacktip complex individuals that were detected at other receivers made smaller movements, to the Keppel Islands, ~85 km away.

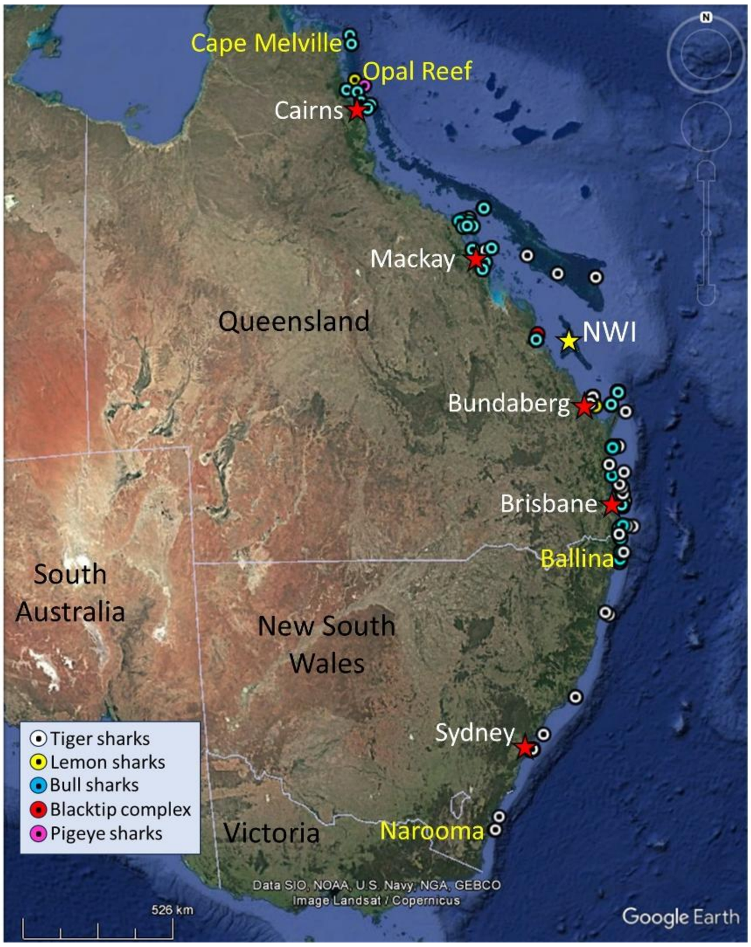


**Figure 12.** Locations where sharks acoustically tagged at North West Island were detected by receivers from other projects. When different species were detected in the same area (e.g. at Opal Reef), symbols were offset to allow for visualisation of presence of both species.

Fifty-one individuals tagged through other projects were also detected at North West Island, and 60 at Heron/One Tree Islands (Table 9 and Table **10**). In general, those sharks were only detected over one (RI = 0.1%) or two days (RI = 0.3%), indicating that North West Island is not a major site of interest. The only exception was a bull shark tagged at Moreton Bay that was detected over 56 days (RI = 7.6%), between April and July 2024, at North West Island (Table

10). This matches the common seasonal patterns of bull sharks moving south in summer and north for winter (Heupel et al. 2015, Lubitz et al. 2023). Interestingly, all other sharks were mainly detected on single days at a time as they passed by North West Island (Table 10), suggesting that North West Island may be on migration routes for several species and/or some individuals may be using the wider Capricorn Bunker Group for periods of the year.

**Table 10**. Sharks tagged at distant locations (>400 km) through other projects and subsequently detected at North West Island during the study period, including number of days detected and dates of detection. Minimum distances to North West Island (NWI) are approximate. Individuals that were detected more than one day are in bold. IMOS/AIMS QATA – IMOS/AIMS Queensland Acoustic Telemetry Array; NSW DPI WWTSP = NSW DPI Whaler, White and Tiger Shark Program; NSW DPI MCS = NSW DPI Movements of Coastal Sharks project; UniSC CBSP = University of Sunshine Coast Bull Shark Program.

| Species/Tagging area | Min dist. from NWI (km) | Date tagged | No. days & month at NWI | Project |
|---|---|---|---|---|
| **Tiger sharks** | | | | |
| Batt Reef | ~1,000 | 18/09/22 | 1 (Nov 23) | IMOS/AIMS ATAQ |
| Coffs Harbour | ~870 | 30/01/18 | 1 (Aug 23) | NSW DPI WWTSP |
| Sydney | ~1,330 | 09/05/19 | 1 (Oct 23) | NSW DPI WWTSP |
| Sutherland | ~1,345 | 02/01/23 | 1 (Oct 23) | NSW DPI WWTSP |
| Kingscliff | ~630 | 17/09/23 | **2 (Mar & Sept 24)** | NSW DPI WWTSP |
| Ballina | ~700 | 23/07/19 | 1 (Dec 24) | NSW DPI WWTSP |
| Angourie | ~770 | 27/07/23 | 1 (Jan 24) | NSW DPI WWTSP |
| Norfolk Island | ~1,750 | 19/02/20 | 1 (Dec 23) | Norfolk Is Project |
| **Bull sharks** | | | | |
| Palm Islands | ~760 | 20/09/21 | 1 (Mar 23) | IMOS/AIMS QATA |
| Crocodile Creek | ~700 | 15/05/21 | 1 (Dec 23) | IMOS/AIMS QATA |
| Whitsundays | ~430 | 12/12/19 | 1 (Mar 23) | IMOS/AIMS QATA |
| Whitsundays | ~430 | 09/06/19 | **2 (Apr & Jun 24)** | IMOS/AIMS QATA |
| Maroochydore River | ~450 | 23/01/20 | 1 (May 23) | UniSC CBSP |
| Moreton Bay | ~540 | 15/11/22 | 1 (Jul 24) | IMOS/AIMS QATA |
| Moreton Bay | ~540 | 05/12/21 | **56 (Apr - Jul 24)** | IMOS/AIMS QATA |
| Moreton Bay | ~540 | 04/12/21 | 1 (Mar 23) | IMOS/AIMS QATA |
| Moreton Bay | ~540 | 30/11/21 | 1 (May 23) | IMOS/AIMS QATA |
| Hastings Point | ~620 | 09/02/22 | **3 (Sept & Oct 24)** | NSW DPI WWTSP |
| Ballina | ~700 | 29/11/17 | **2 (Nov 22; Dec 23)** | NSW DPI WWTSP |
| Ballina | ~700 | 06/07/23 | 1 (Dec 23) | NSW DPI WWTSP |
| Ballina | ~700 | 04/02/16 | 1 (Dec 22) | NSW DPI - MCS |
| Evans Head | ~730 | 29/03/23 | 1 (Jul 24) | NSW DPI WWTSP |
| Evans Head | ~730 | 11/01/22 | 1 (Jun 23) | NSW DPI WWTSP |
| Evans Head | ~730 | 21/01/21 | 1 (Sept 23) | NSW DPI WWTSP |
| Sawtell | ~850 | 15/02/22 | 1 (May 24) | NSW DPI WWTSP |
| Angourie | ~770 | 09/01/24 | 1 (Feb 24) | NSW DPI WWTSP |
| Belligen River | ~890 | 20/11/17 | 1 (May 24) | NSW DPI WWTSP |
| Croki (Manning R) | ~1,060 | 13/12/16 | 1 (May 23) | NSW DPI WWTSP |
| Tuncurry | ~1,080 | 06/03/24 | **3 (Jul, Aug 24)** | NSW DPI WWTSP |
| Sydney | ~1,330 | 20/03/19 | 1 (Jun 24) | NSW DPI MCS |
| Sydney | ~1,330 | 05/03/19 | **3 (Dec 23)** | NSW DPI MCS |
| Sydney | ~1,330 | 30/01/19 | 1 (Dec 22) | NSW DPI MCS |
| Sydney | ~1,330 | 29/01/19 | 1 (Jun 24) | NSW DPI MCS |
| Sydney | ~1,330 | 15/02/18 | 1 (Dec 22) | NSW DPI MCS |
| Sydney | ~1,330 | 03/03/16 | **3 (Dec 22, Apr 23, Mar 24)** | NSW DPI MCS |

**Table 10 (cont.)** Sharks tagged at distant locations (>400 km) through other projects and subsequently detected at North West Island during the study period, including number of days detected and dates of detection. Minimum distances to North West Island (NWI) are approximate. Individuals that were detected more than one day are in bold. IMOS/AIMS QATA – IMOS/AIMS Queensland Acoustic Telemetry Array; NSW DPI WWTSP = NSW DPI Whaler, White and Tiger Shark Program; NSW DPI MCS = NSW DPI Movements of Coastal Sharks project; UniSC CBSP = University of Sunshine Coast Bull Shark Program.

| Species/Tagging area | Min dist. from NWI (km) | Date tagged | No. days & month at NWI | Project |
|---|---|---|---|---|
| **White sharks** | | | | |
| Ballina | ~700 | 27/08/20 | 1 (Aug 23) | NSW DPI WWTSP |
| Ballina | ~700 | 18/12/18 | 1 (Dec 22) | NSW DPI WWTSP |
| Ballina | ~700 | 06/10/17 | **2 (Aug 24)** | NSW DPI WWTSP |
| Ballina | ~700 | 07/10/21 | 1 (Jan 23) | NSW DPI WWTSP |
| Ballina | ~700 | 26/08/21 | 1 (Jul 24) | NSW DPI WWTSP |
| Evans Head | ~730 | 02/10/21 | 1 (Jul 23) | NSW DPI WWTSP |
| Coffs Harbour | ~870 | 10/07/22 | **2 (Jul 24)** | NSW DPI WWTSP |
| Lennox Head | ~680 | 23/12/21 | 1 (Nov 22) | NSW DPI WWTSP |
| Port Macquarie | ~990 | 10/10/22 | 1 (Apr 23) | NSW DPI WWTSP |
| Tuncurry | ~1,080 | 11/12/21 | 2 (Feb 23) | NSW DPI WWTSP |
| **Lemon sharks** | | | | |
| Moreton Bay | ~540 | 19/05/22 | **2 (Aug & Sept 23)** | IMOS/AIMS QATA |
| Moreton Bay | ~540 | 02/12/21 | 1 (Oct 22) | IMOS/AIMS QATA |
| **Sandbar shark** | | | | |
| Coffs Harbour | ~870 | 08/04/13 | 1 (Dec 22) | NSW DPI WWTSP |
| **Pigeye shark** | | | | |
| Brisbane | ~530 | 31/10/21 | **2 (Jul & Aug 24)** | IMOS/AIMS QATA |

## *4.4 Satellite tracking*

Eleven individuals were tagged with satellite transmitters during this project: four lemon sharks, three tiger sharks, three great hammerhead sharks and one pigeye shark, all adults (Table 11). Two additional adult tiger sharks were previously tagged in March 2021 as part of a pilot study for DETSI. Additionally, we also include three tiger sharks (one adult and two juveniles) that were satellite tagged in 2020 and 2021 (Table 11) by Biopixel Oceans Foundation at Lady Elliot Island, Capricorn Bunker Group, in our analyses.

**Table 11**. Details of the sharks tagged with satellite transmitters through the present project, as well as tiger sharks tagged as part of a pilot study conducted prior to the beginning of the project(P), and at Lady Elliot Island (LEI). Maturity indicates if the individual was tagged as an adult (A) or juvenile (J). NDAT = not detected after tagging.

| Species | Sex | TL (cm) | Mat. | Tagging date | Last detect. | No. days tracked | Dist. moved (km) |
|---|---|---|---|---|---|---|---|
| Lemon shark | F | 268 | A | 17/02/23 | 19/02/24 | 367 | 3,496 |
| Lemon shark | F | 266 | A | 18/02/23 | 25/04/24 | 432 | 2,677 |
| Lemon shark | M | 225 | A | 18/02/23 | 03/04/24 | 410 | 1,111 |
| Lemon shark | M | 271 | A | 24/02/24 | 24/10/24 | 243 | 3,598 |
| Tiger shark (LEI) | F | 350 | A | 14/01/20 | 17/05/20 | 124 | 1,428 |
| Tiger shark (LEI) | M | 277 | J | 26/08/21 | 21/11/22 | 452 | 6,568 |
| Tiger shark (LEI) | F | 300 | J | 26/08/21 | 18/09/22 | 388 | 6,701 |
| Tiger shark (P) | F | 383 | A | 16/03/21 | 24/02/22 | 345 | 6,537 |
| Tiger shark (P) | F | 376 | A | 16/03/21 | 05/01/22 | 295 | 4,250 |
| Tiger shark | F | 356 | A | 08/10/22 | 06/10/23 | 363 | 5,547 |
| Tiger shark | F | 369 | A | 08/10/22 | 08/05/23 | 212 | 5,803 |
| Tiger shark | F | 379 | A | 09/10/22 | 09/07/23 | 273 | 13,186 |
| Great hammerhead | F | ~300 | A | 17/02/23 | 06/01/24 | 323 | 6,043 |
| Great hammerhead | M | 285 | A | 23/02/24 | 24/11/24* | 275 | 2,719 |
| Great hammerhead | F | 274 | A | 26/02/24 | 25/11/24* | 273 | 1,004 |
| Pigeye shark | F | 259 | A | 09/10/22 | NDAT | 0 | - |

* Tags still transmitting at the time of reporting.

### *4.4.1 Lemon sharks*

From the three individuals satellite tagged in February 2023, one was tracked for exactly one year, until February 2024, and two until April 2024 (when transmissions stopped). The two females remained at North West Island until May 2023, then moved north for the cooler months before returning to North West Island in late August/September (green and yellow tracks in Figure 13a,c). They then remained around North West Island until their last detection. Note that acoustic tracking recorded another absence from North West Island around July and mid-August 2024 (see yellow timeline in Figure 13c), when the satellite tag was no longer transmitting. The third shark, a male just above size at maturity of 220 cm TL (Last & Stevens 2009), remained in the Capricorn Bunker region throughout its 14-month tracking period, spending significant time at Tryon and North West Islands (see pink track in Figure 13a). Acoustic tracking data confirm that this individual remained in the area until the end of the study (Figure 13c).

The fourth lemon shark, a 271 cm male tagged in February 2024, remained around North West Island until June, then swam ~1,000 km north to reefs off Port Douglas, where it stayed for two months before starting to move south in September 2024, to arrive back at North West Island in October 2024 (see red track in Figure 13a). Acoustic detections aligned with this movement: after tagging, this individual was regularly detected by North West Island receivers until June, after which it was only detected in August at Opal Reef (for one day only), and was detected back at North West Island in October 2024 (Figure 13c). Interestingly, the three larger animals that moved did so using the outer reef (Figure 13a).

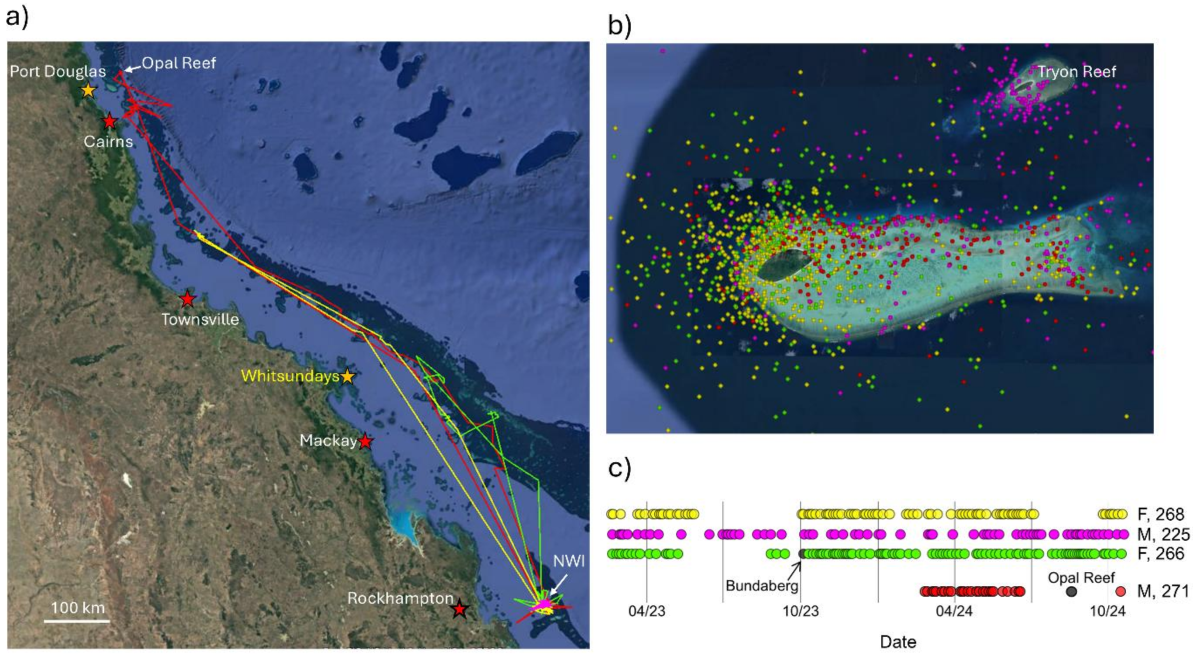


**Figure 13.** a) Satellite tracks of the four satellite tagged lemon sharks, from their tagging date in February 2023 to 30 November 2024; b) zoomed-in view of the satellite-derived locations around North West Island; c) timeline showing the days each individual was detected by the North West Island array, along with size and sex information. Each individual is represented by the same colour in a), b) and c).

### *4.4.2 Tiger sharks*

Tiger sharks showed very different movement patterns and scales. From the five individuals tagged at North West Island, two remained in the Central Queensland region (white and yellow tracks in Figure 14a); two moved >500 km north before returning to North West Island (Figure 14b); while one made a long distance migration throughout the South West Pacific in less than one year (Figure 14c). Individual variability in movement patterns is not uncommon for tiger sharks (e.g. Fitzpatrick et al. 2012; Meyer et al. 2009, Niella et al. 2022).

Two mature females conducted localised movements characterised by using North West Island as a central location, and undertaking forays up to 280 km (yellow and white tracks in Figure 14a). Another mature female moved 680 km north to reefs off Townsville immediately after tagging (October 2022), where it remained for ~2 weeks, before swimming back south to the North West Island region (green track in Figure 14b). The fourth mature female, tagged in March 2021, also moved away after tagging, and swam north, almost reaching the tip of Cape York, >1,600 km away, in June (red track in Figure 14b). This shark then moved south again, moving through the Capricorn Bunker Group, but did not visit North West Island again.

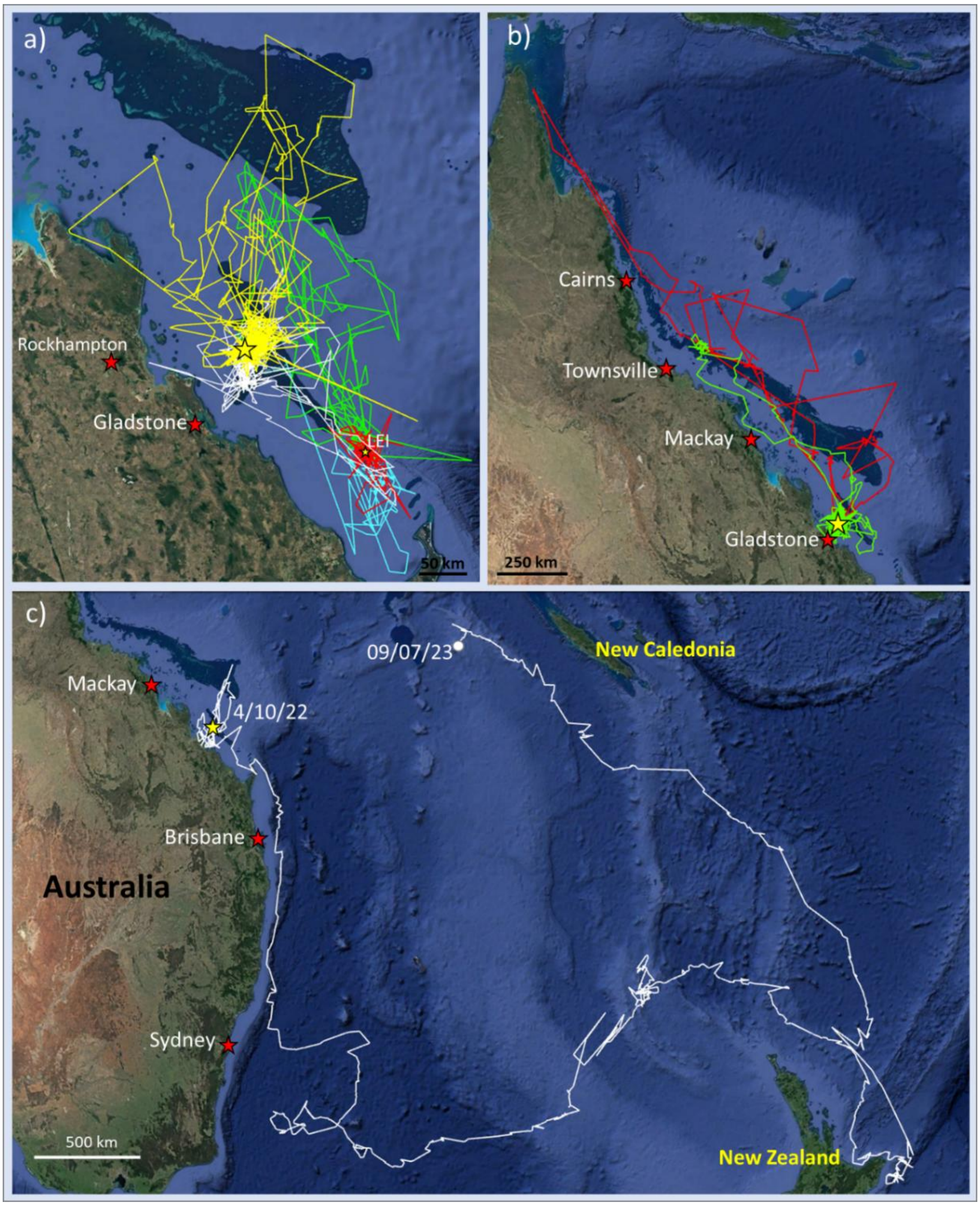


**Figure 14.** Satellite tracks of the eight satellite tracked tiger sharks satellite tagged, including sharks that remained in the tagging region throughout the study period (white and yellow tracks in a), sharks that moved to North and Far North Queensland before returning to the southern GBR (b), and an individual that conducted a large-scale movement of ~13,200 km (c). Tracks of the three tiger sharks tagged at Lady Elliot Island (LEI) (blue, red and green tracks) are also shown in a).

The fifth tiger shark, a mature female, made the most impressive movements, travelling ~13,200 km in one year (Figure 14c). This shark, tagged in October 2022, remained in the Capricorn Bunker region for ~2 months after tagging, and then moved south to the waters off Sydney, then east into the Tasman Sea, visited the north coast of New Zealand in April/May, then moved north to the Coral Sea where it was last detected in October 2023.

Among the individuals tagged at Lady Elliot Island, a mature female was only tracked for 124 days, during which its activity was centred at the Island, moving up to ~75 km away but regularly returning to Lady Elliot Island (red track in Figure 14a). An immature male also had its activity centred around Lady Elliot Island, although it made larger-scale forays (up to 280 km away to the edge of the Swain Reefs) before regularly returning to Lady Elliot Island (green track in Figure 14a). The third individual, an immature female moved between Lady Elliot Island and Hervey Bay, ~110 km south (blue track in Figure 14a). Interestingly, although Lady Elliot Island is only ~140 km south of North West Island, none of these individuals were detected near North West Island. Acoustic data confirm the lack of use of the area, as only one shark was detected by acoustic receivers at the dumping site, and only on one day.

### *4.4.3 Great hammerhead sharks*

Of the three great hammerheads tagged, the ~300 cm female tagged in February 2023 made a round-trip of at least 6,000 km (see yellow track in Figure 15). After tagging, it remained in the general North West Island region until May 2023, when it visited neighbouring reefs for a few days, returning to North West Island regularly. On the 22 April, it started moving north to reefs off Hinchinbrook Island, where it was detected for three days in May, after which it started swimming back south through the outer reef, reaching North West Island on 23 June (Figure 15). At the beginning of July, it did a week-long foray northeast to the outer reef, returning to North West Island once again, where it remained until the end of its tracking period (6 January 2024). Acoustic tracking data also show the high use of the North West Island and the Heron/One Tree Island arrays by this individual, and the absence of detections between late April and June (see top timeline of the great hammerhead panel in Figure 9). The other female remained around the area from its tagging date in February 2024 until February 2025 (red track in Figure 15), when the tag stopped transmitting. This individual had a 17% RI to receivers at the Island (see bottom timeline in the great hammerhead panel of Figure 9).

The third individual, a 285 cm male tagged in February 2024, is still being regularly detected (as of July 2025). It remained in the region until late July 2024, after which moved to the Swain Reefs, and in late August/September was detected near reefs off Townsville (green track in Figure 15). In October, it was detected off Mackay, and returned to the North West Island region in October, where it remained until the present.

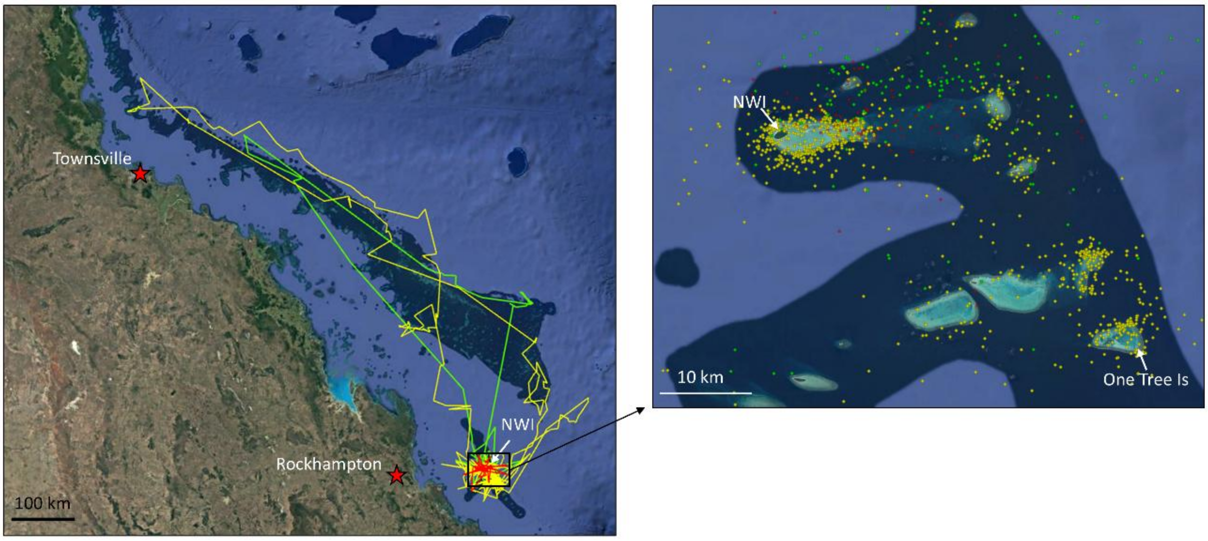


**Figure 15.** Satellite tracks of the three great hammerhead sharks tagged, and zoomed-in view of the satellite-derived locations around North West Island.

### *4.4.4 Pigeye shark*

One pigeye shark was fitted with a satellite transmitter to test if satellite tracking would be a suitable method to track the species. However, the tagged individual did not provide any data, suggesting that the species does not spend time at the surface.

## 5. Impacts of human activities on shark behaviour

North West Island has been a popular fishing site for decades, with people fishing around the island and further offshore. Sustained fishing effort at a location over decades can attract certain shark species, that may steal fish from fishing gear (Mitchell et al. 2023). This behaviour, called depredation, is occurring across most fishing sectors in Queensland, highlighting the scale of the problem (Mitchell et al. 2023). To address this issue, in this component of the study we 1) investigated shark behaviour in relation to boating activity and dumping of fish scraps into the water, 2) conducted fishing sessions to quantify depredation rates around North West Island, and 3) conducted genetic analysis of the remains of fish (if any) to determine the species responsible for depredation, and 4) trialled the use of SoundTrap hydrophones (Ocean Instruments Inc., New Zealand) to quantify boat activity around the island, and to correlate boat activity with shark behaviour.

## *5.1 Shark behaviour in relation to boating activity and dumping of fish scraps*

To investigate anecdotal reports of sharks being attracted to boats dumping fish scraps, camera drop experiments were conducted. The experimental protocol involved a vessel stopping, dropping the anchor, and deploying a 360° camera to record shark interactions. Cameras were first deployed for 5 minutes with no bait to determine if sharks were attracted to the boat in the absence of bait. Bait (either a fish frame or a whole fish) was then thrown into to the water on a rope keep it within the camera's field of view, and recording continued for a further 15 minutes.

Camera drops focused on three areas: 1) off the northwest coast of the island (which includes the historical dumping zone), 2) off the northeast coast, and 3) in the Green Zone. Shark interactions were categorised as either: 1) passive interactions, where sharks approached the boat, camera, or bait but did not feed, or 2) active interactions, where sharks bit or consumed the bait.


**Figure 16.** Locations of baited camera deployments around North West Island. Red symbols indicate locations where interactions were observed, and white symbols where no interactions took place. The yellow square shows the approximate location of the dumping zone. The experimental areas Green Zone, northwest, and northeast of North West Island (NW and NE, respectively) are also indicated. The panel on the right shows a photo of a camera. Map source: Google, 2024 CNES/Airbus.

Over five trips, 134 camera deployments were conducted, from which 12 shark interactions were recorded (seven active and five passive interactions; Table 12 and Table 13), giving an interaction rate of 9.0%. This low rate of interactions suggests that North West Island sharks are not overly attracted to boats or fish scraps, as previously reported. However, the percentage of encounters was higher in the dumping zone compared to the other zones (Table 12). Encounters in the dumping zone also occurred faster than in other zones, and this zone had the highest number of sharks recorded at once (five sharks; Table 12). It is possible that these higher values in the dumping zone reflect residual behavioural conditioning in sharks from the period prior to April 2021, when activities that attract sharks were prohibited.

If shark encounters were previously much more common, as suggested, then the low encounter rates in the current study indicate that management interventions appear to be effective.

Species observed included grey reef sharks, the blacktip complex, and an unidentified carcharhinid (Table 12). One great hammerhead was also attracted to bait, in a passive interaction, but took longer than the experiment's time limit of 20 minutes (26 minutes).

**Table 12.** Data collected from the baited camera deployments around North West Island. MaxN is the maximum number of sharks observed at a single point in time during the video.

| | NW NWI (incl. dumping area) | Green Zone | NE NWI (incl. Mooring 2) | Other sites |
|---|---|---|---|---|
| No. camera deployments | 69 | 6 | 28 | 31 |
| % encounters | 11.6 | 0 | 7.1 | 3.2 |
| No. active encounters | 2 | 0 | 0 | 0 |
| No. passive encounters | 7 | 0 | 2 | 1 |
| Time to arrive (min) | 8:40 ± 6:40 | - | 15:30 ± 6:25 | 11:00 |
| Time to touch bait (min) | 11:20 ± 8:50 | - | - | - |
| MaxN | 5 | 0 | 2 | 2 |
| Shark species observed | Blacktip complex | - | Grey reef shark | Blacktip, grey reef shark |

**Table 13.** Number of interactions from each shark species recorded in camera experiments.

| Species | Passive interactions | Active interactions | Total |
|---|---|---|---|
| Blacktip complex | 3 | 6 | **9** |
| Grey reef shark | 1 | 1 | **2** |
| *Carcharhinus* sp. | 1 | 0 | **1** |
| **Total** | **5** | **7** | **12** |

## *5.2 Depredation experiments*

To quantify depredation rates, 51 fishing sessions were conducted around the island. Each location fished on a given day was considered as a session, and two to four lines were in the water per session. Fishing time at the different locations varied depending on fishing success, as naturally happens with charter and recreational fisheries. One difference between our study and charter/recreational fisheries, however, was that we attempted to target known depredation sites, whereas charter operators would avoid heavily depredated sites. Fishers and charter boat operators informed us that “the whole North West Island is a depredation site”, which was not helpful for targeted fishing experiments. Thus, a number of offshore sites were also used in this experiment (see Figure 17).

In each fishing session, cameras were deployed on fishing lines to record the interactions of sharks with the hooked fish or bait. A camera was also deployed below the vessel to record any shark interactions with the vessel and fishing gear. Fish caught or depredated were recorded, and depredation rates calculated.

From the 51 fishing sessions, 372 fish were hooked and 31 of were depredated, resulting in a depredation rate of 8.3%. This rate was within the lower range of depredation rates that have been reported globally (0.9–26%; Gilman et al. 2008, Mitchell et al. 2018, 2019, Rabearisoa et al. 2018, Romanov et al. 2013). Depredating species included grey reef sharks, bull sharks, and blacktip sharks.


**Figure 17.** Fishing locations used for the depredation experiments.

### *5.3 Species responsible for depredation*

To identify the species responsible for depredation, the bite sites of the depredated fish were swabbed with medium-head Texwipe™ swabs to collect DNA. In the laboratory, DNA was extracted using a DNeasy™ Blood and Tissue Kit (QIAGEN, Chadstone, Victoria, Australia). The PCR amplification protocol followed a modified version of Vardon et al. (2021) and Martin et al. (2024), incorporating a nested two-round amplification approach to increase sensitivity for detecting shark DNA. Universal primers targeting ND2 and ND4 mitochondrial genes were used to amplify DNA from 32 shark species across 14 genera known to occur in Queensland and New South Wales waters. Separate PCR reactions were conducted for each primer pair at 10µL final volume, with thermal cycling conditions of initial denaturation at 95°C for 120 seconds, followed by 34 cycles of denaturation (95°C, 30s), annealing (50°C, 30s), and extension (72°C, 90s), concluding with a final extension at 72°C for 10 minutes. A second nested PCR was performed using 1µL of first-round product as template. PCR products were visualised on 1% agarose gels, with positive controls using scalloped hammerhead shark (*Sphyrna lewini*) DNA and negative controls to monitor contamination. Following cleanup and sequencing on an ABI 3130xl Genetic Analyser, consensus sequences were compared against GenBank using BLAST, with species identification based on 100% identity matches or genetic distance analysis when matches were imperfect. Blacktip shark complex species (*C. limbatus* and *C. tilstoni*) were grouped due to identification difficulties.

From the 26 samples genetically analysed, nine grey reef sharks, six bull sharks, and four blacktip complex sharks were identified. Seven samples failed to provide conclusive results.

## *5.4 Influence of boating/fishing activities on shark movement behaviour*

### *5.4.1 VEMCO Positioning System (VPS)*

Nine VR2AR receivers were arranged in an 800 × 800 m grid VEMCO Positioning System (VPS) design. This allowed for the triangulation of shark positions at fine spatio-temporal scales (drift error ~5 m) from the channel and reef edge (~7 m depth) to ~900 m offshore (15–24 m depth), while incorporating the dumping zone and the main mooring site (Figure 6) and covering a total area of 64 ha.

Positions of tagged animals within the VPS array were calculated using a time difference of arrival and hyperbolic intersection method (Espinoza et al. 2011). To assess the accuracy of position estimates, the relationship between the estimated horizontal position error ($HPE_s$) of the in-built synchronisation transmitters to their true positions ($HPE_m$) was established using the methods described by Smith (2013). Following calculation of $HPE_m$ estimates of animal positions, filtering was conducted using a cumulative frequency distribution to identify a threshold of $HPE_m$= 6 m, resulting in 90% of positional estimates being retained.

The VPS was deployed for two years (October 2022–October 2024). Each year, North West Island is closed to the public between the day after Australia Day and just before Easter. During our study period, the island was also closed from 1 June 2024 to 15 September 2024. Therefore, to identify the effect of human presence on shark activity, the average number of detections during periods when the island was open and closed were calculated and used as a proxy for shark activity in response to human presence.

One hundred and twenty-three of the tagged individuals were recorded within the VPS (1.03 million detections), along with 30 individuals tagged through other projects. The maximum number of individuals detected in the array in one day was 30. Tiger sharks, bull sharks, pigeye sharks, and the blacktip complex used the dumping area more often when the island was open to the public (Figure 18), noting that the seasonal patterns of these species' relative abundance around North West Island (see Figure 11) may also have had an effect on the results. However, given that the winter period was open in 2023 and closed in 2024, and that the data were standardised as average positions per day, any bias is likely minimal. The blacktip complex showed the most pronounced difference in position numbers between open and closed periods, while grey reef sharks and sandbar sharks did not differ in area use between open and closed conditions. The other species had very few position estimates (Figure 18), so no comparisons could be made.

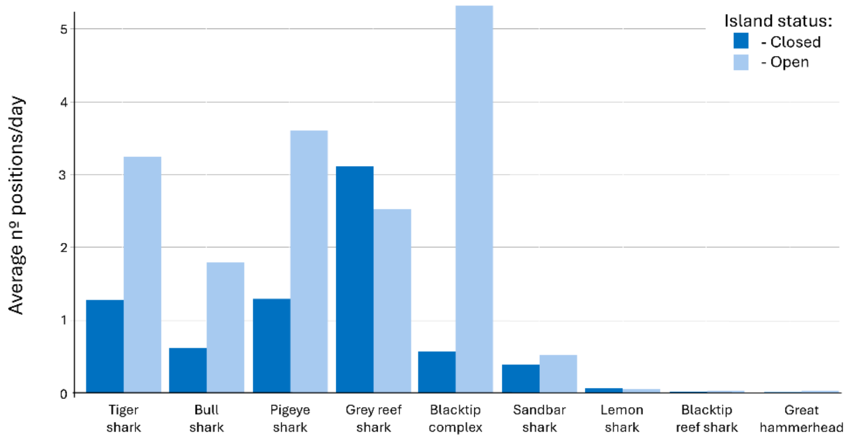


**Figure 18.** Average number of VPS positions per day for each species, for the periods when North West Island was closed/open to the public.

Space use (kernel utilisation distribution) metrics for tagged animals were also calculated for the closed and open periods using the '*kernelUD'* function of the *adehabitatHR* package (Calenge, 2011), with the *adhoc* method used to define the smoothing parameter. Due to variation in sample size and the number of positional estimates, position data from all individuals within species were pooled prior to construction of utilisation distributions. Distinctions regarding how space was utilised by tagged animals were made following the definitions of Clarke (1998), where the contour containing 95% of the position estimates defines their home range and the 50% contour defines their core area of activity.

Tiger sharks, bull sharks, pigeye sharks, and the blacktip complex used the overall VPS area broadly (Figure 19a–c). However, there were differences in core area use between the species. Tiger sharks had wide core area use and, interestingly, the areas closer to the island were used more when the island was open to the public (Figure 19a). Although bull sharks and pigeye sharks also used the whole monitored area, they did not move as close to shore as tiger sharks, and their core area use was in the deeper waters furthest away from the shoreline. Given that these two species are some of the main species involved in depredation, it is interesting that there were no differences in the location of the overall home range or core area use between open and closed island conditions (Figure 19b).

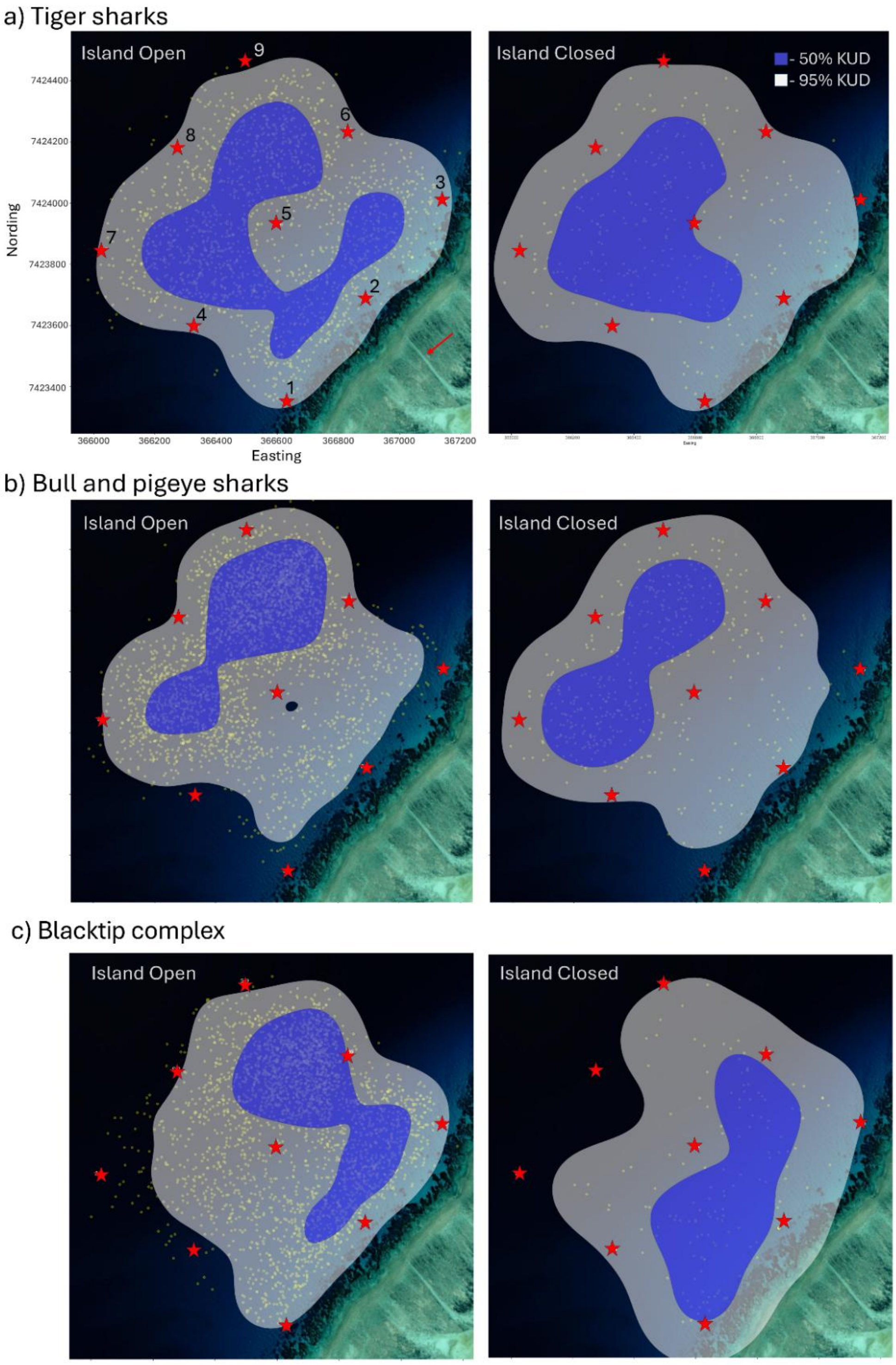


**Figure 19**. Shark area use within the VPS array, showing the core area used (50% KUD) and home range (95% KUD) for each species. VPS receiver numbers and location of the boat channel used to access the island (red arrow) are shown in the first panel.

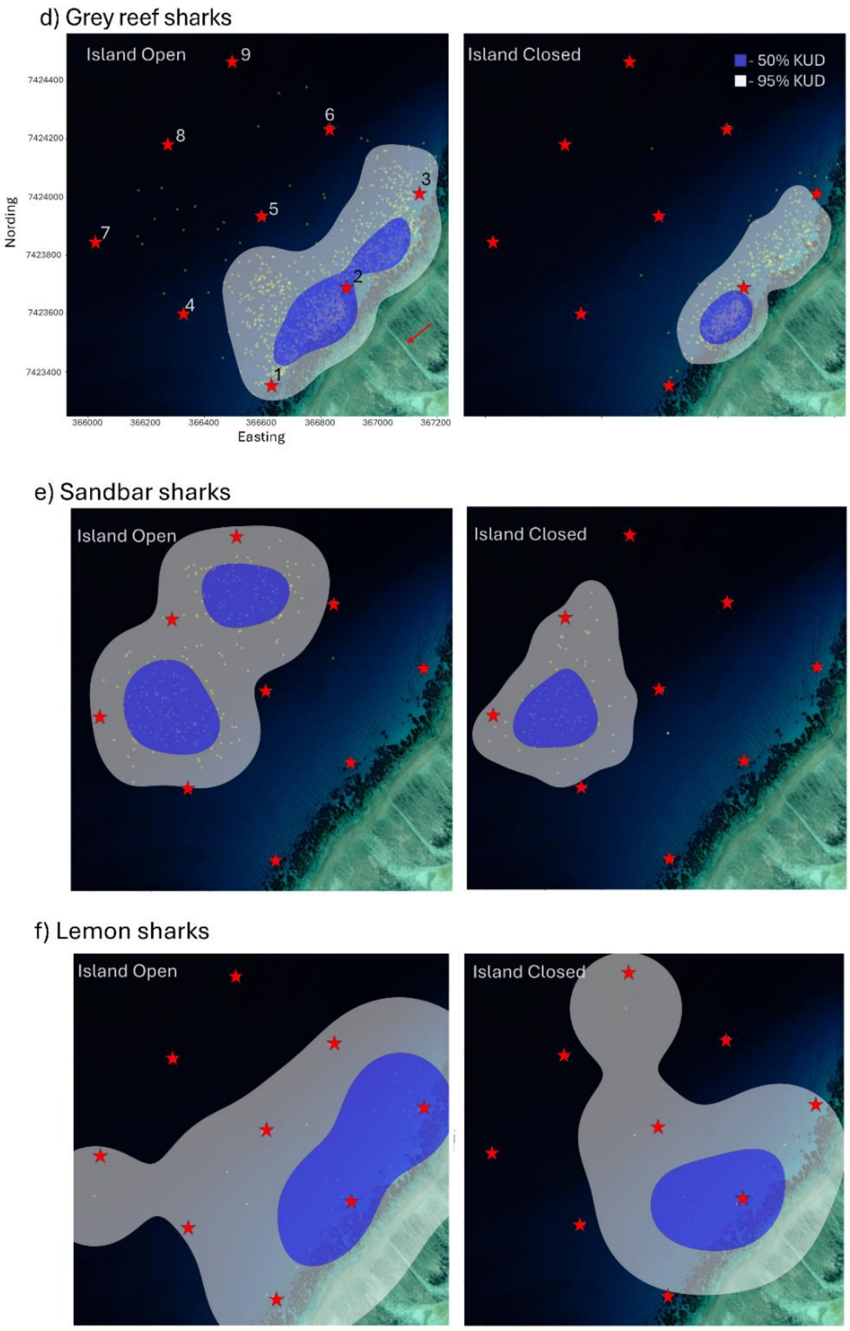


**Fig. 19 (cont.)** Shark area use within the VPS array, showing the core area used (50% KUD) and home range (95% KUD) for each species. VPS receiver numbers and location of the boat channel used to access the island (red arrow) are shown in the first panel.

For the species of the blacktip complex, the core area was mostly on the right side of the channel when the island was open, whereas when the island was closed to the public, the core area use was closer to shore and included positions on the reef crest (

Figure **19**c). Note, however, that this species had the most striking difference in area use between open (>5 positions.day$^{-1}$) and closed (<1 position.day$^{-1}$) conditions (Figure 18).

Grey reef sharks used mostly the areas closest to the reef (and including on the reef crest), around receivers VPS-1, VPS-2, and VPS-3 (

Figure **19**d). Home ranges and core area use were larger during open conditions (

Figure **19**d). Note that this was the only species for which more positions were recorded when the island was closed to the public (Figure 18). Sandbar sharks used the areas furthest away from the reef, with only two positions between the VPS-1 to VPS-3 and the VPS-4 to VPS-6 lines recorded (

Figure **19**e).This aligns with the catch of sandbar sharks occurring on droplines set in deeper waters away from the shoreline. Anecdotal reports of sandbar sharks depredating fish are also mostly from deep-water fishing sites in the North West Island area (Smith pers. comm.). Sandbar shark home range was larger when the island was open to the public. Two core area use regions were present at that time, in contrast to when the Island was closed to the public, when sandbar sharks concentrated mostly between receivers VPS-4, VPS-7, and VPS-8.

Although the four lemon sharks had few positions, triangulated data were useful in identifying the area in front of the channel as the most important for both the open and closed periods (

Figure **19**f). The association with the channel is likely linked to lemon sharks using the channel to enter the lagoon at high tides, as evident from drone observations. As with grey reef and sandbar sharks, lemon shark core area use was larger when the island was open than when the island was closed to the public (

Figure **19**d–f). It is possible that these species move around more in response to the stimulus of human activities.

## *5.4.2 SoundTrap hydrophones*

Hydrophones that record boat noise (used in the present study as a proxy for human activity) were deployed at selected acoustic receivers so that boat activity and movements of acoustically tagged sharks could be compared. This novel approach had never been used before, so our first aim was to test whether it was possible to correlate boat activity with shark movement behaviour. In October 2022, four SoundTrap hydrophones were deployed on receiver moorings at four locations: one in the middle of the VPS array (VPS-5; dumping site), one at the eastern mooring (Mooring 2), and one at each of the two sites reported as heavily fished depredation locations: Fish tail North and South (see Figure 6 and Table 6 for locations).

Hydrophone battery life was shorter than stipulated by the supplier. The first batch of batteries was faulty and only lasted six weeks. Subsequent deployments lasted for ~17 weeks (not the expected six months), meaning it was not possible to obtain continuous sound coverage for the whole study period. Nevertheless, 289 days of data were obtained, spread throughout the year (07/10/2022 to 17/11/2022 (41 days; all sites monitored), 16/02/23 to 17/06/23 (121 days; dumping site only), 12/08/23 to 21/11/2023 (101 days; all sites), and between 09/01/2024 and 04/02/24 (26 days; dumping and mooring sites) (Figure 20), allowing us to analyse differences in boat activity during school holidays vs. non-holiday periods and, for the dumping site only, when the island was open or closed to the public.

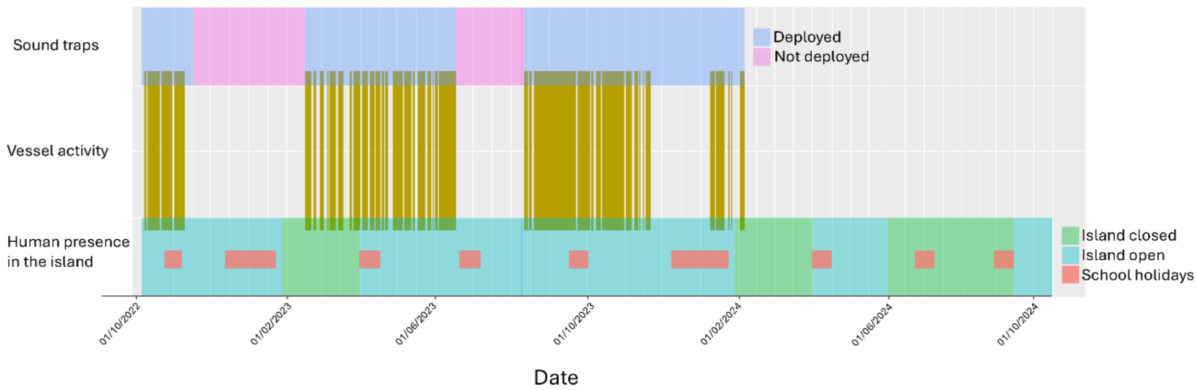


**Figure 20.** Timeline of the study, showing the dates when SoundTrap hydrophones were deployed and vessel activity recorded (for the dumping site), in relation to the periods the island was open/closed to the public, and holiday vs. non-holiday periods.

Among the sites monitored, the dumping area was the most used, with 1,384 vessel events recorded. As expected, holiday periods had the most vessel activity, with 5.5 ± 4.5 (SD) boat detections recorded per day (Figure 21a). Outside the school holiday period, more detections were recorded when the island was open to the public (4.9 ± 5.5 detections.day$^{-1}$) than when the island was closed (3.3 ± 5.9 detections.day$^{-1}$). Mooring 2 also had slightly higher activity during the holiday period (Figure 21a).

For all sites, vessel activity occurred mostly during daytime (Figure 21b). Interestingly, the window of activity was wider for the Dumping site (~05:00 h to 18:00 h) than for Mooring 2 (~06:00 h to 17:00 h) (Figure 21b), possibly reflecting boats leaving and returning to the island (via the channel) at dawn and dusk. Boat activity at the two 'Fish tail' sites was low (Figure 21a). Given the low boat activity and relatively low proportion of sharks using those sites (Figure 8), they do not appear to be popular fishing sites.

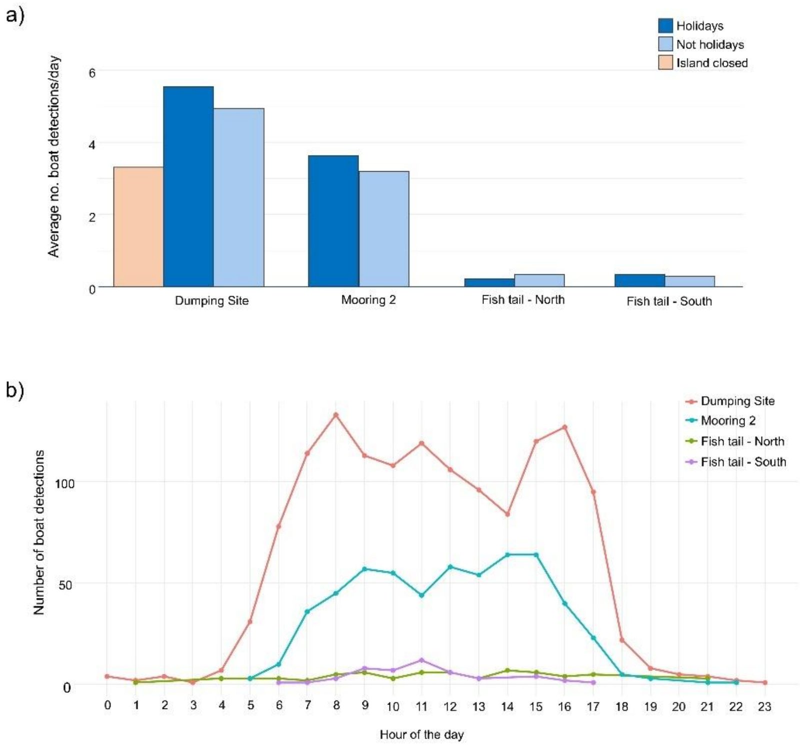


**Figure 21.** a) Average number of boat detections per day during school holiday periods, non-holiday periods, and period when island was closed, for each site; b) daily boat detections at the different sites.

Due to the much higher occurrence of sharks and longer period of vessel activity monitoring around the VPS area, the following analyses concentrated on tracking and sound data from that site. Ninety-seven sharks were recorded by the VPS receivers while the hydrophones were deployed and recording (Table 14).

**Table 14.** Number of individuals of each species recorded by VPS receivers while the hydrophones were deployed and recording.

| Species | No. indiv recorded |
|---|---|
| Tiger sharks | 46 |
| Grey reef sharks | 10 |
| Bull sharks | 10 |
| Sandbar sharks | 9 |
| Pigeye sharks | 8 |
| Blacktip complex | 6 |
| Lemon sharks | 4 |
| Blacktip reef sharks | 3 |
| Great hammerheads | 1 |
| **TOTAL** | **97** |

The durations of vessel activity events were very short, typically <1.5 min (Figure 22), suggesting vessels were mostly transiting through the area or to/from the island. It is also possible that some boats had remained in the area had turned their engines off while fishing. Based on the consistently high engine revolutions recorded during detection events, the majority of boats appeared to be transiting rather than stationary fishing, although further analysis incorporating additional metrics such as vessel speed, direction of travel, and engine idle patterns is needed to conclusively characterise vessel behaviour in the area.

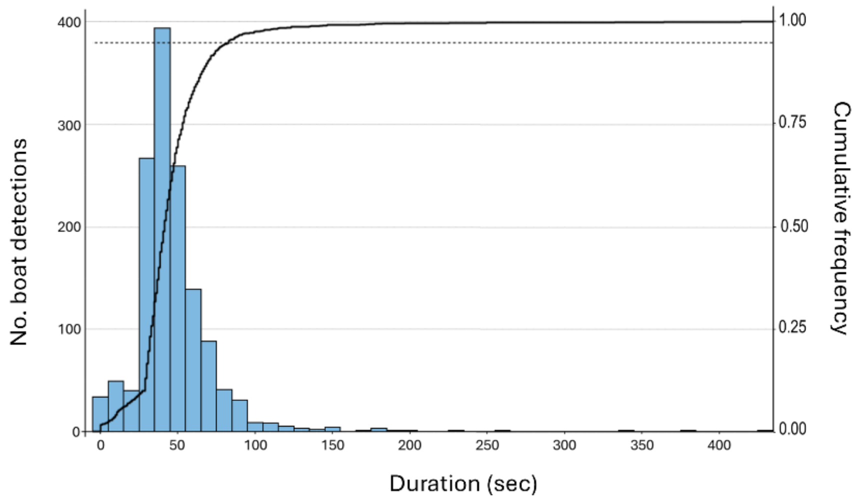


**Figure 22.** Number of boat detections (histogram) and cumulative frequency distribution (curve) of detections at the VPS site. Dashed horizontal line shows that 95% of all vessel activities recorded were <90 sec in duration.

Sequence analysis of daily presence/absence patterns was used to investigate the relationship between boat activity and shark occurrence. Movement sequences were constructed from raw detection data (not positional data) following identification and removal of false positives (Pincock 2012). Since the analysis was designed to compare the presence of animals in relation to open/closed periods and boat activity, detection data were binned into daily intervals and their status was classified as either present or absent. Sequences were compared using a modified version of the optimal matching, as described by Lowe et al. (2020), using the 'substitution' cost regime method of the *'seqdist'* function in the R package *TraMineR* (Gabadinho et al. 2011). To assist with the visualisation of the sequence analysis, a dendrogram was constructed using the agglomerative clustering method 'pvclust' function of the *pvclust* R package (Suzuki and Shimodaira 2006).

Sequence analysis revealed no species-specific clustering. Indeed, the optimal matching algorithm produced a dendrogram with individuals from different species distributed throughout the tree structure, exhibiting high dissimilarity values, and forming numerous small clusters (Figure 23). This scattered distribution means that species identity was not a predictor of the temporal presence patterns at the dumping site in relation to closed/open island periods. The underlying sequence data illustrate the individual-level variation that drove these clustering results, as exemplified by tiger shark presence patterns that can be seen in Figure 24 (see Figure S3 for the other species), showing that individual tiger sharks showed highly variable temporal patterns, with some individuals detected consistently during specific periods while others exhibited more sporadic or brief site visits. The presence patterns did not align with island closure periods, indicating that shark presence at the dumping site was not driven by human activity levels for any species.

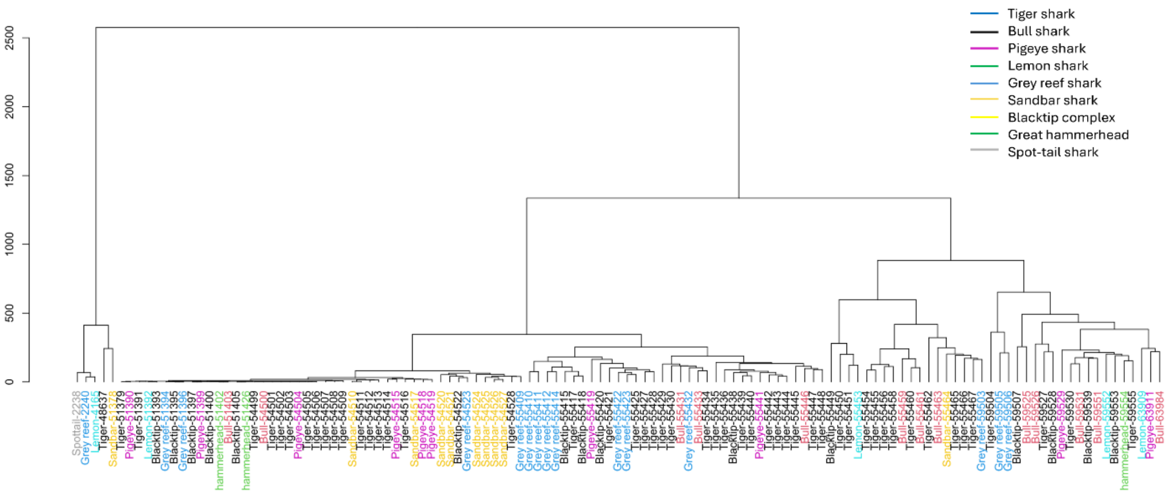


**Figure 23.** Dendrogram based on the sequence analyses of the different species, showing that no pattern was present and suggesting no effect of boat presence or island open/closed status on shark occurrence, for any species.

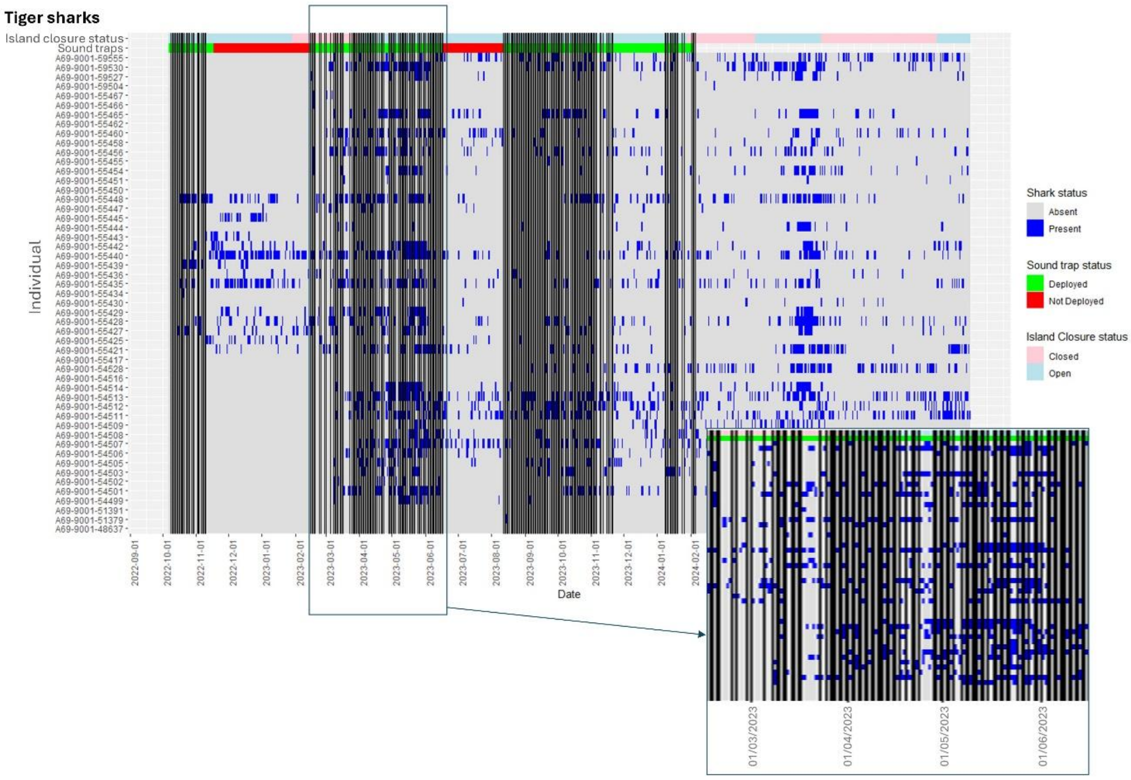


**Figure 24.** Sequence analysis showing the timelines of daily tiger shark presence (blue) in relation to boat activity at the dumping site (black vertical lines), and the days the island was closed or open to the public.

# 6. Discussion

Understanding the behaviour and prevalence of different shark species can help in assessing human-shark negative interactions (Payne et al. 2018, Meyer et al. 2018, Lee et al. 2019, Barnett et al. 2022). Taking into account all methods used in this project and sharks tagged as part of other projects, 13 shark and four ray species were reported for North West Island. This includes bull sharks, tiger sharks, and white sharks, the three species most implicated in shark bites (Australian Shark-Incident Database, Bradshaw et al. 2025). Tiger sharks were the most abundant species at North West Island. The four white sharks recorded were tagged in NSW and were likely on their migration to/from their winter habitats in the Coral Sea (Lee et al. 2021, Coxon et al. 2022). Interestingly, the vast majority of bull sharks acoustically tracked in this project had very short residency times (see Figure 9), suggesting they were just passing North West Island, likely as part of the species' large-scale migrations (Heupel et al. 2015, Lubitz et al. 2023, 2024). Other potentially dangerous sharks to humans included the blacktip complex species and grey reef sharks (Bradshaw et al. 2025) — all target species for the Queensland Shark Control Program. Dusky shark (*Carcharhinus obscurus*) was the only species of the seven target species that was not recorded at North West Island. Of interest, lemon sharks have been responsible for six bites in Australia (three provoked, two unprovoked, and one with no information; Bradshaw et al. 2025), including the two bites at North West Island. Tellingly, three of those bites occurred at sites of extremely high human use: North West Island and Lizard Island (Barnett & Fitzpatrick personal observations since the 1990s). Of the other large-bodied shark species capable of biting humans, the pigeye shark was one of the main species occurring at North West Island.

Shark catch rates at North West Island (0.09–0.12 ind.hr$^{-1}$) were high compared to the Whitsundays (CPUE 0.03 ind.hr$^{-1}$; Barnett et al. 2022), but on par with catches at the Palm Island group (CPUE 0.08–0.09 ind.hr$^{-1}$) (Table 15). However, the vast majority of sharks caught at North West Island were adults (based on size), with some species including individuals towards the larger end of their size ranges (e.g. for the blacktip complex), whereas smaller whalers (spot-tail sharks and whitecheek sharks (*Carcharhinus coatesi*)) made up 29% of the catch for the Palm Islands (Barnett, *unpub. data*). Bull shark catches were similar for North West Island and Palm Island, and higher than at other sites, including Réunion and the Whitsundays Islands (Table 15), sites for which bull sharks have been implicated in bites.

**Table 15**. Catch per unit effort for the overall shark assemblage and for individual species, from studies that used dropline methods. CPUE is in ind.hook$^{-1}$.h$^{-1}$. Adjusted CPUE: for North West Island, corresponds to the overall study with the exception of Trip 5, due to high water temperatures that led to unusual lower catches at that time; for Palm Islands, adjusted CPUE was calculated with the smaller shark species removed.

| Species | North West Is | Whitsundays[1] | Palm Is.[2] | Shark Bay[3] | Reunion Is[4] | Florida[5] |
|---|---|---|---|---|---|---|
| Assemblage | 0.09 | 0.03 | 0.09 | | | |
| Adjusted CPUE | 0.12 | | 0.06 | | | |
| Tiger sharks | 0.04 | 0.008 | 0.01 | 0.06 | 0.006 | |
| Bull sharks | 0.01 | 0.002 | 0.02 | | 0.003 | 0.004 |

References: [1]Barnett et al. 2022; [2]Barnett unpublished data; [3]Heithaus et al. 2001; [4]Blaison et al. 2015; [5]Hammerschlag et al. 2012.

Surprisingly, bull shark catch was not higher in winter (Trip 4), when individuals from New South Wales migrate north for the cooler months (Heupel et al. 2015, Lubitz et al. 2023). Acoustic tracking suggests that catch might have been lower than expected because bull sharks do not remain at North West Island for long periods. Bull shark catch and residency were also low in Cid Harbour, Whitsundays, where a similar study was undertaken following shark bite incidents (Barnett et al. 2022). Given bull sharks' record of being implicated in negative human-shark interactions, their movement patterns can be seen as unexpected. Despite showing both residency and migratory behaviour in Queensland (Heupel et al. 2015, Espinoza et al. 2016, Barnett et al. 2022, Lubitz et al. 2023), in general, bull sharks appear to be constantly on the move, suggesting home ranges of resident bull sharks are over regional scales as opposed to local scales. For instance, residency could be the broader Capricorn Bunker group or the southern Great Barrier Reef (e.g. Gladstone to Swain Reefs). The constant movement of bull sharks goes against the ongoing anecdotal reports from fishers of resident bull sharks at certain fishing sites. It also implies that, if a bull shark was responsible for a shark bite incident, attempts to catch the individual shark responsible would likely be unsuccessful.

In contrast, pigeye sharks, a close relative of bull sharks, spend more time at North West Island and, in particular, more time in the dumping zone, and are less likely to make large-scale movements. Given that pigeye sharks are one of the species most often implicated in depredation studies, a better understanding of their ecology is required to assess if they are a risk to humans at sites of high human activity, and if they could be responsible for some of the negative human-shark interactions attributed to bull sharks.

Acknowledging that five sampling periods across two years is not a robust sample size for temporal comparisons, the initial data point towards some seasonal patterns in shark occurrence. In particular, tiger shark catch was low in winter (Trip 4), while sandbar shark catch was highest at that time. Tracking results support these seasonal patterns. Sandbar sharks are likely migrating from southern habitats for winter. This species has been implicated in depredation in southern Queensland, with anecdotal reports also from North West Island.

Tiger shark catches were high in comparison to other sites except for Shark Bay, Western Australia (Table 15). The generally low residency of tracked sharks, coupled with the high occurrence in catches, suggests that individuals continually move to and from North West Island and/or that the number of tiger sharks using the island is very high. The high tiger shark catches at North West Island coincide with higher abundance of turtle and nesting sea birds in the area, both important prey for tiger sharks (Lowe et al. 1996, Simpfendorfer et al. 2001, Hammerschlag et al. 2016, Ferreira et al. 2017), that likely influence tiger shark occurrence and movement patterns (Niella et al. 2022). Accordingly, tiger shark catch and tracked shark occurrence were considerably lower in winter, outside of turtle and seabird nesting periods, aligning with prey likely being the main driver of tiger shark occurrence. The slight peak in tiger shark occurrence in April–May could be influenced by a different pulse in prey availability, as this coincides with the time when fledgling seabirds leave the Island (Congdon et al. 2007). In Shark Bay, high relative abundances are also related to seasonal exploitation of productive feeding grounds that contain key prey species such as dugong, turtles, seabirds, and dolphins (Heithaus 2001, Wirsing et al. 2006).

A 16% recapture rate is considered high for shark studies (Kohler & Turner 2001, Wirsing et al. 2006, Barnett et al. 2010, Dale et al. 2011), suggesting that North West Island is an important site for at least some individuals, if not some species. The tiger shark recapture rate of 5% in the current study is closer to other mark-recapture studies, including the 6% recapture rate over seven years for tiger sharks in Shark Bay, Western Australia (Wirsing et al. 2006). However, many other studies would have considerably higher fishing effort or used returns from fishers (e.g. Kohler & Turner 2001, Wirsing et al. 2006). On the 5$^{th}$ field trip, three of six tiger sharks (50%) caught were recaptures. The catch and recapture rates of tiger sharks suggest a mark-recapture program with sufficient fishing effort, similar to Dudgeon et al. (2015), could be implemented, where acoustic telemetry data are merged into mark-recapture models to estimate the abundance of tiger sharks using North West Island.

Lemon sharks, a species implicated in at least one of the negative human interactions at North West Island (and a focus species of this study) showed low catch rates and did not occur in dumping and depredation experiments. However, they were the most sighted shark species in drone surveys conducted in February and March. The limited data suggest seasonal patterns in the use of North West Island, lower occurrences in winter and higher in summer–autumn, with February–March possibly peak times in lemon shark occurrence. This is when the island is closed to tourism, meaning human activities would not be attracting lemon sharks at that time. For all methods, a larger sample size, collected over a longer time period, is required to understand the prevalence and behaviour of lemon sharks in relation to human behaviour at North West Island.

The high occurrence of reef sharks (blacktip reef shark, grey reef sharks) was expected, as North West Island is appropriate reef habitat for these species. Accordingly, grey reef sharks were prominent in the human activity-shark behavioural experiments. Grey reef, bull, and blacktip complex sharks are the main species interacting with humans at North West Island. These species are also some of the main species implicated in depredation in Queensland and Western Australia (Fotedar et al. 2019, Mitchell et al. 2019, 2020, Vardon et al. 2021). In a broader DNA-based study that incorporates data from North West Island as part of sampling effort in Central Queensland, bull, grey reef, and blacktip complex were responsible for 59 out of 69 depredated fish samples (Vardon 2025). Tiger sharks, the most abundant species in catch rates at North West Island, did not interact with any of the human activity experiments, which suggests that the large number of tiger sharks at North West Island are there to feed on abundant prey species.

The behavioural study targeting the dumping of fish scraps led to very few shark interactions. The 5-minute and 15-minute durations of boat and fish scrap treatments are likely longer time periods than would be expected if sharks were as strongly conditioned to human activities as anecdotal reports suggested for North West Island. A similar pilot study testing shark response to baited cameras dropped below the vessel at Ningaloo Reef (Western Australia) showed comparable times for lemon and pigeye shark arrival (on average <10 min) and first feeding on bait (<13 min) to the present study, while noting that the time of shark arrival and first feeding decreased over the six experimental days (Mitchell et al. 2020). Pigeye sharks, a prominent depredating species in Queensland and Western Australia (Fotedar et al. 2019; Mitchell et al. 2019, 2020; Vardon et al. 2021) were not associated with the behavioural experiments at North West Island, nor were lemon sharks, the species that may have previously been intentionally attracted by campers.

Overall, results from the behavioural experiments do not align with anecdotal reports and online footage of sharks aggregating around boats waiting for scraps. However, something similar was observed n Trip 1, when deploying the droplines for the first time: four large blacktip sharks followed our boat as we set the lines in the dumping zone, with one shark taking the droplines before we had set the fifth line. A second event occurred in a camera drop experiment in the dumping zone, where five blacktip sharks were quickly attracted to the boat/bait. In a third incident, we observed a single blacktip from the drone quickly approach our boat to investigate a researcher retrieving bolt cutters dropped from the boat.

These somewhat unexpected results may be driven by 1) the occurrence of sharks around boats was not as common as we were led to believe; 2) the enforcement and education of campers in relation to dumping food/fish scraps outside of the Special Activity Area attenuated shark habituation; 3) 138 camera drops are not enough replicates to detect patterns in shark behaviour; and/or 4 ) the small amount of fish scraps used (one to two frames tied to a rope) is not representative of previous rates and quantities of dumping, and therefore is not attracting groups of sharks, as previously reported. Minimal scraps were used in our experiments due to concerns about human safety. In February 2024 (when the island was closed) larger quantities of scraps were used in the dumping experiment to assess if the amount of food scraps could have contributed to fewer sharks being present around boats, but interactions did not increase. Catch rates were also lower than during other trips, and we suspect high water temperatures in February 2024 likely impacted shark occurrence and catch. However, drone surveys and tracking data at that time do not agree with lower shark occurrence.

In conclusion, the broad habitat use patterns around North West Island show that most species spend significant time around the dumping and mooring sites, and very little time at receivers further along the island. This may indicate that decades of dumping scraps from boats have habituated sharks to those areas, so they keep returning. High visitation rates to North West Island, but short residency periods, also suggest behaviours associated with animals passing through areas of high return, i.e. areas with high prey abundance and/or scavenging opportunities. Similar shark behaviour was evident in Cid Harbour, Whitsundays. However, the fine-scale VPS analysis and behavioural experiments do not strongly support for dumping driving shark habitat use at the finer-spatial scale, suggesting that if sharks were previously associated with boats, the ban on dumping over a year prior to this study is working to some extent.

Tiger and great hammerhead sharks spent the least time in the dumping zone, with a more even spread of habitat use around the island. We hypothesise that these two species are at North West Island to hunt their main prey, and are less likely to be influenced by human activity. For example, the broad sandflats provide optimal foraging grounds for hammerhead sharks, providing an abundance of ray species. Of the other species, blacktip complex, grey reef sharks, lemon sharks and sandbar sharks showed fine-scale movement patterns that may be related to human activities when the Island is open to campers, i.e. larger spatial use, habitat use closer to the reef edge/island and to the boat channel and Mooring 1. In contrast, pigeye and bull sharks showed no difference in habitat use between when the Island was open or closed, with core habitats occurring in the deeper offshore section of the VPS.

## *Recommendations and considerations beyond the contracted project*

This project provided two years of tracking data. Results so far indicate that North West Island is a high use area for sharks in general, and may be a key component of some species' home ranges. *A* ***strong recommendation is to keep some of the receivers in the water for at least another 3-4 years****, ideally longer.* Movement behaviours over multiple years and seasons can be very informative and may lead to different conclusions. For example, the Department of Primary Industries project that followed the Cid Harbour shark bite incidents initially only focused on Cid Harbour (Barnett et al. 2022). Initial results showed that shark prevalence and behaviour in Cid Harbour was not unusual in terms of abundance and residency, e.g. sharks did not reside in Cid Harbour for long periods of time. However, two extra years of tracking data that expanded acoustic receiver coverage to other key tourist locations within the broader Whitsundays Region to better understand shark movements in relation to areas of high human activity (e.g. anchorages, snorkelling /swimming and fishing areas) showed that Cid Harbour is in fact used much more than the other Whitsundays locations. Residency times might have been short, but visitation rates were far higher in Cid Harbour than at any other site in the Whitsundays, suggesting that Cid Harbour is a key site for sharks, as they move around the Whitsundays and beyond. The broader extension of that study also showed that anchorages were visited far more often than other sites of human activity such as swimming and snorkelling (Barnett et al. 2023).

Given the tags' 10-year battery life and the number of tagged sharks from this and other projects, leaving some receivers deployed at key locations for the long-term would be ideal. Receivers would also continue to contribute to the larger Integrated Marine Observing System (IMOS) Queensland array, currently consisting of >320 receivers, and about to expand with additional infrastructure from IMOS. Given the number of tagged sharks at North West and sharks moving through the island from other locations in Queensland and NSW, North West Island could become a key monitoring location for the east coast of Australia. In the long-term, this would allow us to better understand the significance of North West Island in relation to the broader shark habitat use patterns on the east coast of Australia.

### *Recommendation for North West Island*

The sample size of tagged sharks is skewed towards tiger sharks. However, tiger sharks have not interacted with behavioural experiments and are likely at North West Island to feed on natural prey. An option for the future would be to continue tagging to increase the numbers of other species that are likely influenced by human activities, in particular lemon sharks, bull sharks, pigeye sharks, grey reef sharks, sandbar sharks and blacktip sharks. Research in Queensland is starting to show that these are some of the main species interacting with humans through depredation (Vardon 2025). The low number of lemon sharks caught/sighted at North West Island was surprising, given the high fishing levels and anecdotal reports of people previously feeding them. However, this could have been an artefact of sampling effort, especially since fishing effort in each trip was over only 3–4 days. Although the seasonal patterns in catch rates to date are interesting, a more comprehensive assessment of temporal changes in shark relative abundance is needed. Continued sampling effort over 3-4 years would generate the data required for robust temporal abundance modelling (Dudgeon et al. 2015).

***Recommendation:*** *Continue catch and drone surveys and acoustic tagging, to better understand shark abundance and long-term use of North West Island*

*Recommendation for the Capricorn Bunker Group*

Given the number of sharks tagged with 10-year battery lives, it would be beneficial to remove most of the VPS receivers and deploy them around the Capricorn Bunker Group, targeting sites of different human activities. This would allow a better understanding of human-shark overlap. A similar change in receiver coverage was done for the Whitsundays project, which led to a clearer picture of shark movement behaviour in relation to human activities in that region, highlighting the importance of Cid Harbour. The main results were that sharks used anchorages significantly more than other monitored sites of human activity, including swimming beaches that were predominantly in Green Zones. That information was useful for providing management advice, e.g. where not to swim and keeping the 'no swim' signs deployed. Note that, over the last year, we already deployed receivers in collaboration with the DETSI mooring maintenance program at five anchorages, and Heron and One Tree Islands have permanent receiver coverage from IMOS.

The large number of receivers deployed at Heron Island (managed by IMOS) and the easy access for working at Heron Island provide an ideal site for human-shark interactions comparisons. Heron Island is a location of high in-water human activities, with high Green and Yellow Zone coverage when compared to North West Island, where fishing is the main activity. To undertake such a project, sharks would need to be tagged at Heron Island as well.

# 7. Management considerations

Given that the ban on dumping fish and food scraps was implemented a year prior to this project, it is difficult to clearly determine the extent to which human activities drive shark behaviour. However, considering results from the current project alongside broader knowledge of shark-human interactions (including tourism, depredation, and shark bites), species-specific behaviour, and lessons from other locations, it is likely that some species exhibited high levels of conditioning to human activities prior to the implementation of the above-mentioned management interventions. Therefore, a precautionary approach should involve continuing to manage the dumping of waste and fish scraps, while further managing human behaviour where possible. This includes reducing practices that may attract sharks and managing stakeholders to avoid overlapping activities, such as spatially and/or temporally separating fishing from swimming, diving, and snorkeling.

In general, sharks showed higher occurrence and greater activity in and around the dumping zone when the Island was open. This provides the clearest indication that shark occurrence and behaviour have been and continue to be influenced by human activities. However, disentangling this information at the species level, in a way that can inform the management of human-shark interactions is complex due to several factors: 1) the absence of baseline data on human influence over shark behaviour after decades of provisioning (prior to the 2021 management intervention); 2) small sample sizes for most species and the project's short timeframe; and 3) interpretation of results being more dependent on general knowledge of shark behaviour than on robust empirical data. For instance, large-scale movements, low residency indices, and seasonal patterns suggest that sharks are not unusually attracted to North West Island. On the other hand, sharks tagged in the present study exhibited lower residency (or no detections for some species) at Heron Island while continually returning to North West Island. These somewhat contradictory findings, combined with extremely low residency at North West Island for sharks tagged elsewhere, challenge the hypothesis that sharks are particularly attracted to the Island. Furthermore, while vessel noise had no effect on shark occurrence at finer spatial scales, the changes in spatial use between open and closed periods observed across most species suggest behavioural modifications in response to human activities.

***Shark behaviour in the context of managing human activities***

The tendency for tiger, grey reef and lemon sharks to use the reef edge more frequently when the Island is open could be influenced by human activities, including fishing on the reef, ongoing dumping (particularly by campers without boats), spearfishing at the reef edge, or sharks investigating snorkelers. Understanding the extent of island-based fishing activities (both spearfishing and rod-and-reel fishing) and identifying which reef sections are most affected by these activities could help improve management of human-shark interactions. Additional information on snorkeling and diving patterns may also be needed to assess stakeholder overlap.

The high use of the area extending from the front of the channel toward offshore waters by the blacktip complex suggests they may follow vessels. However, with only eight individuals acoustically tagged, interpretation of this group's behaviour is limited by the small sample size. For instance, blacktips recorded by far the most position fixes in the dumping zone when the Island was open, yet showed lower residency at North West Island than most other species. Given that they are also one of the primary species interacting with fishing and dumping activities at North West Island (and throughout Queensland), the limited data suggests the blacktip complex is attracted to North West Island specifically by human activities. Decades of provisioning may also have had have lasting effects on grey reef shark behaviour, as even when the Island was closed, grey reef shark habitat use was concentrated at the entrance to the channel, possibly in anticipation of human activities.

The higher use of the more offshore part of the VPS by sandbar sharks may relate to this species' preference for deeper habitat, but no clear hypothesis emerges to explain bull and pigeye shark behaviour patterns. Indeed, all components of this project suggest that bull sharks are not particularly problematic at North West Island. However, we did not fish in the deeper waters, where bull sharks spent more time (due to adverse weather conditions), and this may have affected bull shark catch rates. The area the VPS was installed in serves as an anchorage for commercial fishing boats, so it is possible that sandbar, pigeye and bull sharks are attracted to the area when vessels are present.

An important consideration for future management plans involves the shark species showing some of the highest residency: pigeye, grey reef and lemon sharks, as well as the blacktip complex and bull sharks. Recent research identifies these species as key contributors to negative human-shark interactions. These species appear particularly susceptible to conditioning through repetitive human activities involving fishing, shark provisioning, or disposal of fish scraps.

**Consideration for management**

1. ***Continue managing waste and fish scraps***. Possibly with a focus on non-boat-based fishers.
2. ***Reduce practices that may attract sharks.*** Options could include:
    - Prevent commercial fishing vessels anchoring in the Special Activity Area
    - Close the island to campers indefinitely or for an extended period of time (e.g. one year or more)
3. ***Reduce the likelihood of stakeholder overlap.*** Possible actions could include:
    - Implement a 'do not swim' zone in the area where vessel activity could attract sharks, i.e. in front of the channel and adjacent reef, incorporating the mooring.
    - Implement no fishing zones in areas of high in water use (snorkeling, swimming, diving)
    - Warn swimmers to avoid areas of fishing activity
4. ***Education and information.*** Introduce signs and/or online materials on the possible effects of human activities on the different shark species' behaviour. For example:
    - Install 'Do not feed sharks' signage
    - Display Shark Smart messaging. Species example: "*Lemon shark occurs in lagoon and are typically harmless under natural conditions. However, they have bitten people when baited and harassed. This species is particularly difficult to handle when hooked, as it continually spins and bites."*
    - Include a survey as part of the booking system to understand planned activities and potential area usage. Visitors could select from options such as: fishing with boats, shore fishing, spearfishing, snorkeling, swimming, and diving. Area usage can be presented in grid format, making visitors more comfortable selecting general zones rather than revealing exact fishing locations. Caretakers could directly record area usage patterns around the Island.

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## Supplementary Material

**Figure S1.** Location of receivers deployed along the Queensland coast through a range of projects, showing the receiver coverage of coastal and reef habitats.

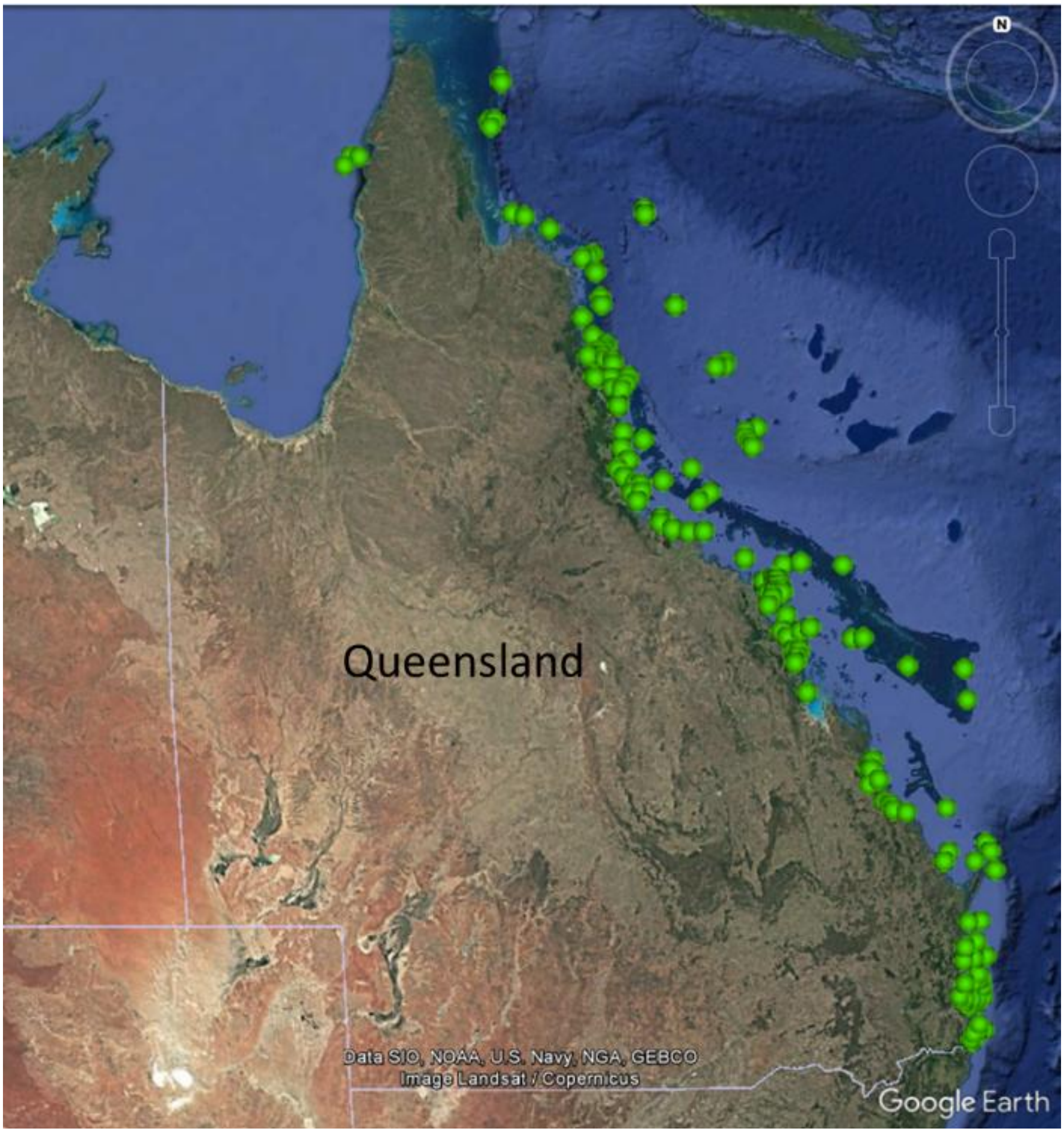
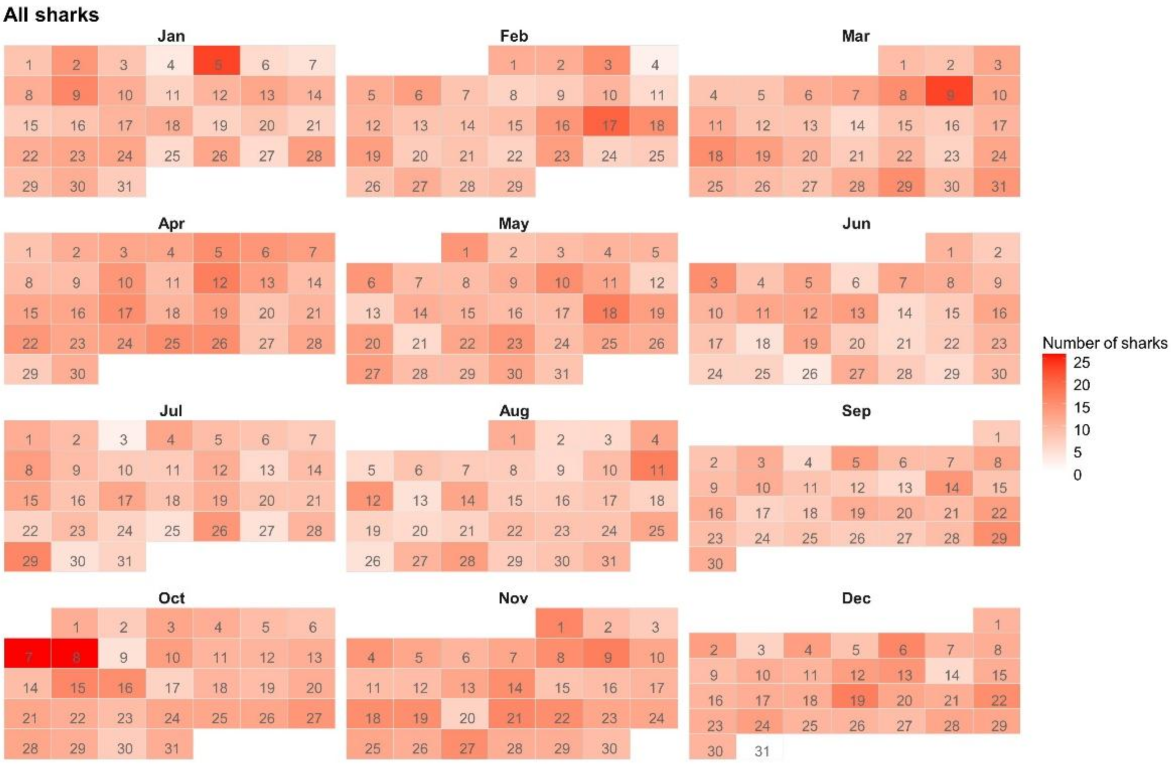
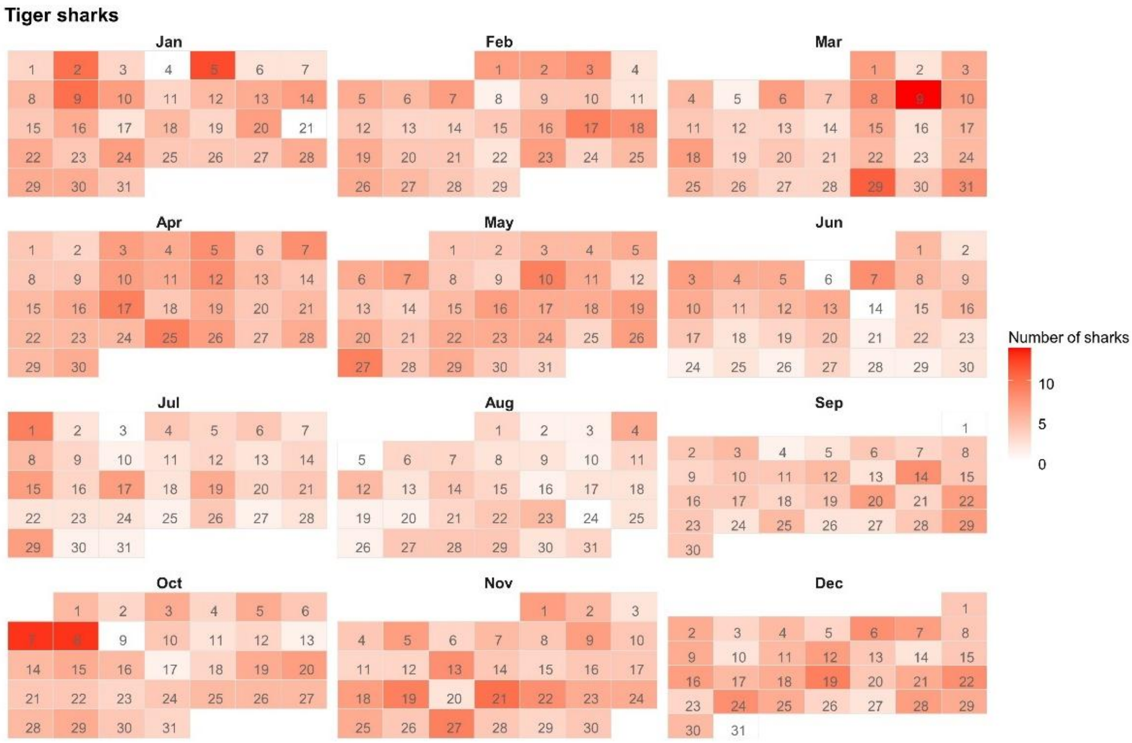
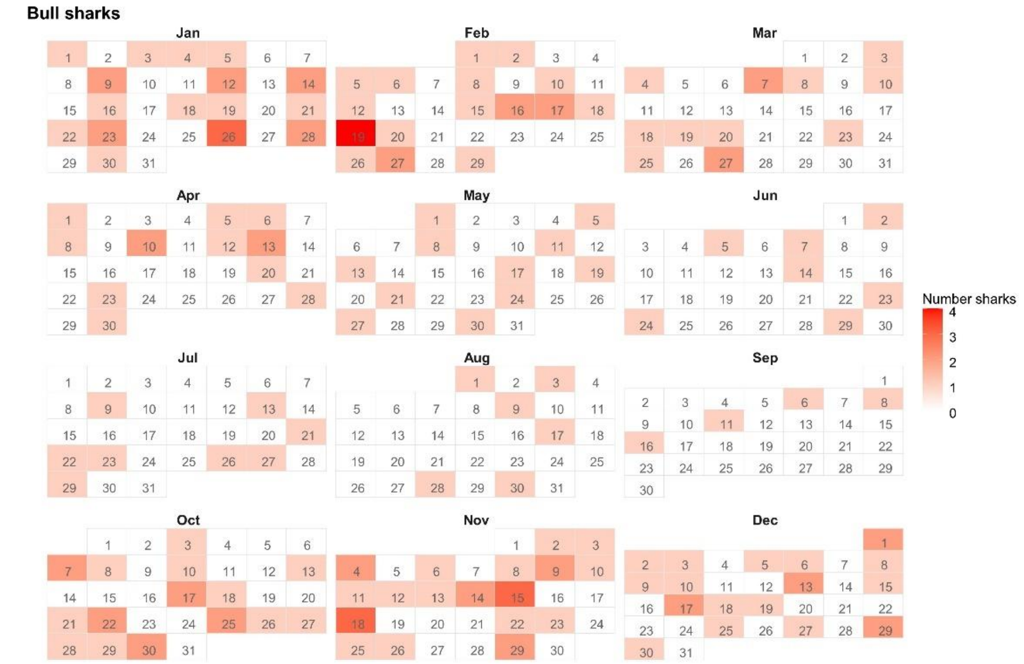
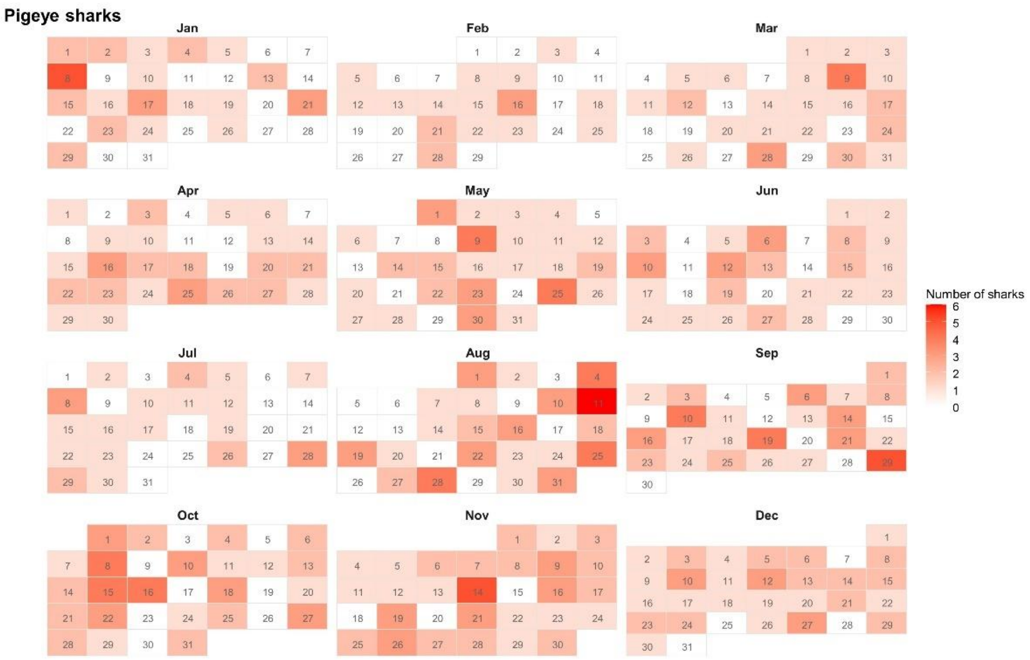


**Figure S2.** Heatmaps on the number of individual sharks detected per day, throughout the calendar year, for all sharks, and for each species separately

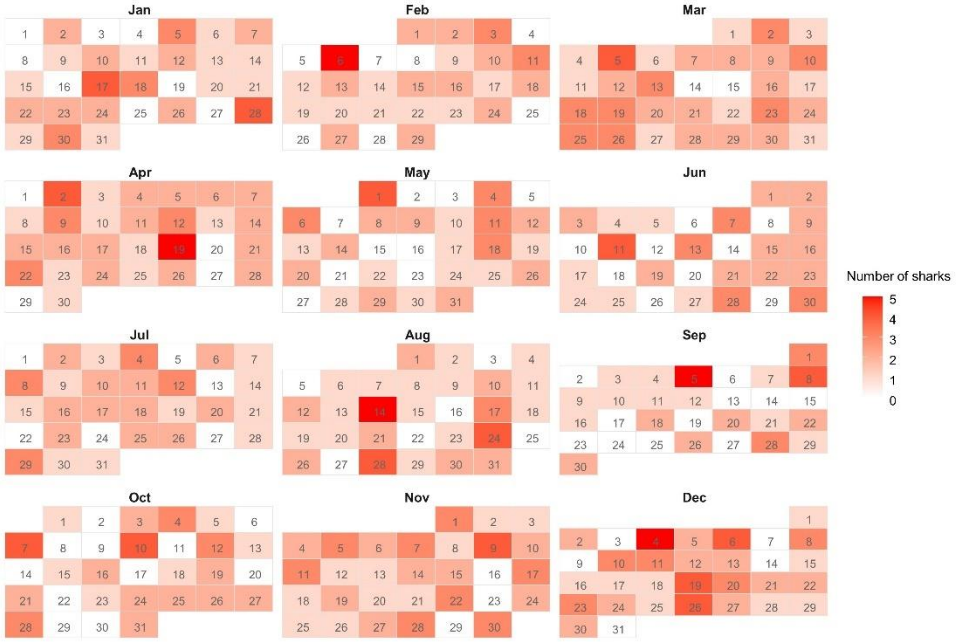



Bull sharks
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Number sharks
4
3
2
1
0


Pigeye sharks
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Number of sharks
6
5
4
3
2
1
0

**Grey reef sharks**




**Sandbar sharks**

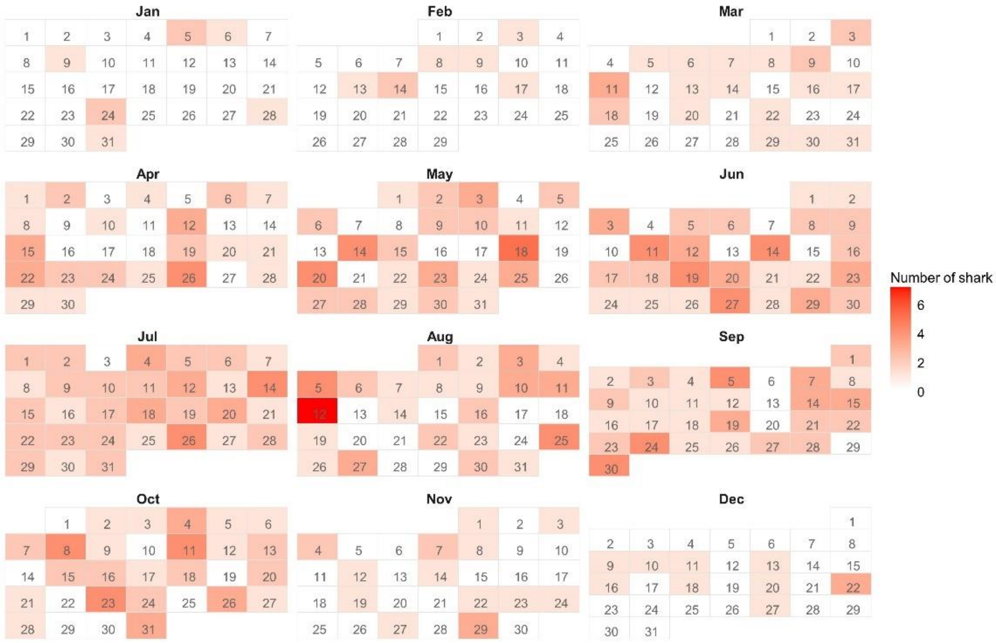
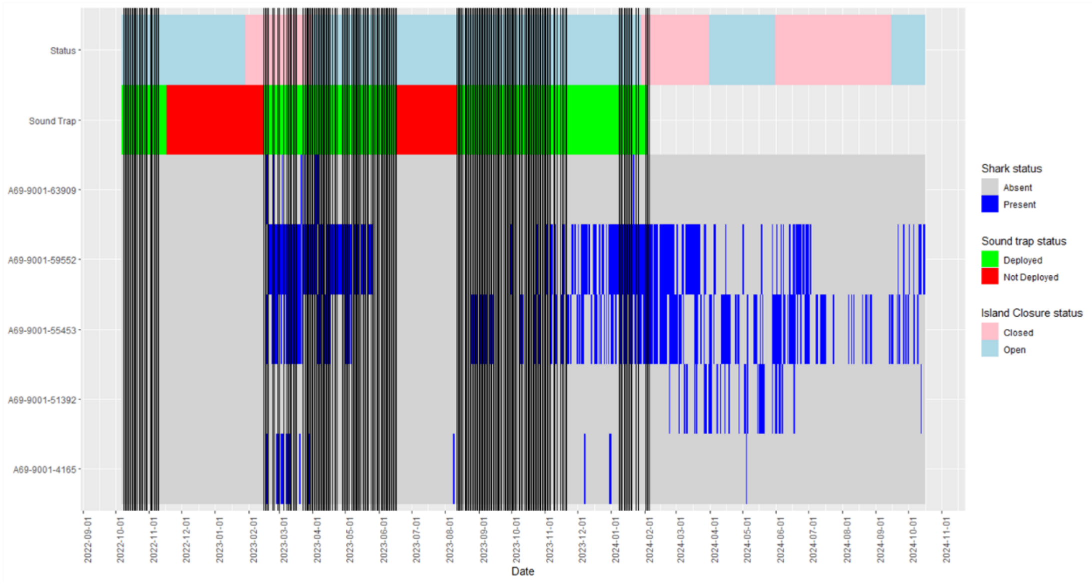
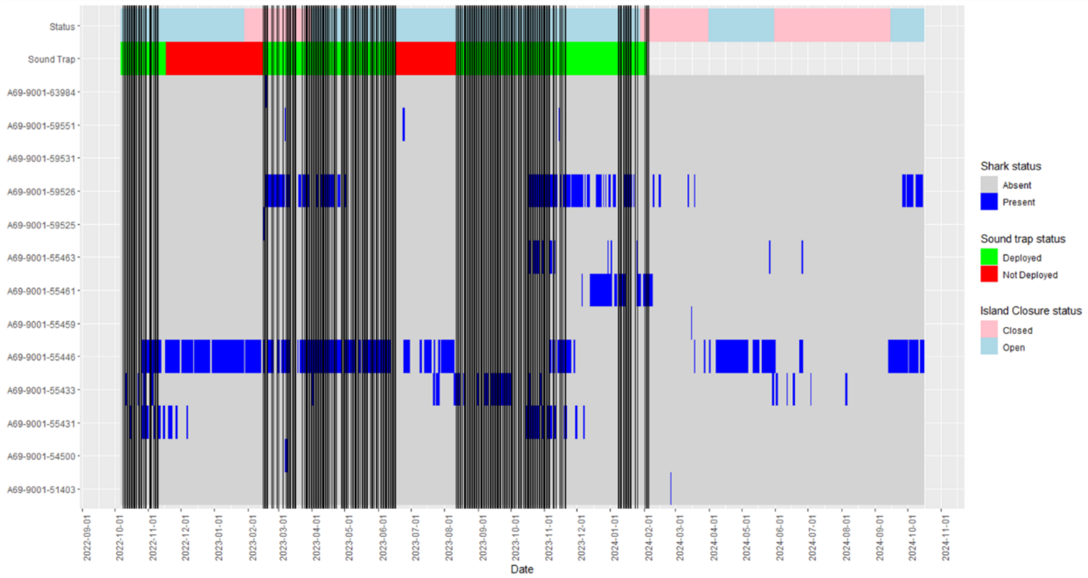


**Figure S3.** Sequence analyses showing the timelines of daily shark presence (blue) in relation to boats presence at the dumping site (black vertical lines), noting the days the island was closed or open to the public

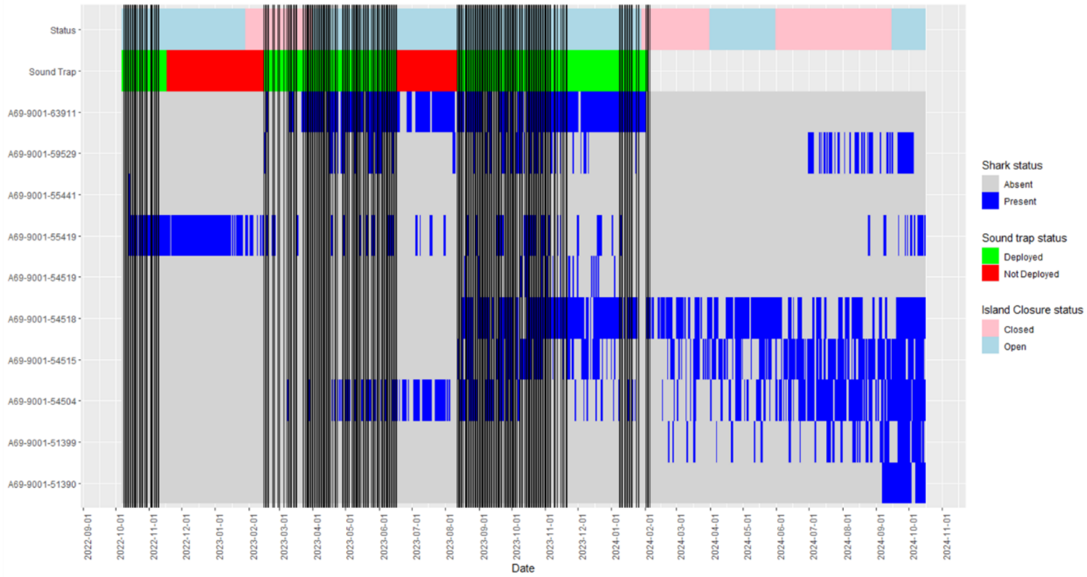
Lemon sharks



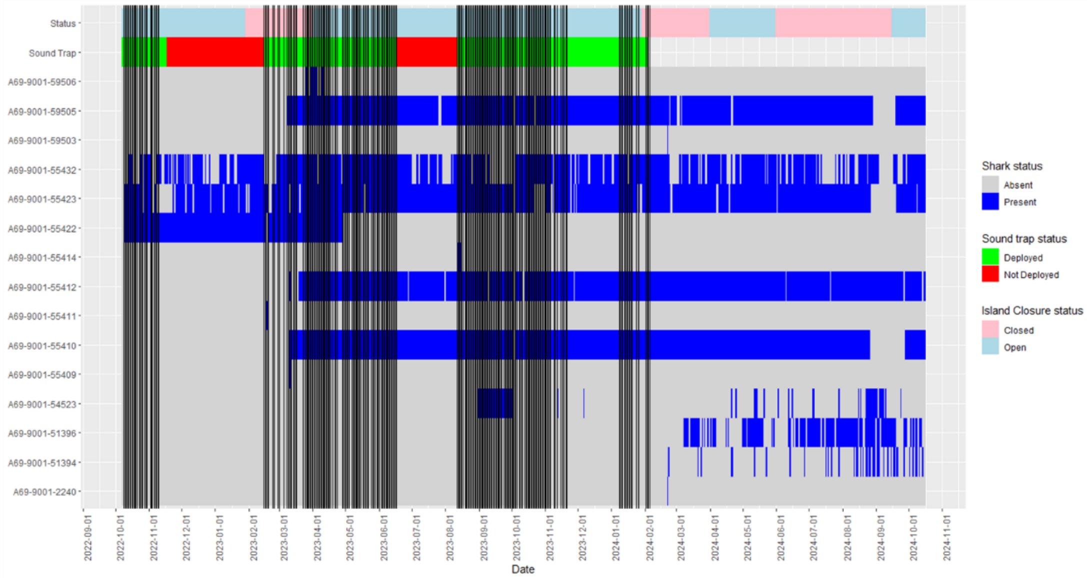

Bull sharks



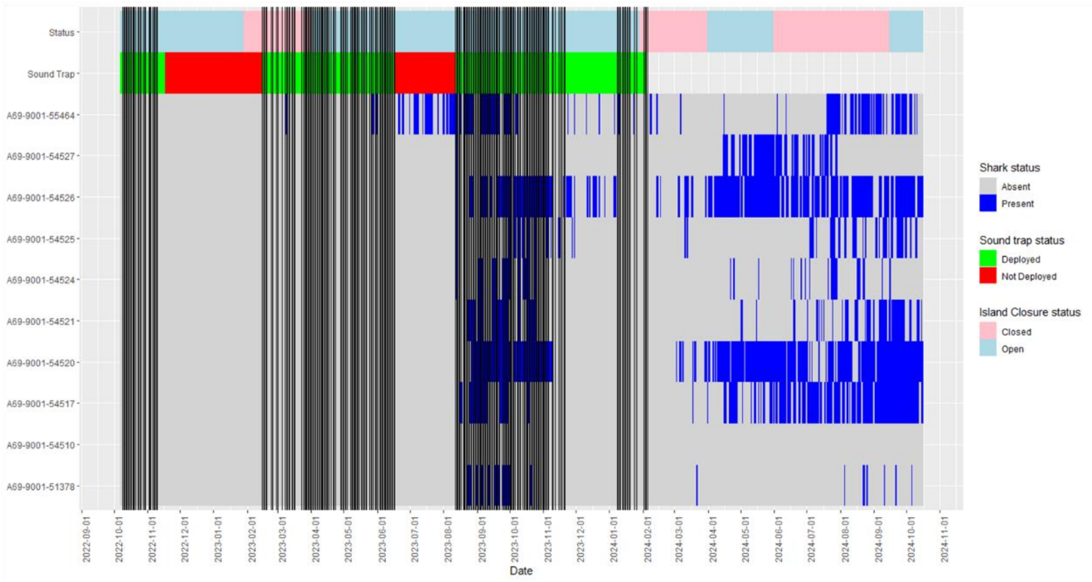
## Pigeye sharks



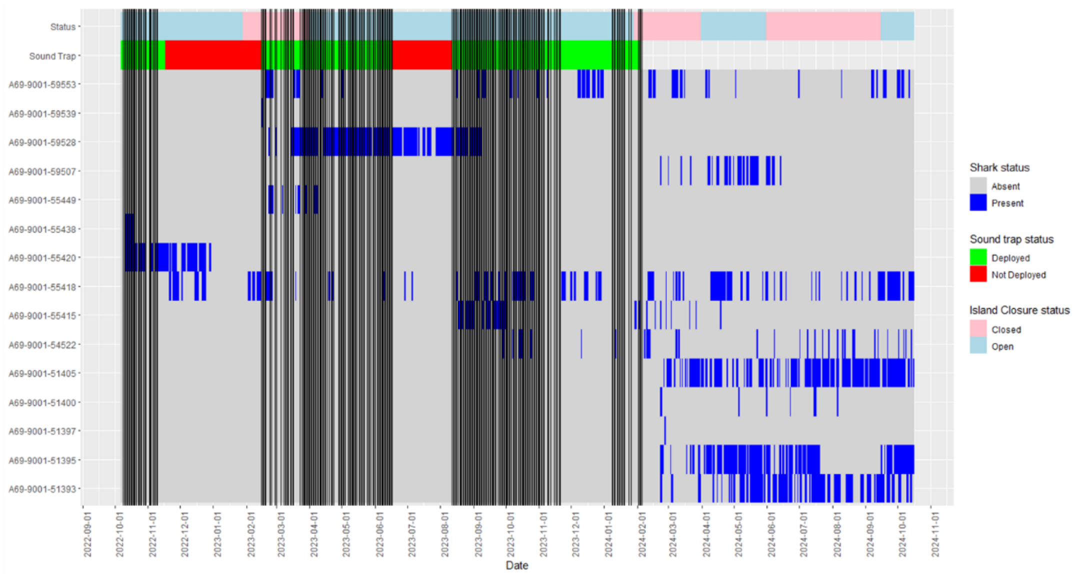

## Grey reef sharks



## Sandbar sharks




## Blacktip sharks



## Great hammerhead sharks