Queensland SharkSmart Drone Trial (2020 – 2024) Final Report

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The Department of Primary Industries proudly acknowledges all First Nations peoples (Aboriginal peoples and Torres Strait Islanders) and the Traditional Owners and Custodians of the country on which we live and work. We acknowledge their continuing connection to land, waters and culture and commit to ongoing reconciliation. We pay our respect to their Elders past, present and emerging.

Contents

List of figures

List of tables

List of acronyms

AI – Artificial Intelligence

CASA – Civil Aviation Safety Authority

DPI – Department of Primary Industries

EPBC Act - Environment Protection and Biodiversity Conservation Act

GLM – Generalised Linear Model

IUCN – International Union for the Conservation of Nature

NSI – North Stradbroke Island

NSW – New South Wales

NQ – North Queensland

SCP – Shark Control Program

SEQ – South-East Queensland

SLSQ – Surf Life Saving Queensland

TEPS – Threatened Endangered and Protected Species

1. Executive Summary

Remotely Piloted Aircraft Systems, commonly called drones, provide a high-definition aerial view of a wide expanse of ocean, allowing the detection of sharks in real-time, whilst having negligible impact on the environment and non-target species. In addition, they are capable of spotting a range of marine hazards and can assist in beach rescue operations, thus providing numerous safety benefits for water users. The Queensland SharkSmart drone trial commenced on 19 September 2020, as a partnership between the Queensland Government Department of Primary Industries (DPI) and Surf Life Saving Queensland (SLSQ). The trial was part of the Queensland Government's commitment to research to compare non-lethal alternatives with traditional shark control measures. For the first 12 months of the trial, drones were operated at two beaches on the Sunshine Coast (Alexandra Headland and Coolum North), two beaches on the Gold Coast (Southport Main Beach and Burleigh Beach) and one beach on North Stradbroke Island (NSI; Ocean beach) as well as two beaches in North Queensland (NQ) (Alma Bay, Magnetic Island, and Palm Cove in Carins). After the 12-month trial period, an evaluation was conducted on the effectiveness of drone operations across these seven locations (Mitchell et al., 2022a,b). Following the recommendations of this report, drone operations were continued at all of the South-East Queensland (SEQ) beaches and four extra beaches in SEQ were added to the trial (Rainbow Beach, Noosa, Bribie Island and Kurrawa). In NQ, flights continued at Alma Bay, but Palm Cove was discontinued due to high water turbidity levels. Drones were operated by SLSQ pilots on weekends, public holidays and school holidays, with two flights per hour from approximately 7am until midday. Flights lasted 20 - 30 minutes and followed a 400 m transect behind the surf break. All footage was collected in 4K resolution and securely archived for later analysis. Key operational and environmental data were collected for every flight. When a shark was sighted, the pilot lowered the drone to determine the species and size while estimating distance of the animal from water users. The current report presents results from the SharkSmart drone trial, from the beginning of the trial in September 2020 until 30 April 2024.

Across the ten beaches, 17,954 drone flights were conducted (16,601 at SEQ beaches, 1,353 at NQ beaches), covering 7,181 km of flight path. Drones were able to operate in varying weather conditions, including up to 20 knot winds. A relatively low number of flights (5%) were cancelled due to bad weather. In total, 676 shark sighting events occurred (where a sighting event can be one shark or multiple) across the trial, including 190 large shark (estimated to be >2 m in total length) sighting events. Of these, 23 bull sharks (*Carcharhinus leucas*) and one white shark (*Carcharodon carcharias*) were identified, and there were 39 occasions where SLSQ evacuated people from the water due to potential risks from large sharks sighted on the drones. The shark sighting rate (i.e. percentage of flights where sharks were sighted) was 3.8% when averaged across all beaches, with NSI having the highest sighting rate (24%) and Alexandra Headland and Southport Main Beach the lowest (0.3% and 0.6%). Most sightings were of singular sharks, although larger groups of sharks with >10 animals were seen in 14% of cases, with five instances where there were over 100 sharks sighted in a single flight. These large group sizes were typically smaller whaler sharks (*Carcharhinus spp.*) feeding on bait balls. The total number of sharks seen across the trial was 4,959.

Statistical analysis indicated that location, the sighting of other fauna, season, wind speed and direction, turbidity, tidal state, glare, atmospheric pressure all had a significant influence on the probability of sighting sharks. Shark sightings were most likely at NSI and Burleigh Beach, possibly because the former is a highly productive area where there is a high density of fauna and key shark prey species (large fish and bait balls (a closely packed group of small fish)), and the latter is close to the mouth of a creek which can lead to higher productivity in the local area. Summer had the highest probability of shark sightings, likely due to higher levels of rainfall leading to greater productivity in the coastal zone. Higher wind speeds, especially those from easterly or southerly directions, greater turbidity and higher glare all led to lower probability of sighting sharks, as would be expected. Greater probability of sightings also occurred during high atmospheric pressure (i.e. calm weather) and during high and falling tidal states. High resolution movement tracks and heatmaps of shark presence were generated for each drone trial beach, revealing relatively linear south to north movements at NSI, whereas at Burleigh Beach, shark presence was clustered close to the southern end of the beach near a rocky headland, possibly because this area has rocky habitat and is close to a river mouth, thus supporting higher productivity and more prey for sharks.

When data from all beaches were combined, the total number of shark sighting events by drones (676), as well as those larger than 2 m (190), were significantly greater than those caught in adjacent Shark Control Program (SCP) gear (284 and 133, respectively). This was despite drones operating for only approximately

2.9% of the time that SCP nets were deployed and 5.1% of the time drumlines were actively fishing. NSI and Burleigh Beach had significantly higher shark sighting events than catches, with 314 vs 32 and 168 vs 24, respectively. Numbers of large shark sighting events were also significantly greater than those caught in nets and drumlines at NSI, Burleigh Beach, Kurrawa and Bribie Island. Conversely, Alexandra Headland, Rainbow Beach and Alma Bay all had significantly higher shark catches on SCP gear than sightings by drones. When comparing drone sightings to SCP catch, it is important to note the differences in the amount, type (i.e. nets and/or drumlines) and positioning (distance offshore) of SCP gear at the various beaches. Across all drone trial beaches, a similar number of bull sharks were detected by drones (23) and caught in SCP gear (26), yet 64 tiger sharks (*Galeocerdo cuvier*) were caught in SCP gear with none being seen by drones. This may be related to the different movement patterns of bull and tiger sharks, as bull sharks are known to spend more time in nearshore waters and would be more likely to be detected on drones, whereas tiger sharks are known to be further offshore. Time of day may also be influencing this disparity for tiger sharks, as the drones were only operating during the morning whereas SCP gear operates 24 hours of the day. Five white sharks were caught in SCP gear vs one sighting on drones. Overall, it is important to note that drones and SCP gear operate in a very different way, with the former being a surveillance tool aimed at detecting sharks and warning water users in real time, whereas the latter is designed to catch and kill sharks before they can get to beaches. The two methods also operate on very different spatial and temporal scales, so these factors must be carefully considered.

SCP gear had a substantially higher environmental impact than drones due to the capture of 123 non-target animals (not including non-target sharks) at these ten beaches during the trial period, the majority of which were protected under the Environment Protection and Biodiversity Conservation Act 1999 (e.g. dolphins, whales, turtles and dugongs (*Dugong dugon*)). Conversely, drones observed a wide range of fauna in a non-invasive way, including turtles, stingrays, manta rays (*Mobula alfredi*) and eagle rays (*Aetobatus ocellatus*) on 7% of flights. NSI had a very high prevalence of other fauna sightings, with marine animals seen on 84% of flights. The prevalence was much lower other beaches. Sightings of large fish and bait balls, which can be prey for sharks, as well as jellyfish (some of which were stinging species), highlight the ability of drones to provide real time information to assist SLSQ in risk assessment at Queensland beaches. Further collaborative research projects are being developed with other government research institutions and universities to maximise the scientific value of the archived drone footage and contribute to management and conservation of key species.

This project demonstrated that drones can consistently detect sharks at SEQ beaches, as well as Alma Bay in NQ, and are able to operate across a range of environmental conditions. The real-time monitoring capability of drones provides an extra level of safety for water users. Throughout the trial, the drones have also been used to rescue swimmers from rip currents and assist with missing person searches, highlighting their value as an holistic beach safety tool. Based on these positive outcomes, it is recommended that drones continue to be operated at the existing SEQ beaches. Drones should also be trialled at other beaches, which should be chosen based on rigorous criteria, including CASA regulations, the suitability of environmental conditions, beach visitation rates, historical SCP catch and SLSQ presence. To enhance the capability of the drone program further, new advancements such as extended and beyond visual line of sight flying protocols, autonomous drone technology and improved data transfer and storage processes, should be investigated and tested at the existing drone trial beaches. Further testing and development of AI algorithms and advanced camera technologies should be pursued to assess where they can improve detection rates of sharks and increase operational efficiency. Analysing movement data from tagged sharks, alongside drone sightings and SCP catch data, should also be pursued, to increase our understanding of shark movements and behaviour at beaches to inform on risk to water users. Lastly, increasing public awareness of the drone trial through education should be a priority, to effectively communicate how the drone trial improves safety for water users.

2. Background

Drones are becoming increasingly used in marine science research, for quantifying fauna presence (Benavides et al., 2019; Schofield et al., 2019) and behaviour (Raoult et al., 2018; Torres et al., 2018), and monitoring fishing activity (Bloom et al., 2019; Provost et al., 2020) and beach usage (Provost et al., 2019). Detecting and monitoring sharks from drones to improve the safety of water users is another field that has recently developed, particularly in Australia (Butcher et al., 2020; Colefax, 2020; Butcher et al., 2021). Drone technology has rapidly advanced in recent years, to the point where lightweight, affordable, easy-to-pilot drones are now available, with AI systems in development to automatically detect and identify sharks (Saqib et al., 2017; Sharma et al., 2018). This technology therefore offers new opportunities to monitor sharks in real-time and collect a wide range of information on the species present, their behaviour and potential risk to water users. Drones also increase the safety of ocean users by allowing the timely implementation of operational responses to mitigate risk of shark bites.

A large body of research has been conducted in recent years as part of a drone trial for shark monitoring in New South Wales. This research has produced a range of valuable data, including the ability of drones to detect marine fauna across a variety of environmental conditions (Colefax et al., 2019; Butcher et al., 2020), the influence of environmental conditions on shark sightability (Kelaher et al., 2020), the behaviour of white sharks in the vicinity of surf beaches and around whale carcasses (Colefax et al., 2020b; Tucker et al., 2021), and the abundance and diversity of other marine fauna (Colefax et al., 2018; Tagliafico et al., 2020). Surveys of public sentiment found that support for drones was high (>85%), predominantly due to the fact they have minimal impact on fauna and the environment (Stokes et al., 2020; DAF 2021). However, certain limitations of drones can reduce their effectiveness for detecting sharks and subsequently their effectiveness as a shark bite mitigation tool; particularly their inability to operate during rain or when wind speeds are >20 knots, and their reduced ability to detect sharks in deeper and more turbid water. However, the overall success of trials across many beaches in NSW where they were able to detect sharks and other marine fauna under a range of environmental conditions, has led to the development of an operational drone program at 50 beaches along the NSW coastline, delivered by Surf Life Saving NSW.

In Queensland, the Shark Control Program has operated since 1962, using nets and drumlines to catch and remove large sharks that may pose a threat to water users. However, the use of nets and drumlines also leads to the catch of a diverse range of non-target marine fauna, some of which are classed as Threatened, Endangered and Protected Species (TEPS) (Paterson, 1990; Gribble et al., 1998; McPhee et al., 2021). This can represent a threat to local populations of these species. The public increasingly expect that effective beach safety measures are implemented that minimise impacts on non-target species and sharks.

Alternative non-lethal shark control approaches have been trialled in a number of locations around the world. These include: physical barriers (O'Connell et al., 2018); electrical shark deterrents (Huveneers et al., 2018); shark spotter programs (Engelbrecht et al., 2017); tracking/monitoring of tagged sharks (Lipscombe et al., 2020; Spaet et al., 2020); and plane, helicopter and drone based aerial monitoring (Kelaher et al., 2019). These methods offer a means of reducing risk to water users whilst significantly reducing the impact on non-target marine fauna (McPhee et al., 2021). The Queensland Department of Primary Industries (DPI) commissioned Cardno to prepare a report on alternative non-lethal shark control methods available, and their potential for use in Queensland waters (Cardno, 2019). Drone-based surveillance was identified as being one of the most promising alternatives available, especially for South-East Queensland (SEQ) where water clarity is relatively high all year round. Building on the findings of this report and discussion by members of the SCP Scientific Working Group in March 2020, a drone trial was recommended for SEQ beaches, to test their suitability across a range of Queensland conditions.

The trial commenced in September 2020, with drones operating at five beaches in SEQ and two in North Queensland (NQ). After the first 12 months of the Qld SharkSmart drone trial, an interim evaluation was undertaken to analyse the effectiveness of the program for detecting sharks and providing safety benefits to water users (Mitchell et al., 2022a,b). During the first 12 months, 3,669 flights were conducted across the five SEQ beaches and two NQ beaches, covering 1,468 km of flight paths. In total, there were 174 shark sighting events (a sighting event could include one or more sharks) across the seven beaches, including 48 large shark sighting events where the shark(s) was estimated to be >2 m in length. North Stradbroke Island and Burleigh Beach had the highest numbers of sighting events (94 and 73 respectively) and Coolum North the least (0). The overall shark sighting rate (i.e. percentage of the total number of flights where sharks were sighted) was 3% across all locations combined. Location, sighting of other fauna, season and time of day had significant influences on the sightability of sharks, with higher probability of sightings occurring during summer and autumn and during early morning flights. Drone sightings were markedly higher than SCP catch at the same beaches, both for all sharks combined and for large sharks >2m. Drones sighted more bull sharks than were caught in adjacent SCP gear (nets and drumlines), whereas SCP gear caught more tiger sharks than were sighted by drones. The environmental impact of the drone trial was minimal, compared to SCP gear, which caught 19 non-target animals during the period. Trial flights were conducted at Palm Cove in North Queensland, but these were discontinued due to high turbidity levels preventing sharks or other marine fauna from being detected by drones. Following the recommendations in the interim evaluation, drone flights were continued at the five SEQ beaches and one NQ beach (Alma Bay), with four new drone trial sights added on the Gold Coast and Sunshine Coast, based on a set of selection criteria. This report expands on the results presented in the interim evaluation, presenting the results of the entire drone trial conducted to date, from 19 September 2020 to 30 April 2024 (not including the discontinued Palm Cove site in Cairns).

2.1 Research Aims

Key aims of the Queensland SharkSmart drone trial are as follows:

1. Determine the capacity of drones to operate in a range of weather and environmental conditions
2. Evaluate the influence of environmental conditions and operational factors on the sightability of sharks
3. Compare the sighting rate of sharks in the drone trial to catch in the traditional SCP gear (nets and drumlines) installed at the same beaches
4. Maintain high levels of public and work health and safety, ensuring compliance with civil aviation regulations; and
5. Ensure data privacy is upheld

3. Methods

3.1 Drone trial locations

Based on the recommendations of the Cardno report on alternative approaches to shark control in Queensland (Cardno, 2019), advice from the SCP Scientific Working Group and Civil Aviation Safety Authority (CASA) regulations, five beaches in SEQ and two in NQ were selected for the initial trial period from September 2020 – October 2021 (Mitchell et al. 2022a). Following successful adoption of drone patrols at six of these sites (seven sites were used initially, with one subsequently dropped), another four sites were added between September and November 2022.

A range of locations were identified as potential sites for the drone trial, noting that restricted airspace close to airports and other no-fly areas had to be excluded. Other key factors which determined the choice of locations were the presence of SCP gear, SLSQ lifeguard presence at beaches, levels of beach usage, historical catch of potentially dangerous sharks and proximity to river mouths. Based on all of these factors, the following beaches were chosen to be part of the Queensland SharkSmart drone trial:

South-East Queensland

- Alexandra Headland, Sunshine Coast (September 2020)
- Bribie Island (September 2022)
- Burleigh Beach, Gold Coast (September 2020)
- Coolum North, Sunshine Coast (September 2020)
- Kurrawa, Gold Coast (November 2022)
- Noosa, Sunshine Coast (November 2022)
- Ocean Beach, North Stradbroke Island (September 2020)
- Rainbow Beach (September 2022)
- Southport Main Beach, Gold Coast (September 2020)

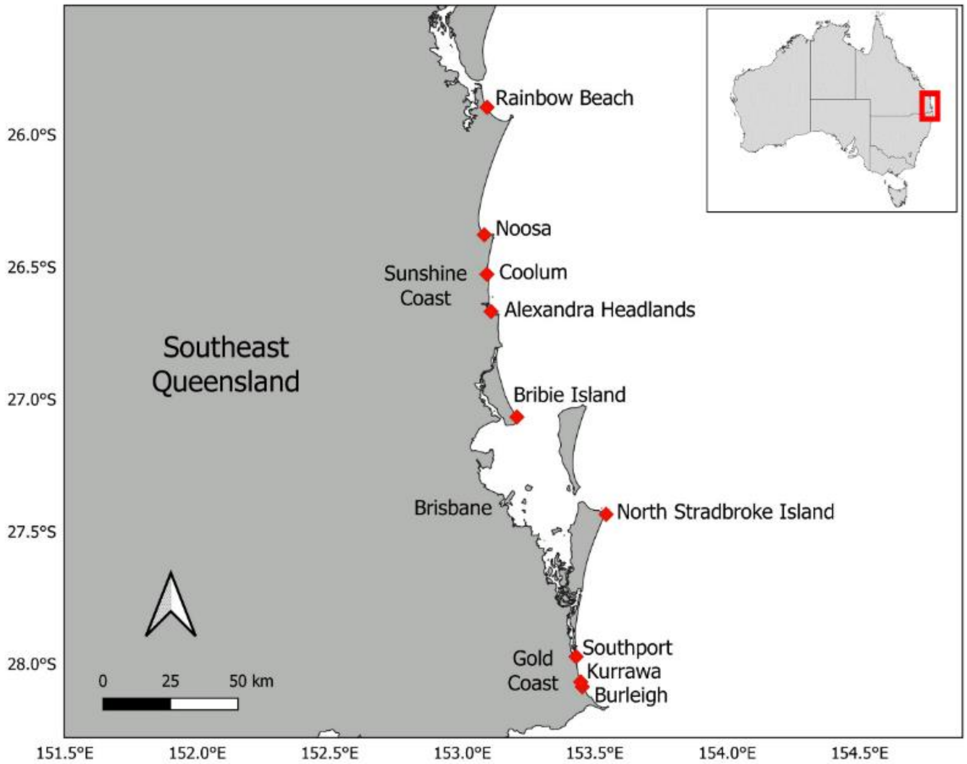


Figure 1 Map of the nine South-East Queensland drone trial locations.

North Queensland

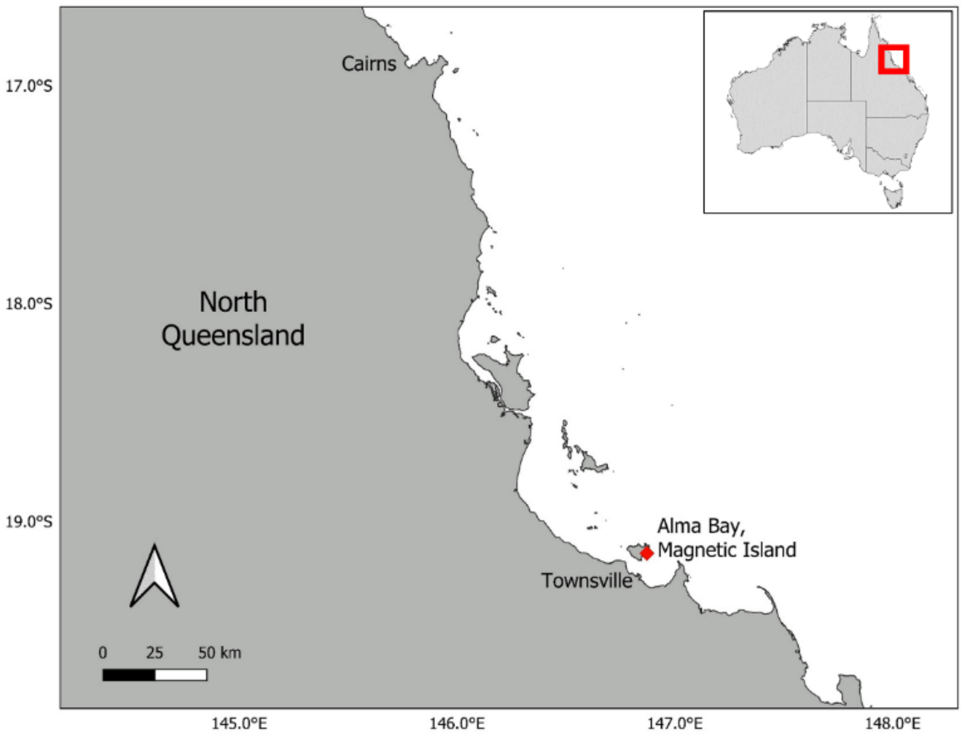


Figure 2 Map showing the location of the Alma Bay site in North Queensland.

3.2 Flight schedule

To achieve optimal coverage of these ten beaches during times of highest public usage, the trial ran flights during:

- Saturdays
- Sundays
- Public holidays
- School holiday weekdays

3.3 Flight times

Flights were conducted at 30-minute intervals, commencing when the beach opened for the day (usually between 7-8 am) and ending after a final flight at approximately 12 pm. The project team decided to only run drone operations during the morning, because higher winds usually occur during the afternoon in Queensland, which would have resulted in a greater number of flights being cancelled. Two flights were conducted per hour, which allowed time in between for changing drone batteries and recording flight log and environmental data. This typically resulted in eight flights per day for each beach. If a potentially dangerous shark was sighted or another situation required a flight sooner, then situational adjustments were made.

3.4 Flight transects

Flight paths were designed as a transect, with the inside edge of the viewable area lining up with the 'backline' of the surf break. The position of the surf break can change significantly due to tide and weather variables, so flights were made with manual control (as opposed to automated flight paths). Each flight path extended up to 200 m north and south of the ground control station, covering up to an 800 m flight circuit (Figure 3). Flights lasted between 15 and 30 minutes, with the drone flying at approximately 10-20 kmh-1 and making multiple passes of the transect. Drones were flown at a constant altitude of 60 m, providing a field of view width of approximately 110 m with the camera at a 45° angle. The full length of the SLSQ flagged area was included within the flight path. Drones took off and landed from a 30 m exclusion zone on the beach and they were not flown directly above water users or people on the beach. To protect the privacy of beach users, cameras were only turned on once the drone was beyond the surf break.

Figure 3 Schematic showing the position of drone transects relative to the flagged area of the beach. The position of the exclusion zone relative to the SLSQ flags is variable but within the extent of the transect.

During the first 12 months of the trial, DJI Mavic Pro and Mavic 2 Pro drones were used for the majority of flights, with a small number of flights using DJI Phantom 4 drones when the Mavic Pro drones were grounded due to technical malfunctions. Following this, Mavic 2 Enterprise and Mavic 2 Enterprise Zoom drones were used. Most recently, the Mavic 3 Classic with ND filter has been the main model of drone used. Throughout the trial, all footage has been recorded in 4K video (Figure 4) to maximise the resolution for detecting sharks, and all telemetry data was recorded in the form of accessory SRT files.

When a shark was sighted, the pilot lowered the drone to assist in accurate identification of the species where possible and estimation of its length. The shark was then tracked until a drone battery change was necessary or the shark moved out of the area. When tracking a shark, the animal was maintained in the centre of screen with the shark's heading aligning with the forward aspect of the drone, as much as possible. Shark tracking was conducted at an appropriate height (ideally 10-20 m) to suit conditions. All shark sightings throughout the trial were recorded by pilots in a dedicated log, which contained the location, date, time, approximate length, species and behaviour of the shark. All sightings were verified by the primary author using the recorded footage from the flight. If the shark was deemed to be a risk to water users, standard SLSQ procedures for beach evacuation were followed. Factors such as shark species, size, number of animals, distance from water users, swimming direction and shark behaviour were considered in determining risk.

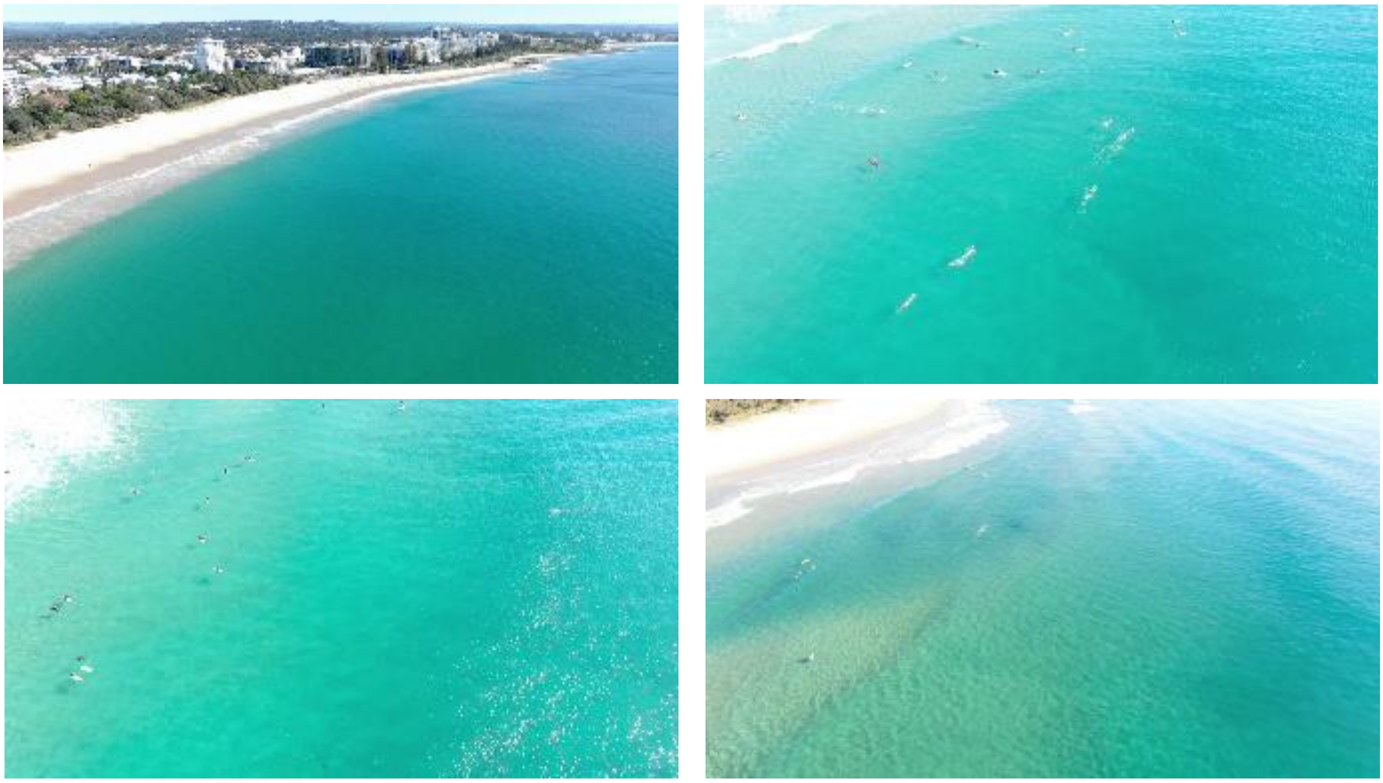


Figure 4 Example images from drone footage taken at Alexandra Headland, showing the path of the transect behind the surf break and the perspective seen from the drone.

3.5 Data collection

An extensive range of environmental and operational data were collected for every drone flight and recorded in a database. These included:

- Pilot name
- Location
- Flight number for the day
- Video filename
- Transect direction
- Date
- Start time
- End time
- Duration of flight
- Start latitude
- Start Longitude
- Flight speed
- Rainfall
- Wind speed
- Wind direction
- Cloud cover (Oktas, 1-8 scale, estimated by the pilot)
- Temperature
- Atmospheric pressure
- Sea state (Beaufort state, 1-12 scale)
- Tidal state
- Swell height
- Swell direction
- Turbidity (0-100% scale, estimated by the pilot)

- Glare (1-5 scale, estimated by the pilot)
- Season
- Humidity
- Fauna sighted

Environmental data were collected from the nearest Bureau of Meteorology weather station for each flight. Turbidity, glare and cloud cover were estimated by the pilots.

3.6 Data analysis

Shark sighting rates were calculated at a beach level to identify the percentage of flights where sharks were observed, enabling comparison between beaches. Leopard sharks (*Stegostoma tigrinum*) were excluded from the analyses due to their high abundance at multiple beaches, which would have inflated the number of sharks recorded, and because they pose no risk to water users. A subset of videos (5% of the total number collected) were reviewed by the project leader to check whether any sharks had been missed by pilots.

A Generalised Linear Model (GLM) was applied to determine how a range of environmental and operational factors (including location) influenced the sightability of sharks across the combined from all trial beaches. Sightability represented the likelihood of sighting sharks, which is influenced by both shark presence/absence and the ability of drones to detect sharks in the current conditions. Yet, it must be noted that no ground truthing was undertaken to determine what could not be seen by drones, so the sightability variable only represents what could be seen. A separate GLM was also run for the beach with the highest numbers of shark sightings. The response variable of these GLMs was modelled with a binomial distribution (i.e. shark sighted or not sighted). Predictor variables were checked for correlation, which indicated all variable combinations had <0.5 Pearson correlation coefficients. The distributions of predictor variables were also visualised and a square root or log +1 transformation was applied to achieve more uniform distributions if necessary. To determine the best-fitting model and identify significant variables which explained a meaningful proportion of the deviance in the response variable, we applied a backward stepwise approach to drop individual predictors one step at a time to identify how this changed the Akaike Information Criterion (AIC; Akaike, 1974) values. The best performing model was identified as having the lowest AIC and only those predictor variables which were significant.

Positional data collected for shark sightings were used to map the movement tracks of individual sharks at drone trial beaches. The track length, direction of movement of sharks, their distance from shore and from water users and whether they interacted with any other fauna or floating objects was also recorded.

Comparative analysis of drone shark sighting events and shark catch in adjacent nets and drumlines was undertaken to assess how the total number of sharks, large sharks >2 m in length and species of most concern (bull/tiger/white sharks) differed between the two methods at an individual beach level. Binomial tests with a probability level of 0.5 were applied to determine whether there was a significant difference ($p<0.05$) between sightings and catch. Linear regression was applied to determine whether there was a relationship between the number of shark sighting events from drones and catch in SCP gear across all the beaches covered by the trial. Sighting rates of other key faunal groups were also quantified, as well as catch of non-target animals in SCP gear.

To map the spatial movements of sharks at each drone-trial beach, the raw tracks of each shark were plotted in QGIS, using the latitude and longitude values recorded on the drone when it was directly overhead following a shark. Once all tracks had been plotted, a kernel density heatmap of all individual track points was created for each beach, to indicate which areas sharks spent the most time in.

4. Results

4.1 Operational results

Between 19 September 2020 and 30 April 2024, SLSQ operated 17,954 individual drone flights across the 10 SEQ and NQ beaches, representing a total minimum flight distance of 7,181 km (Table 1). Mean flight time across this period was 20 min (± 5.1 min SD) for both regions, during which multiple passes were made of the transect. Drones were able to operate in a range of weather conditions across seasons, although they could not fly in winds greater than 20 kn or during rainfall. This resulted in a minimum of 964 individual flights being lost to bad weather across all the trial beaches, which represented 5% of the total number of flights conducted

(Table 1). The number of days lost to bad weather was variable across beaches, with NSI being the highest (16%) and Kurrawa the lowest (1%). The drones operated by SLSQ were mechanically reliable, with few malfunctions. Where issues arose, these were primarily due to sand getting into the drone and causing camera gimbal issues, although these were easily rectified by cleaning the internal parts of the drones. Four drones were lost throughout the trial, due to suspected sensor failure and/or loss of connection between the drone and pilot controller. High numbers of people on the beach (e.g. during beach carnivals and other events) also caused some difficulty on a small number of days, with flight days having to be ended early due to the pilot being unable to fly directly above people, however this issue was partially mediated by adding observers at the busier Gold Coast beaches to manage people on the beach, mainly during take-off and landing. Some staffing issues also resulted in lost flying days, for example where pilots were unable to work due to the COVID-19 pandemic or other medical issues.

In addition to providing a platform to sight sharks and warn the public of the presence of potentially dangerous sharks, drones offered an added safety benefit of being able to identify other marine safety issues and assist with rescue operations. This was demonstrated by the involvement of SLSQ drone pilots in the rescue of four people from a strong rip current at Coolum North during the trial. Also, SLSQ drone pilots assisted the Queensland Police Service with several land and sea-based missing person search operations.

Table 1 Operational metrics for each beach covered by the Queensland SharkSmart drone trial.

Location	Total number of flights	Distance covered (km)	No. of flights lost to bad weather and percentage of total flights
South-East Queensland (SEQ)			
Alexandra Headland	2,746	1,098	110 (4)
Bribie Island	968	387	47 (5)
Burleigh Beach	2,591	1,036	95 (4)
Coolum North	2,320	928	208 (8)
Kurrawa	1,310	524	19 (1)
Noosa	1,338	535	51 (4)
North Stradbroke Island	1,307	523	241 (16)
Rainbow Beach	1,408	563	38 (3)
Southport Main Beach	2,613	1,045	106 (4)
Sub-Total SEQ	**16,601**	**6,640**	**915 (5)**
North Queensland (NQ)			
Alma Bay	1,353	541	49 (3)
TOTAL	**17,954**	**7,181**	**964 (5)**

4.2 Shark sighting events

A total of 676 shark sighting events occurred during the Queensland SharkSmart drone trial, with the vast majority occurring at SEQ beaches. A shark sighting event included instances of one or multiple sharks. This total does not include leopard sharks as they are not considered dangerous to humans and because they were ubiquitous at NSI, so would inflate the number of shark sightings if included. Numbers of sighting events were highly variable across beaches, ranging from seven shark sighting events at Alexandra Headland to 314 sightings at NSI (Table 2). Most of these sighting events were smaller whaler sharks <2 m in length, and therefore posed a lower risk to water users. However, 190 large sharks were observed, mostly at Burleigh Beach and NSI. For the species considered most likely to be dangerous to humans (white, tiger and bull sharks), there were 23 sightings of bull sharks across NSI, Burleigh, Noosa and Rainbow Beach, and one sighting of a white shark at Southport main beach (Table 2). No tiger sharks were sighted during the trial period. Drone pilots were usually able to differentiate between the main groups of sharks, including white/tiger/bull and whaler sharks (Figure 5), as well as leopard sharks and shovelnose rays. However, in certain ocean conditions such as higher turbidity or if the shark remained close to the seabed, identification to species/group was not possible (by either the pilot or primary author). In total, sharks were sighted on 3.8% of all flights, with the sightings rates varying from 0.3% at Alexandra Headland to 24% at NSI (Table 3).

Table 2 Number of shark sighting events at Queensland SharkSmart drone trial beaches.

Location	Total number of shark sighting events*	No. of large (>2 m) shark sighting events	No. of white, bull, tiger sighting events	No. of water evacuations
South-East Queensland				
Alexandra Headland	7	2	0	4
Bribie Island	14	1	0	1
Burleigh Beach	168	17	6 bull	9
Coolum North	22	2	0	2
Kurrawa	19	3	0	0
Noosa	69	0	2 bull	5
North Stradbroke Island	314	151	14 bull	12
Rainbow Beach	30	3	1 bull	0
Southport Main Beach	16	7	1 white	0
North Queensland				
Alma Bay	17	4	0	6
TOTAL	**676**	**190**	**24**	**39**

*total does not include leopard sharks

Table 3 Percentage of flights where shark sightings occurred at SharkSmart drone trial beaches.

Location	Percentage of flights where sharks were sighted*
South-East Queensland (SEQ)	
Alexandra Headland	0.3
Bribie Island	1.4
Burleigh Beach	6.5
Coolum North	0.9
Kurrawa	1.5
Noosa	5.2
North Stradbroke Island	24.0
Rainbow Beach	2.1
Southport Main Beach	0.6
North Queensland (NQ)	
Alma Bay	1.3
All SEQ and NQ locations combined	**3.8**

*total does not include leopard sharks

Figure 5 Example images of sharks recorded during the Queensland SharkSmart drone trial. a) white shark recorded at Southport Main Beach, Gold Coast in September 2020, b) a group of five large whaler sharks observed at Ocean beach, North Stradbroke Island in November 2020, c) a whaler shark from the blacktip complex recorded at North Stradbroke Island in December 2020, d) a large whaler shark sighted at Kurrawa in May 2023, with fishing line trailing from its mouth, e) a bull shark recorded at North Stradbroke Island in June 2023, and f) whaler shark at North Stradbroke Island in December 2020.

The numbers and rates of sighting events reported above were irrespective of group size, i.e. the sighting could have been one shark or 100. Although sightings were singular sharks in many cases (313 out of 598, 52%), larger numbers of sharks >10 were seen in 14% of cases, with five instances where there were over 100 sharks sighted in a single flight (Figure 6). Overall, the total number of sharks sighted was 4,959, although it must be noted that some sharks would have been sighted across multiple flights on the same day, so this number may be an overestimate. Large group sizes were typically sighted when bait balls were present (Figure 7). Mean number of individuals sighted was highest at Noosa (19.5 per flight) and lowest at Bribie Island (1.09 per flight) (Figure 8). Many large groups were sighted at NSI, however the large number of individual sharks also sighted resulted in the mean being lower at this location (8.9) (Figure 8).

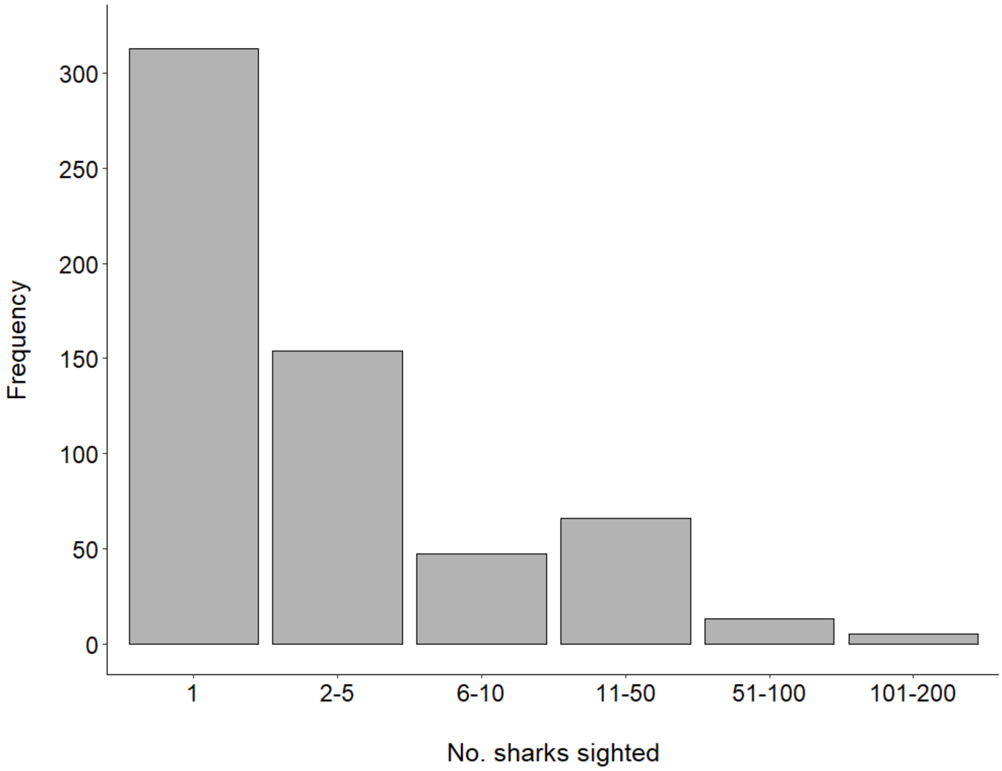


Figure 6 Number of individual sharks sighted on a single flight and the frequency of occurrence throughout the Qld SharkSmart drone trial (excluding flights were no sharks were sighted).

Figure 7 Image of a large bait ball with 25+ whaler sharks sighted at North Stradbroke Island.

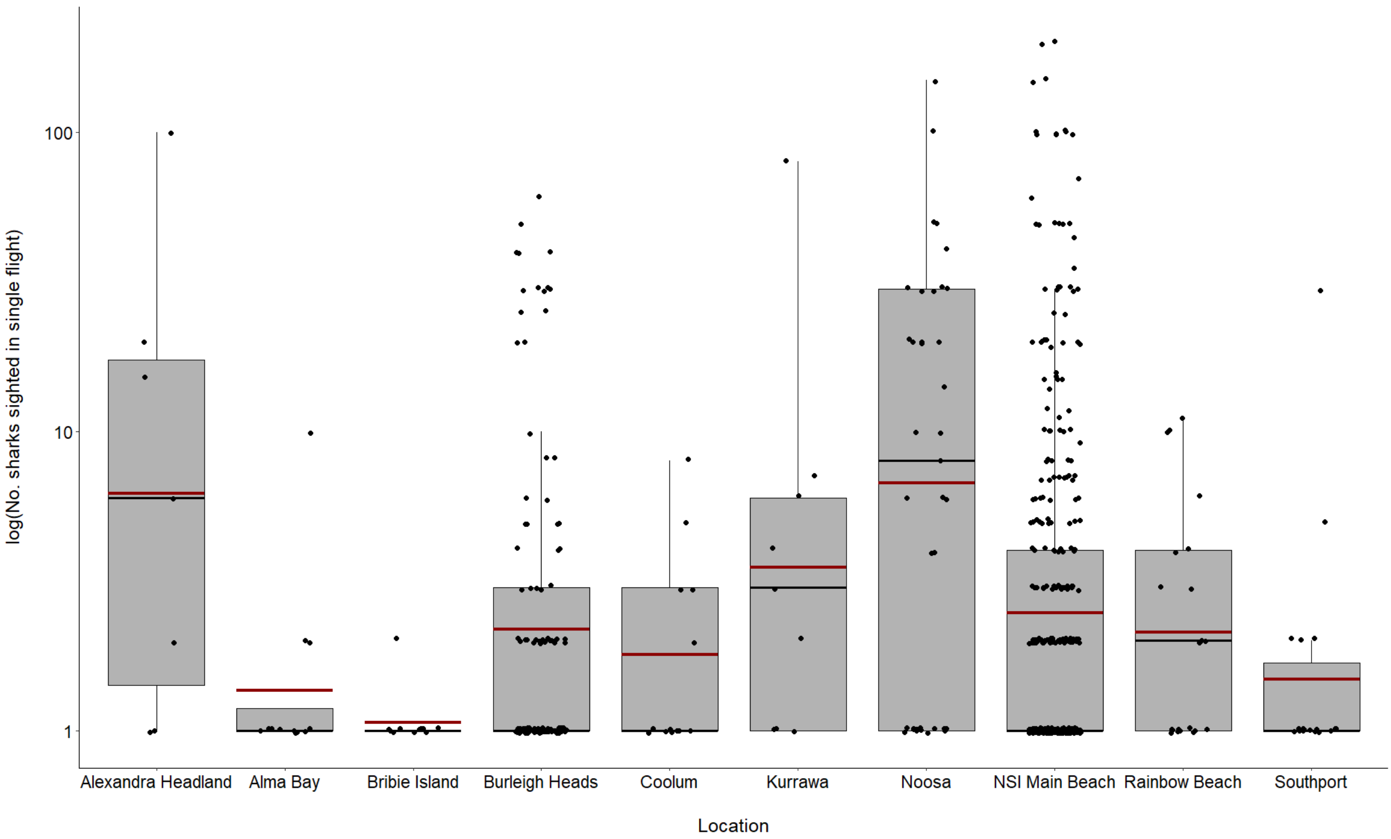


Figure 8 Boxplot showing the range in the number of sharks sighted in a single flight for each of the Qld SharkSmart drone trial locations (excluding flights where no sharks were sighted). Dark red lines = mean no. sharks sighted in a single flight, black lines = median, grey boxes = 25-75% quartiles, black points = raw data.

4.3 Environmental and operational factors influencing shark sightability

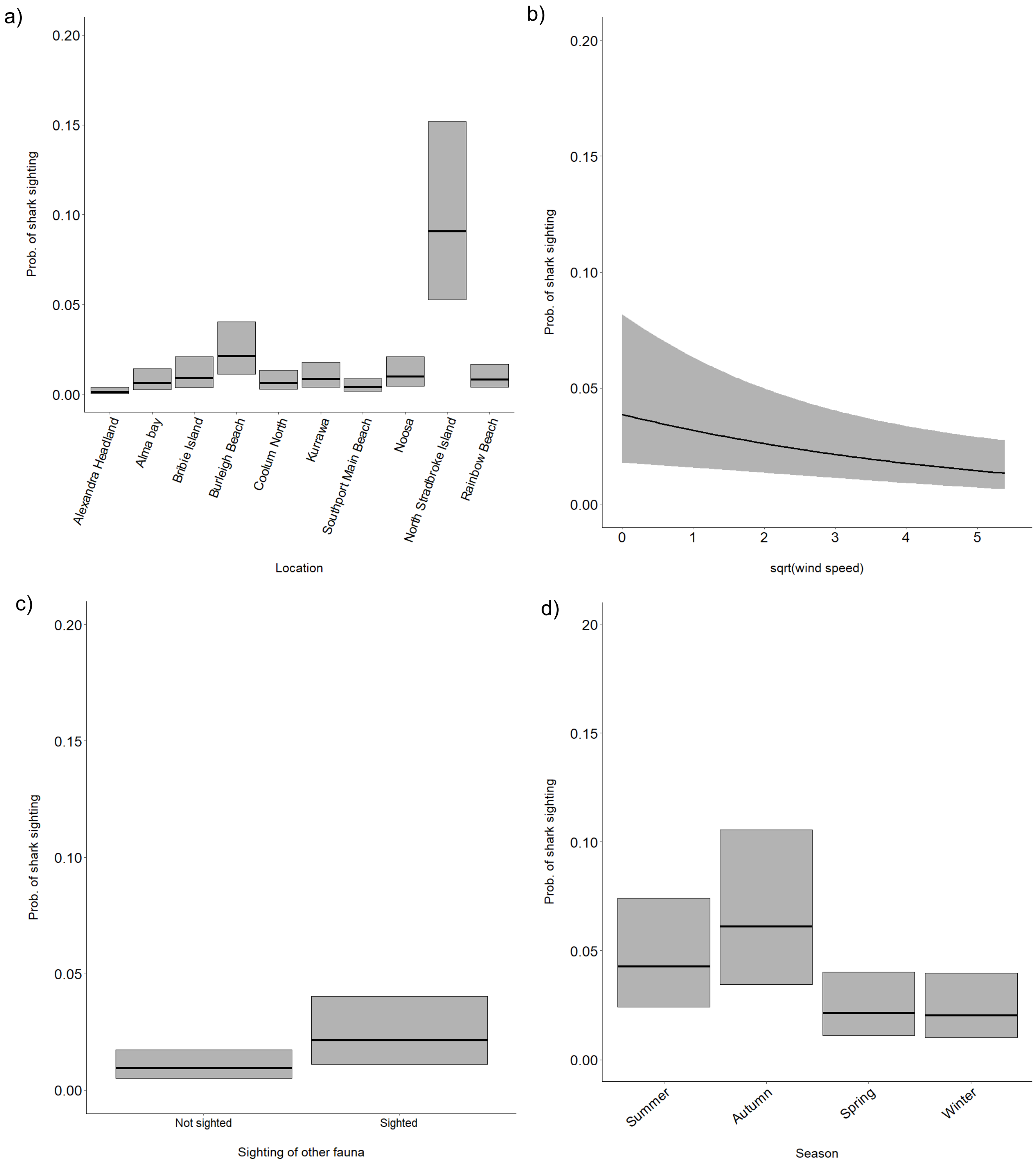
Drones operated across a wide range of environmental conditions during the trial, providing important data to assess how environmental factors affected shark sightings. For example, wind speed varied between 0 and 29 km h-1 (mean = 9.7 km h-1) and was recorded from all compass directions, most commonly from the south-southeast and least often from the west-northwest. Rainfall was recorded as the total rainfall over the previous seven days, because there is a lag time between rain falling and river outflow into the coastal zone.

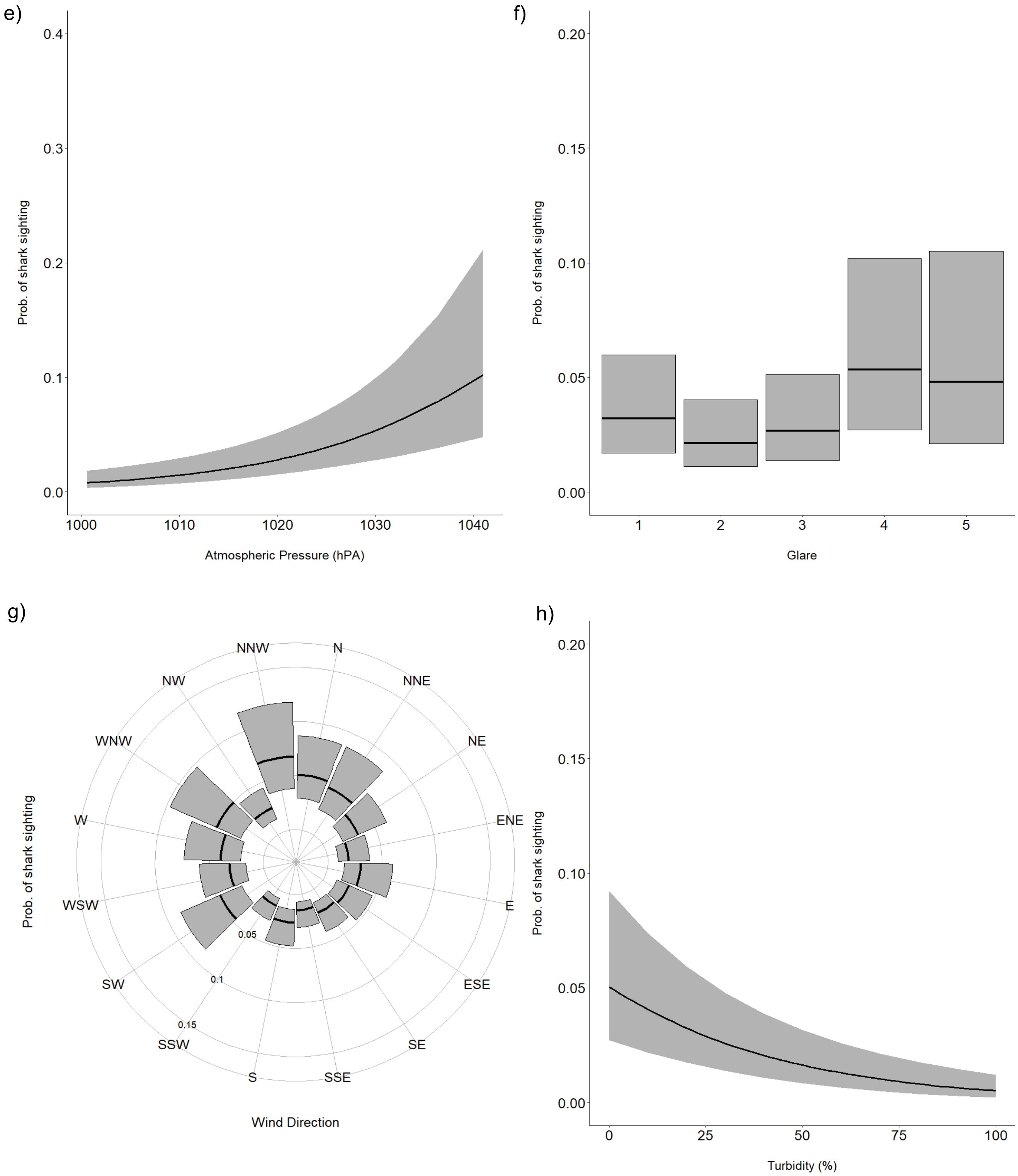
Table 4 Summary data for environmental variables included in Generalised Linear Modelling analysis.

Variable	Data range
Air temperature	5 – 37.8 °C (mean = 23.7 °C ± 4.2 S.D)
Swell height	0 – 6 m (mean = 0.89 m ± 0.52 S.D.)
Wind speed	0 – 29 km h^{-1} (mean = 9.7 km h^{-1} ± 4.4 S.D.)
Wind direction	All 16 directions (max = SSE 1790 flights, min = WNW 614 flights)
Cloud cover	0 – 8 oktas (mean = 3.0 oktas ± 2.5 S.D.)
Glare	1 – 5 scale (mean = 2.4 ± 1.1 S.D.)
Turbidity	0 – 100% (mean = 38.3 % ± 23.1 S.D.)
Atmospheric pressure	1000.6 – 1051.0 mbar (mean = 1015.6 mbar ± 5.3 S.D.)

Sea state	Beaufort 1 – 10 (mean = 2.9 ± 1.6 S.D.)
Humidity	0 - 100% (mean = 65.0% ± 19.3 S.D.)
Rainfall (previous 7 days)	0 – 389.4 mm (mean = 29.8 mm ± 46.2 S.D.)

GLM outputs indicated that there were nine predictor variables that had a significant influence on the sightability of sharks across all drone trial beaches. Location, wind speed, the sighting of other fauna, season, atmospheric pressure, glare, wind direction, turbidity and tidal state were the most important factors that had a significant influence on the sightability of sharks, explaining 30% of the deviance in the response variable (see further detail on model outputs and diagnostics in Appendix). The probability of sighting a shark was highest at NSI (0.09), followed by Burleigh Beach (0.02), with all other locations having markedly lower probabilities (<0.01, Figure 9a). Wind speed had a negative linear effect on sightability of sharks, with decreasing probability of sighting sharks with increasing wind speed (Figure 9b) (although it must be noted that drone flights were cancelled at windspeeds >30 km h-1 so the effect of windspeeds higher than this threshold could not be assessed). The sighting of other fauna during the drone transect led to a greater probability of sighting sharks (0.02), compared to when no other fauna were sighted (0.009) (Figure 9b) and the probability of shark sightings was also greater during autumn (0.06) and summer (0.04) (Figure 9c,d). Atmospheric pressure had a positive linear effect on probability of shark sightings, with lowest sightability of 0.009 at 1001 hPA ranging to 0.16 at 1051 hPA (Figure 9e). Higher levels of glare led to lower sightability of sharks (1 = high glare, 5 = low glare) (Figure 9f) and wind direction had a complex effect on sightability, with winds including a westerly component leading to generally higher sightability and easterly lower sightability (Figure 9g). The highest probability of shark sightings occurred during NNW wind direction (0.07) and the lowest at ENE winds (0.01) (Figure 9g). Turbidity also had a negative linear effect on shark sightability (Figure 9h) and the falling tide (0.021) and high tide (0.020) states led to the highest probability of shark sightings (Figure 9i).


a)
0.20
0.15
0.10
0.05
0.00
Prob. of shark sighting
Alexandra Headland
Alma bay
Bribie Island
Burleigh Beach
Coolum North
Kurrawa
Southport Main Beach
Noosa
North Stradbroke Island
Rainbow Beach
Location
b)
0.20
0.15
0.10
0.05
0.00
Prob. of shark sighting
0
1
2
3
4
5
sqrt(wind speed)
c)
0.20
0.15
0.10
0.05
0.00
Prob. of shark sighting
Not sighted
Sighted
Sighting of other fauna
d)
20
0.15
0.10
0.05
0.00
Prob. of shark sighting
Summer
Autumn
Spring
Winter
Season


e)
0.4
0.3
0.2
0.1
0.0
Prob. of shark sighting
1000
1010
1020
1030
1040
Atmospheric Pressure (hPA)
f)
0.20
0.15
0.10
0.05
0.00
Prob. of shark sighting
1
2
3
4
5
Glare
g)
NNW
N
NNE
NE
ENE
E
ESE
SE
SSE
S
SSW
SW
WSW
W
WNW
NW
0.05
0.1
0.15
Prob. of shark sighting
Wind Direction
h)
0.20
0.15
0.10
0.05
0.00
Prob. of shark sighting
0
25
50
75
100
Turbidity (%)

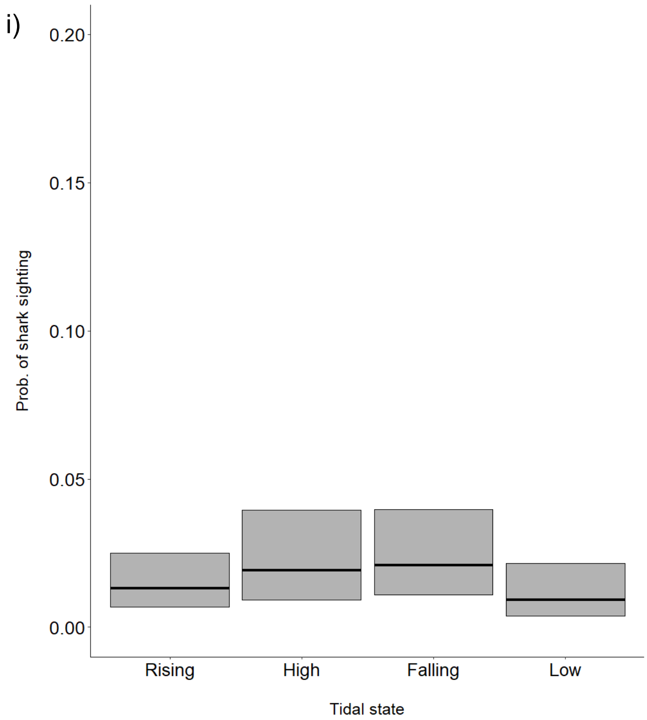
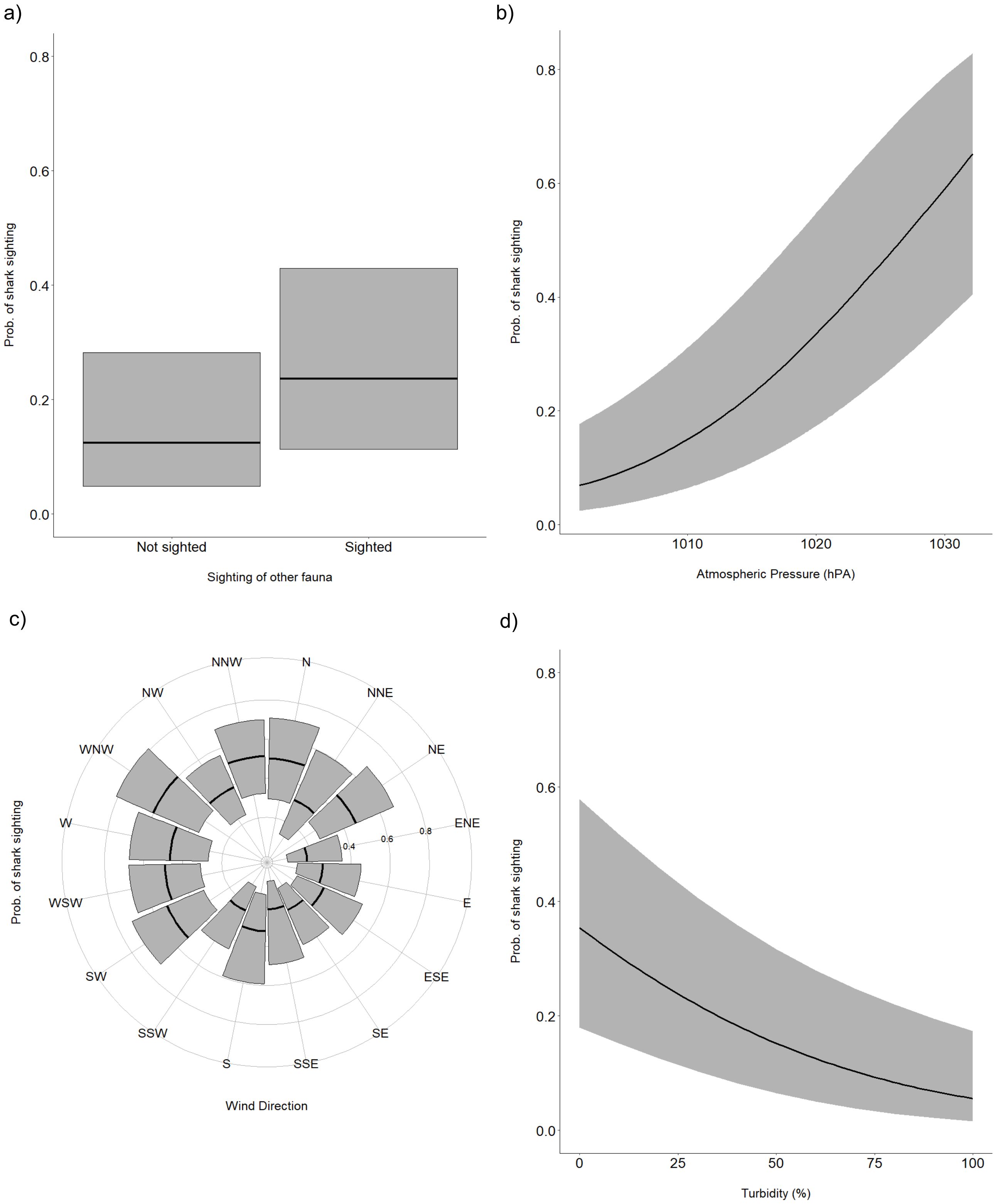


Figure 9 Influence of significant predictor variables on the probability of sighting sharks, across all beaches combined. a) location, b) wind speed, c) sighting of other fauna, d) season, e) atmospheric pressure, f) glare (1 = high glare, 5 = low glare), g) wind direction, h) turbidity, i) tidal state. Solid black lines indicate model fitted values. Grey shaded areas indicate 95% confidence intervals.

In addition to the overall GLM for all beaches, a separate GLM was run for NSI, because it had by far the most sightings. For NSI, the predictor variables of sighting of other fauna, atmospheric pressure, wind direction, turbidity, tidal state, flight number, cloud cover and swell height, explained 18% of the deviance in the response. The sighting of other fauna led to a substantially higher probability of sighting sharks (0.24 vs 0.12) (Figure 10a). Atmospheric pressure had a positive linear effect on probability of shark sightings, similar to the overall GLM, with lowest sightability of 0.009 at 1001 hPA and highest of 0.16 at 1051 hPA (Figure 10b). Westerly and northerly wind directions led to higher probability of sightings, with easterly and southerly directions generally lower (Figure 10c). The lowest probability of sightings occurred for ENE winds (0.18) and the highest for WNW winds (0.60) (Figure 10c). Turbidity showed a negative linear effect on shark sightability, with decreasing probability as turbidity increased (Figure 10d). Tidal state showed a more complex relationship with the probability of shark sightings, with higher probability during falling tides (0.24) and high tide (0.22) and lowest at rising tide (0.14) (Figure 10e). The probability of sightings was higher at the start of the day during the first flight (0.35), with probability steadily decreasing until the lowest probability for flights 5 and 6 (0.14) (Figure 10f). Higher probability values generally occurred at intermediate levels of cloud cover, with highest values at 6 oktas (0.36) and 5 oktas (0.25) and lowest at 1 okta (0.09), 0 oktas (0.13) and 8 oktas (0.13) (Figure 10g). Lastly, swell height had a positive linear effect on probability of shark sightings (Figure 10h).



a)
0.8
0.6
0.4
0.2
0.0
Prob. of shark sighting
Not sighted
Sighted
Sighting of other fauna
b)
0.8
0.6
0.4
0.2
0.0
Prob. of shark sighting
1010
1020
1030
Atmospheric Pressure (hPA)
c)
NNW
N
NW
NNE
WNW
NE
W
ENE
0.4
0.6
0.8
WSW
E
SW
ESE
SSW
SE
S
SSE
Prob. of shark sighting
Wind Direction
d)
0.8
0.6
0.4
0.2
0.0
Prob. of shark sighting
0
25
50
75
100
Turbidity (%)

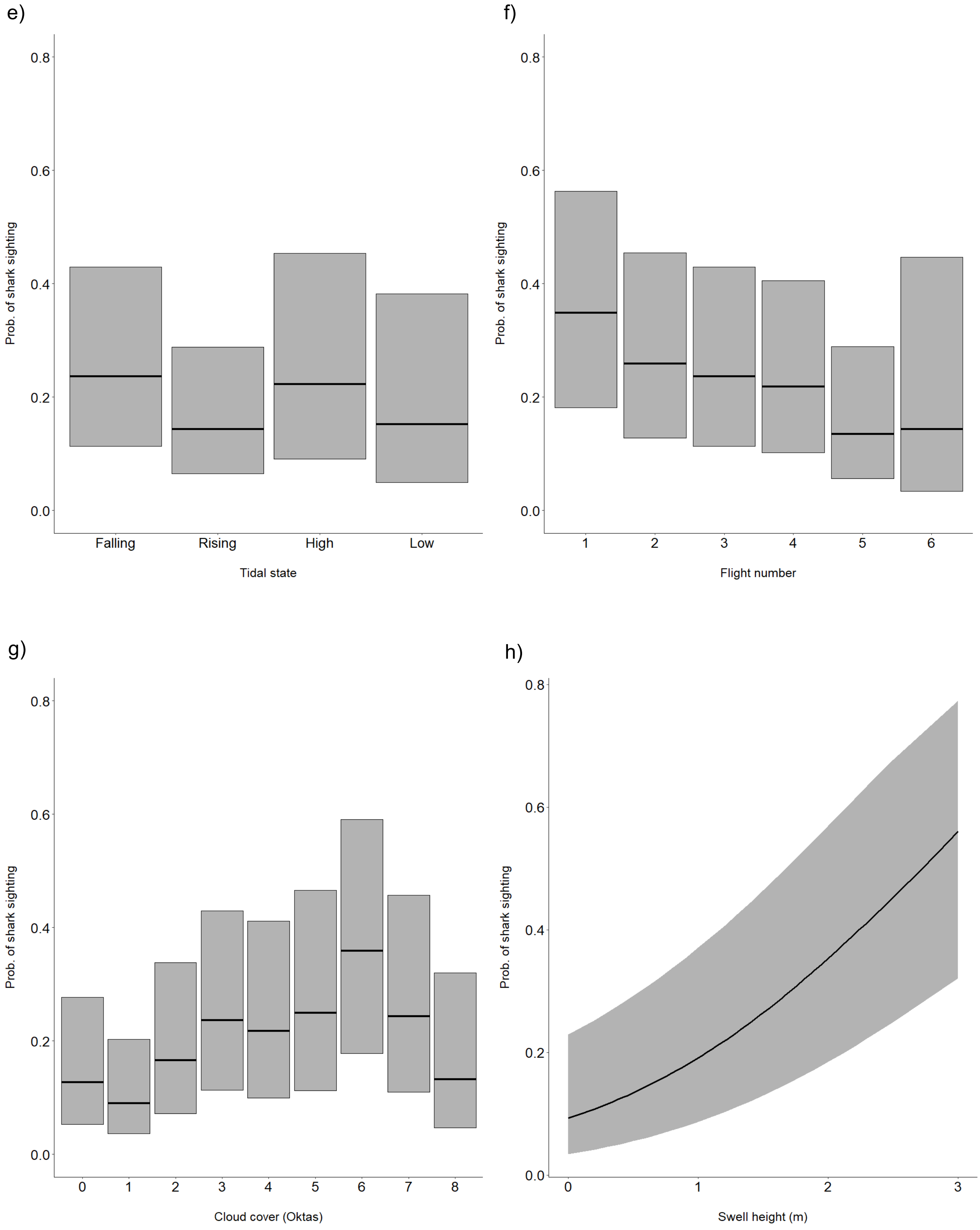


Figure 10 Influence of significant predictor variables on the probability of sighting sharks at North Stradbroke Island. a) sighting of other fauna, b) atmospheric pressure (hPa), c) wind direction, d) turbidity, e) tidal state, f) flight number, g) cloud cover h) swell height. Solid black lines indicate model fitted values. Grey shaded areas indicate 95% confidence intervals.

4.4 Shark movement tracks and behaviour

Analyses were undertaken to map shark movement tracks at drone trial beaches and classify their behaviour. Tracks were generated for all sharks at each beach, as well as kernel density heatmaps based on all the individual track points. At NSI, most of the movement tracks were relatively linear, in a north-south orientation, with sharks moving further offshore to navigate around the headland at the northern end of the beach (Figure 11a). Typically, most sharks were moving in a northerly direction and the highest concentration of track points was located towards the northern end of this beach and relatively far offshore (Figure 11b). At Burleigh Beach, shark tracks were more variable and spread across a larger area, with many coming in closer to the beach, especially towards the southern end of the beach, where a headland is located (Figure 12a). This is also reflected in the kernel density heatmap, which shows a clear concentration of shark presence at the southern end of the beach closest to the headland (Figure 12b). Shark tracks at Noosa were spread relatively evenly along the beach, at approximately the same distance offshore (Figure 13a), with the highest concentration of points occurring at the western portion of the beach, closer to the mouth of the Noosa River (Figure 13b). The shark tracks for the remaining beaches are not included here due to lower numbers of sightings occurring. The white shark sighted at Southport Main Beach was tracked for 6 mins 40 seconds and travelled in a southerly and south-easterly direction, with a minimum distance from shore of 150 m to a maximum of 310 m at the end of the track as the shark headed offshore (Figure 14).

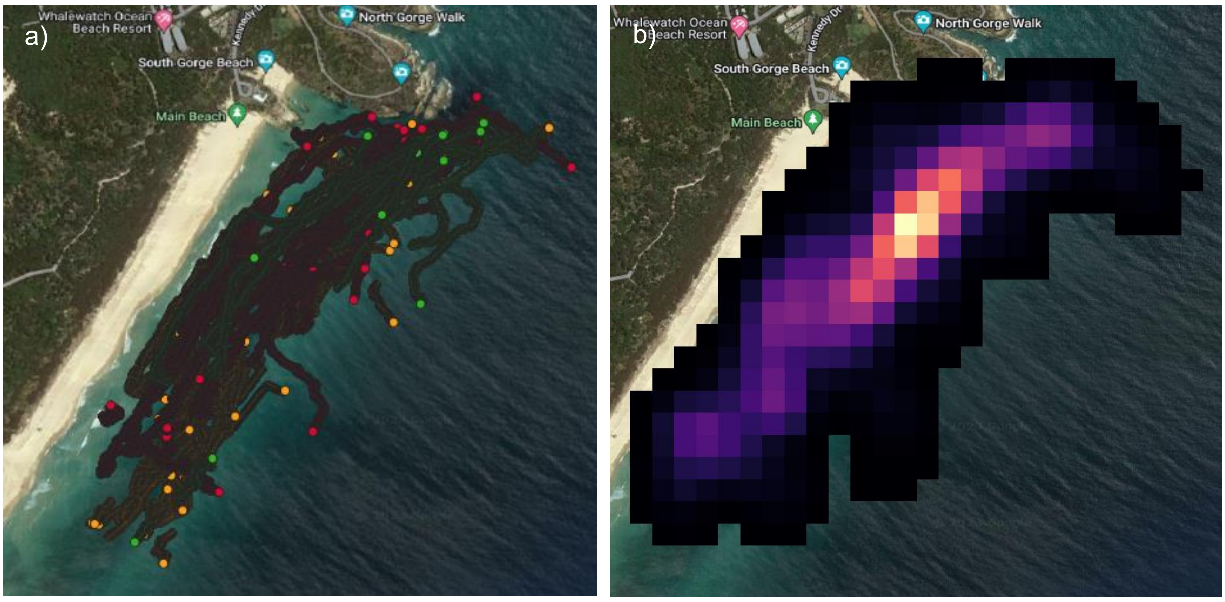


Figure 11 Space use of sharks sighted by drones at North Stradbroke Island. A) raw movement tracks, b) kernel density heatmap of all tracks, black = low, orange = high.

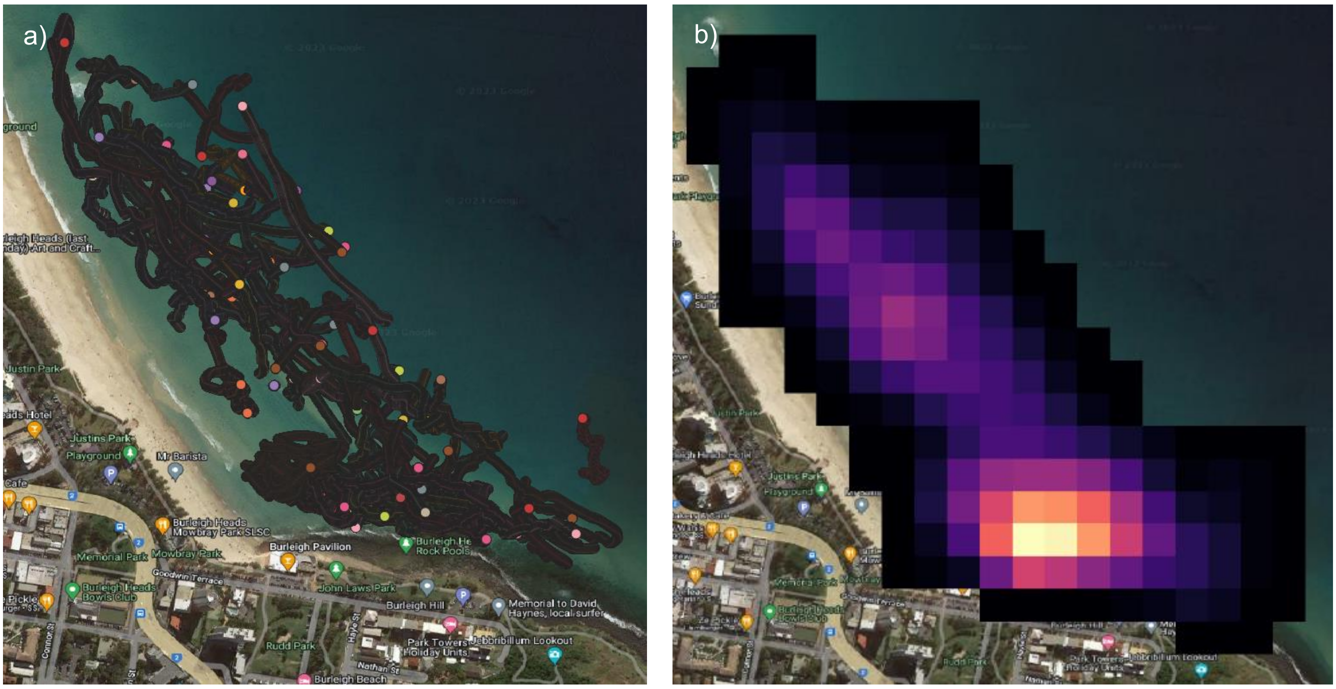
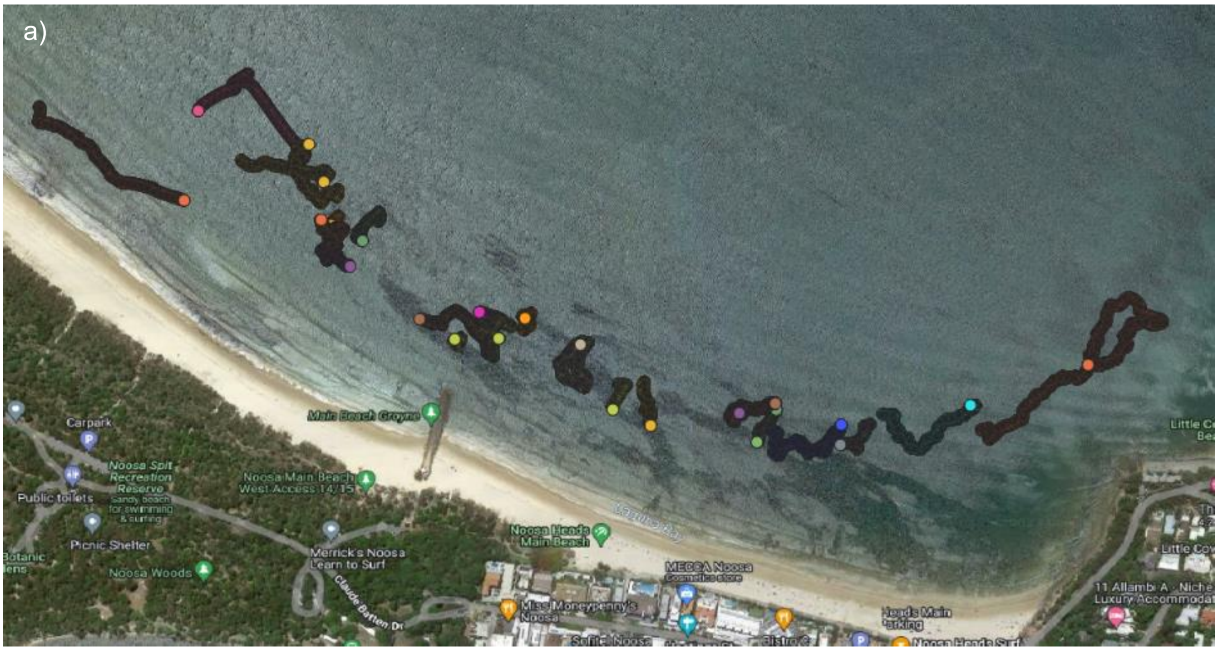


Figure 12 Space use of sharks sighted by drones at Burleigh Beach. a) raw movement tracks, b) kernel density heatmap of all tracks, black = low, orange = high.



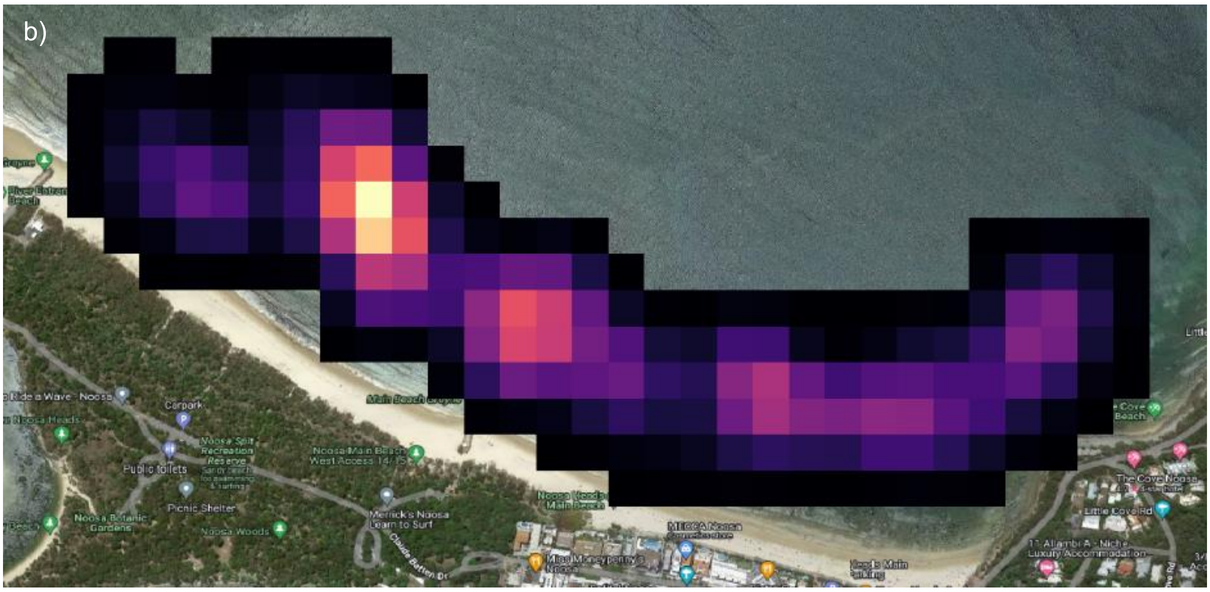


Figure 13 Space use of sharks sighted by drones at Noosa. a) raw movement tracks, b) kernel density heatmap of all tracks, black = low, orange = high.

Figure 14 Movement track of a white shark sighted at Southport Main Beach, as indicated by the black line. Red box indicates start of the track; yellow box indicates end of the track.

4.5 Comparison of drone sighting events vs catch in SCP gear

There was a significantly higher (p = <0.001, binomial test) number of shark sighting events on drones (676) compared to the number caught in SCP nets (181) and drumlines (103), across all the 10 drone trial beaches during the trial period (Table 5). For individual beaches, however, results were more variable, with some beaches having higher numbers of shark sighting events on drones and some higher numbers of sharks caught in SCP gear. NSI and Burleigh Beach had significantly higher shark sighting events than catches, with 314 vs 32 (p = <0.001) and 168 vs 24 (p = <0.001), respectively (Table 5). Bribie Island and Kurrawa also had significantly higher numbers of sighting events on drones than catch in SCP gear, with 14 vs 3 (p = 0.01) and

19 vs 4 (p = 0.003), respectively (Table 5). Conversely, Alexandra Headland, Rainbow Beach and Alma Bay all had significantly higher shark catches on SCP gear than sighting events by drones, with 21 vs 7 (p = 0.01), 58 vs 30 (p = 0.004) and 43 vs 17 (p = 0.001), respectively (Table 5). There were marginally higher numbers of sighting events on drones (69) compared to catch on SCP gear (57) at Noosa, but this was non-significant (0.33). Likewise, Coolum North and Southport Main Beach had similar numbers of shark sighting events on drones and caught in SCP gear, resulting in non-significant differences (p = 0.67 and p = 1, respectively) (Table 5). Results of a linear regression indicated that for all beaches combined, there was no significant relationship between the number of sharks sighted on drones and the numbers caught in SCP gear (r2 = 0.02, t value = 0.39, p = 0.71).

In terms of large sharks >2 m, only NSI had significantly higher numbers of sighting events on drones compared to those caught in SCP gear, with 151 vs 27 (p = <0.0001) (Table 5). Burleigh Beach and Kurrawa had marginally higher numbers of sighting events than catches in adjacent SCP gear, although this difference was non-significant (p = 0.06 and p = 0.63, respectively). Alexandra Headland, Bribie Island and Southport Main Beach all had low numbers (<10) of large shark sighting events or catches in SCP gear, with the differences being not significant (p = 0.45, p = 1 and p = 1, respectively). The remaining four beaches, Coolum North, Noosa, Rainbow Beach and Alma Bay, all had significantly higher numbers of large sharks caught in SCP gear compared to sighted by drones, with 15 vs 2 (p = 0.002), 31 vs 0 (p = <0.0001), 18 vs 3 (p = 0.001) and 19 vs 4 (p = 0.003), respectively (Table 5). Across all beaches, a linear regression showed that there was no significant relationship for the number of large sharks sighted on drones and caught in SCP gear across the trial beaches (r2 = 0.19, t value = 1.37, p = 0.21).

The number of bull, tiger and white sharks sighted by drones were generally low across most beaches, with none sighted at Alexandra Headland, Bribie Island, Coolum North, Kurrawa and Alma Bay (Table 5). Yet, small numbers (<5) of bull or tiger sharks were caught by SCP gear at the first four of these beaches, and 16 tiger and 2 bull sharks were caught at Alma Bay (Table 5). Burleigh Beach had higher numbers of sightings of these species than the SCP gear catch, although this difference was not significant (6 bull vs 1 tiger, p = 0.13). The numbers of bull and tiger sharks caught on SCP gear at Noosa and Rainbow Beach were significantly higher than those sighted on drones, with 20 vs 2 (p = 0.0001), 20 vs 1 (p = <0.0001), respectively (Table 5). Catch on SCP gear was only marginally higher than sightings at NSI (25 vs 14, p = 0.11), although white, tiger and bull sharks were caught on drumlines compared to only bull sharks being sighted on drones (Table 5). No tiger sharks and only one white shark was sighted by drones across all 10 drone trial beaches.

Table 5 Number of shark sighting events by drones and caught by Queensland Shark Control Program fishing gear (nets and drumlines) at each of the beach locations.

Location	Total number of shark sighting events*	No. of large (>2 m) shark sighting events	No. of white, bull, tiger sighting events	No. of sharks caught in SCP gear	No. large sharks (>2 m) caught	No. white, tiger and bull sharks caught
South-East Queensland						
Alexandra Headland	7	2	0	21 (net)	5	5 bull
Bribie Island	14	1	0	3 (drumlines)	2	3 tiger
Burleigh Beach	168	17	6 bull	24 (net)	7	1 tiger
Coolum North	22	2	0	26 (net)	15	1 bull
Kurrawa	19	3	0	4 (net)	1	0
Noosa	69	0	2 bull	44 (net), 13 (drumlines)	31	12 tiger, 7 bull, 1 white

North Stradbroke Island	314	151	14 bull	32 (drumlines)	27	20 tiger, 4 white, 1 bull
Rainbow Beach	30	3	1 bull	46 (net), 12 (drumlines)	18	11 tiger, 9 bull
Southport Main Beach	16	7	1 white	16 (net)	8	1 bull, 1 tiger
North Queensland						
Alma Bay	17	4	0	43 (drumlines)	19	16 tiger, 2 bull
TOTAL	**676**	**190**	**24**	**284**	**133**	**95**

*total does not include leopard sharks

When comparing the shark sighting rate of drones to the catch rate of SCP gear, it is important to note that the two methods operate very differently and have different spatial and temporal scales. For example, drones were only operating for a small percentage of the time that SCP gear was operational. For the seven beaches where nets were deployed 24-hours per day (Alexandra Headland, Burleigh Beach, Coolum North, Kurrawa, Noosa, Rainbow Beach and Southport Main Beach), drones were operational for only 2.9% of the time that nets were operational. During the trial drones were operated for a total of 4,775 hours based on 14,326 flights averaging 20 mins. In comparison, SCP nets were deployed for a total of 165,576 hours, based on 24 hours x 1,319 days x four beaches (Alexandra Headland, Burleigh, Coolum North and Southport Main Beach), plus 24 hours x 541 days x three beaches (Kurrawa, Noosa, Rainbow Beach).

For the five beaches where drumlines were present (Bribie Island, Noosa, NSI, Rainbow Beach and Alma Bay), drones operated for 2,125 hours (based on 6,374 flights running for 20 mins), which equates to 5.1% of the total time that drumlines were operational, Drumlines were operated for a total of 41,280 hours, based on 31,656 hours for NSI (24 x 1,319 days), 24,936 hours for Alma Bay (24 x 1,039 days) and 25,968 hours for Noosa and Rainbow Beach (24 x 541 days x 2). This assumed that the drumlines were operational for 50% of the time (i.e. the total number of hours for drumlines was divided by two), because drumlines are only operational while bait remains on the hook. For the purpose of this analysis, an assumption was made that baits were removed or fell off for 50% of the time, although there are no data to assess the operational time for drumlines.

It is also important to note that drones operated closer to the shore than SCP gear, with most transects flown at a distance of <250 m offshore, compared to the SCP gear, which was set 300-500 m offshore. The 400 m long drone transects covered a larger spatial area than SCP nets, which are 186 m long and 6 m deep. The bait plume from drumlines would be variable depending on currents and other factors so estimating the effective area of a drumline or series of drumlines is not possible but would extend beyond the physical area of deployment.

In addition to the generally higher detection rate of sharks by drones than that caught by SCP nets and drumlines, the drones also had a negligible impact on non-target species, whereas SCP apparatus caught 123 non-target animals (Table 6). Highest catches occurred at Rainbow Beach, where the combination of nets and drumlines caught 53 non-target animals, most notably 26 endangered loggerhead turtles (*Caretta caretta*) (Table 6) and three humpback whales (*Megaptera novaeangliae*). Catches of species listed under the Environment Protection and Biodiversity Conservation Act 1999, including Australian humpback dolphin (*Sousa sahulensis*), devil and manta rays (*Mobula spp.*), humpback whales, green (*Chelonia mydas*), loggerhead and leatherback turtles (*Dermochelys coriacea*)) and dugongs, occurred on 73 occasions (59% of all non-target catch) across all beaches apart from Alma Bay (Table 6). Non-target animals in this analysis did not include any shark species, although it should be noted that the SCP target species list was amended from 19 species to seven (white, bull, tiger, dusky (*Carcharhinus obscurus*), Australian blacktip (*Carcharhinus tilstoni*), common blacktip (*Carcharhinus limbatus*) and grey reef shark (*Carcharhinus amblyrhynchos*)) in January 2023, so any species other than these could also be classed as non-target animals.

Table 6 Catch of non-target animals at each beach by Queensland Shark Control Program nets and drumlines, including species.

Beach	Non-target animals caught, size and number
South-East Queensland	
Alexandra Headland	1 Australian humpback dolphin, 3 cownose rays (*Rhinoptera neglecta*), 3 devil rays (*Mobula sp.*), 1 dugong, 1 humpback whale, 1 mulloway (*Argyrosomus japonicus*), 2 manta rays, 3 white spotted eagle rays
Bribie Island	2 common dolphins, 1 loggerhead turtles
Burleigh Beach	3 common dolphins, 1 cownose ray, 2 devil rays, 1 eastern shovelnose ray (*Aptychotrema rostrata*), 1 manta ray
Coolum North	1 cownose ray, 1 devil ray, 1 eagle ray, 1 giant shovelnose ray (*Glaucostegus typus*), 2 humpback whales, 3 loggerhead turtles, 1 white spotted eagle ray
Kurrawa	2 common dolphins, 1 giant shovelnose ray, 1 green turtle,
Noosa	1 bottlenose dolphin, 1 cownose ray, 2 devil rays, 1 dugong, 1 green turtle, 1 humpback whale, 1 loggerhead turtle, 1 manta ray, 1 marlin, 2 tuna (*Thunnus sp.*), 1 white spotted eagle ray
North Stradbroke Island	1 humpback whale, 6 leatherback turtles, 4 loggerhead turtles, 1 manta ray
Rainbow Beach	2 common dolphins, 1 cownose ray, 1 devil ray, 1 unidentified dolphin, 2 green turtles, 3 humpback whales, 26 loggerhead turtles, 1 manta ray, 3 queenfish (*Scomberoides commersonnianus*), 1 snapper (*Chrysophrys auratus*), 12 tuna
Southport Main Beach	1 common dolphin, 1 cownose ray, 1 manta ray, 2 tuna
North Queensland	
Alma Bay	1 cod
TOTAL	**123 non-target marine animals**

4.6 Sightings of other fauna

Similar to the shark sightings, the numbers of other marine fauna sighted varied widely between beaches, with NSI having by far the highest number of sighting events (fauna sighted on 84% of flights) and the greatest diversity of fauna; and Alexandra Headland (12% of flights) the lowest. Sighting events could be one or multiple animals of the same group, the same as a sighting event for sharks. A wide range of non-shark fauna were sighted during the drone trial, the most prevalent of which were turtles, which were seen on 7.7% of flights across all beaches combined) and were most prevalent at NSI, where they were sighted on 36% of flights (Table 7, Figure 15). The first recorded occurrence of green turtles mating at NSI was also observed during the trial (Figure 15e). Manta rays and eagle rays (Figure 15c,f) were also sighted regularly across all locations, with a sighting rate of 7.4% across all beaches combined, similar to stingrays (7.2% sighting rate) (Table 7). Important prey species for sharks, including large fish and bait balls (a closely packed group of small fish), were also observed during the trial, occurring on 5.4% and 3.3% of flights across the pooled drone trial locations, respectively. Dolphins were commonly observed at NSI (24% of flights); however they were relatively rare at all other beaches, with sighting rates generally <5% (Table 7). Groups of Australian humpback dolphins were also observed at NSI and a single adult was observed at Coolum North (Figure 15a). This latter sighting was notable because it was approximately 85 km from the nearest known habitat at Great Sandy Strait, suggesting that humpback dolphins in the area may have a larger home range than has been previously considered. Shovelnose rays were notably rarer, although this was likely due to the fact they are harder to detect from drones, due to the fact they remain close to the bottom. A small number of humpback whale sightings and a singular sighting of a dugong mother and calf occurred, all at NSI (Figure 15b,d).

Table 7 Number and percentage (in parentheses) of flights in which other fauna were sighted during the Queensland SharkSmart drone trial, for each beach.

Number and percentage of flights sighted								
Beach	**Turtles**	**Dolphins**	**Stingrays**	**Manta/ eagle rays**	**Shovelnose rays**	**Large fish**	**Bait balls**	**Jellyfish**
South-East Queensland								
Alexandra Headland	157 (5.7)	6 (0.2)	34 (1.2)	31 (1.1)	0 (0)	49 (1.8)	83 (3)	16 (0.6)
Bribie Island	14 (1.4)	53 (5.5)	71 (7.3)	21 (2.2)	0 (0)	32 (3.3)	32 (3.3)	23 (2.4)
Burleigh Beach	18 (0.7)	21 (0.8)	274 (10.6)	188 (7.3)	0 (0)	88 (3.4)	96 (3.7)	0 (0)
Coolum North	141 (6.0)	15 (0.6)	79 (3.4)	198 (8.5)	1 (0.004)	87 (3.4)	52 (2.2)	11 (0.5)
Kurrawa	8 (0.6)	29 (2.2)	53 (4.0)	75 (5.7)	0 (0)	15 (1.1)	28 (2.1)	1 (0.008)
Noosa	35 (2.6)	16 (1.2)	217 (16.2)	41 (3.0)	0 (0)	56 (4.2)	51 (3.8)	12 (0.9)
North Stradbroke Island	467 (35.7)	306 (23.4)	393 (30.1)	569 (43.5)	103 (7.9)	359 (27.5)	84 (6.4)	7 (0.5)
Rainbow Beach	113 (8.0)	21 (1.5)	24 (1.7)	56 (4.0)	3 (0.2)	191 (13.6)	82 (5.8)	128 (9.1)
Southport Main Beach	38 (1.5)	63 (2.4)	141 (5.4)	153 (5.9)	2 (0.007)	77 (2.9)	88 (3.4)	10 (0.4)
North Queensland								
Alma Bay	385 (28.5)	2 (0.1)	4 (0.3)	4 (0.3)	0 (0)	17 (1.3)	2 (0.1)	0 (0)
TOTAL	**1376 (7.7)**	**532 (3.0)**	**1290 (7.2)**	**1336 (7.4)**	**109 (0.6)**	**971 (5.4)**	**598 (3.3)**	**208 (1.2)**

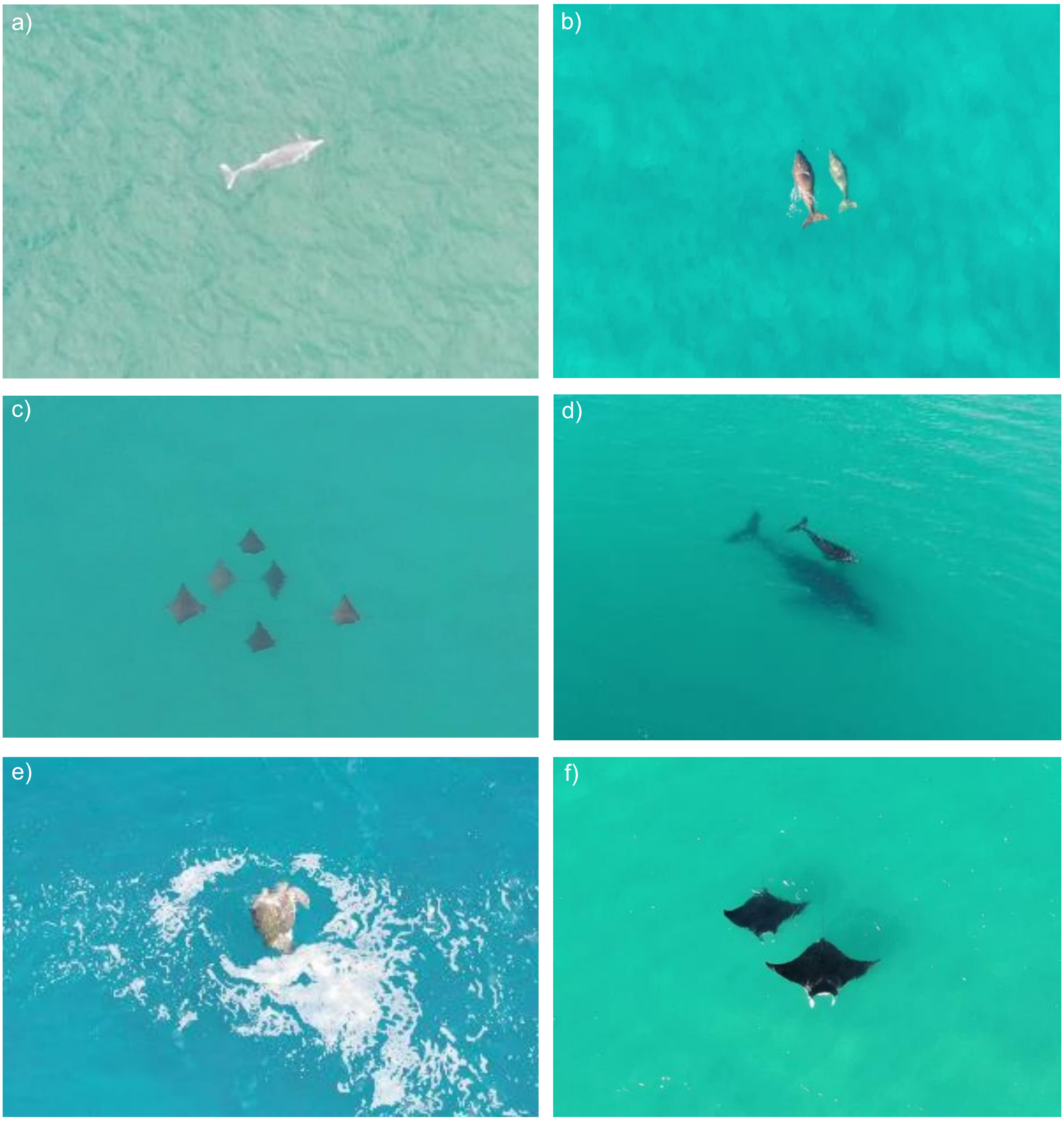


Figure 15 Examples of other marine fauna detected during the Queensland SharkSmart drone trial. a) an Australian humpback dolphin sighted at Coolum North, b) a dugong and calf sighted at NSI, c) eagle rays at NSI, d) humpback whale and calf at NSI, e) first recorded sighting of green turtles mating f) manta rays at NSI.

To maximise the scientific value of the footage of other non-shark fauna collected during the drone trial, collaborations with other researchers have been established to investigate the following:

- Species present, group size, seasonality of calf presence and behaviour of dolphin species. This research is being conducted in collaboration with researchers from the Queensland Government, Department of Environment and Science.
- Species presence, abundance, seasonality and behaviour of marine turtles. This work is in collaboration with the Queensland Government, Department of Environment and Science.
- Presence, seasonality and identification of individual manta rays. This work is a collaboration with researchers from The University of the Sunshine Coast and Project Manta.
- Abundance, seasonality and behaviour of leopard sharks. This research is a collaboration with researchers at The University of the Sunshine Coast and The University of Queensland.

- The diversity, abundance and seasonality of key faunal groups was analysed as part of Maddison Cross' (University of the Sunshine Coast) Honours thesis and has recently been published (Cross et al., 2024).
- Footage of cownose rays and eagle rays has been shared with researchers from Macquarie University, who are analysing their occurrence, group size and seasonality across the Australian East Coast.

5. Discussion

5.1 Operational results

The Queensland SharkSmart drone trial demonstrated the capability of operating drones as a public safety tool to detect sharks, running 17,954 flights across ten beaches and covering a flight distance of over 7,181 km. The ability to detect and track sharks at beaches when people were in the water provided a safety benefit because the pilots were able to monitor these sharks in real time, so they could warn water users and close the beach if a shark posed a risk to safety. This strategy relies on minimising the likelihood of sharks coming into close proximity to water users, although it is important to note that proximity does not mean that a bite would occur.

Bad weather prevented drones from flying on many days across the trial period, resulting in at least 5% of possible flights being cancelled. This was expected, given the unpredictable and variable weather that occurs in Queensland, especially during summer months when storms and heavy rain can occur. However, from a public safety perspective, it is important to note that fewer people would likely be in the water on those days when drone flights were cancelled due to the prevailing weather. Beaches that were sheltered from certain wind directions, including Kurrawa, Alexandra Headland and Burleigh Beach, had the lowest loss of flights, compared to those that were more exposed, such as NSI and Coolum North. Future advances in drone technology will likely result in drones that are more resistant to rain and can operate in higher winds. This would reduce the amount of cancelled drone flights, although rainy and/or windy conditions may still impact the ability of drones to see into the water column to detect sharks.

From an operational perspective, it is also important to note that drones provide a range of public safety benefits at beaches, in addition to detecting sharks. This is demonstrated by the use of drones to rescue people caught in rip currents and assist with missing person searches, both of which occurred during the drone trial.

5.2 Shark sighting rates

Throughout the Queensland SharkSmart drone trial, 676 shark sighting events occurred, 190 of which were large sharks (>2 m). These sighting events included sightings of either single or multiple sharks. On many occasions multiple sharks were sighted from the drones on the same flight, therefore the overall number of sharks sighted in the trial was substantially higher than the total sighting events reported. However, it must be noted that this number likely includes instances where the same individual(s) sharks were sighted across multiple flights on the same day. Overall, the prevalence of shark sighting events was low, with sharks detected on only 3.8% of flights when data from all beaches were combined. This result was similar to, albeit slightly higher than, the results for the first 12 months of the trial (Mitchell et al. 2022a,b). It is also similar to findings from the NSW drone trial, where only 1.9% of flights recorded bull, white and/or whaler sharks (Kelaher et al., 2020). Importantly, there were only 24 sightings of bull or white sharks during the current trial, highlighting that sightings of these shark species close to beaches are rare. Likewise, water users were evacuated on just 39 occasions, which represents only 0.2% of flights in total, showing that risks to bathers from sharks at monitored beaches is very low.

The level of sighting events varied substantially between beaches. This was likely due to a combination of shark presence/absence and the prevailing environmental conditions at each location. NSI had by far the greatest number of sighting events, which was likely due to this location being closer to the edge of the continental shelf and thus being more productive than other coastal beaches. NSI also sits within the path of the strong southward flowing East Australian Current (EAC), which may also result in more prey species moving through the area. Additionally, there was a substantially greater presence of other marine fauna sighted at this location during the drone trial, including turtles, rays, large fish and bait balls, all of which can be important prey species for sharks, which may contribute to the higher prevalence of shark sightings at this location. The relatively high number of sighting events at Burleigh Beach, many of which occurred over the summer months, was likely influenced by its proximity to Tallebudgera Creek, where increased outflow occurs during summer due to rain, bringing nutrients into the surrounding area and increasing the density of bait fish and other potential shark prey. Likewise, Noosa and Rainbow Beach, both of which are close to river mouths, had relatively high numbers of shark sighting events, despite only being operational since the end of 2022. Higher catches of sharks in SCP gear are known to occur at Queensland beaches close to river mouths and after rainfall, especially for bull sharks (Haig et al., 2018; Werry et al., 2018). Greater numbers of fauna sightings were also recorded for the beaches closest to river mouths in the NSW drone trial (Kelaher et al., 2020), and other research has demonstrated the important link between nutrients and the presence of predators close to river mouths (Schlacher & Connolly, 2009). Yet, Alexandra Headland had only low numbers of shark sightings in the current trial, despite being close to the Mooloolah and Maroochy River mouths, so other habitat related factors, such as the proximity to reefs, may also be important.

The three other Sunshine Coast beaches (Alexandra Headland, Coolum North and Bribie Island), as well as the two central Gold Coast beaches (Southport Main Beach and Kurrawa) had much lower numbers of sighting events, likely because they were open sandy beaches, with little benthic habitat and were a greater distance from productive river mouths (apart from Alexandra Headland). This low number of sighting events can act as an important message that sharks are relatively rare at these beaches and the chances of encountering one is thus minimal. The communication of this message can improve public knowledge of the risks posed by sharks and increase confidence in water users. Such information can also be useful to water users on an individual level, when deciding which beach to visit if they are concerned about encountering sharks. To increase the cost efficiency of the drone trial in future, operations could be transitioned away from these beaches where very few sightings have occurred, to instead allocate resources to higher priority locations where sharks are more likely to be sighted, based on SCP catch data and other information (e.g. shark tracking data). However, the risk of a shark bite occurring is not necessarily related solely to the prevalence of sharks at beaches, so careful consideration would need to be given to such decisions. Additionally, the presence of drones monitoring for sharks can act as an important peace of mind for water users and influence their choice of beach to visit, so clear messaging around why flights were stopped at a given beach would need to occur.

5.3 Environmental and operational influences on shark sightability

Environmental factors exerted an important influence on the sightability of sharks. Sightability represented the likelihood of sighting sharks, which was influenced by both shark presence/absence and the ability of drones to detect sharks in the prevailing conditions, noting that it is only possible to know what was seen, not what was not (i.e. a shark could be present but not detectable by the drone). Location had a marked effect on sightability as previously discussed, with NSI and Burleigh Beach having markedly higher sightings, likely due to being located in high productivity areas close to the continental shelf and a river outflow, respectively.

Wind speed had a significant effect on shark sightability for the GLM including all beaches, with lower probability of sighting sharks as wind speed increased. This would be expected, due to the effect of wind increasing surface disturbance on the water and reducing the ability of pilots to see into the water column. Wind speed has been found to affect shark sighting rates in other drone based studies, with similar lower sightability at higher windspeeds (Benavides et al., 2019). However, it did not have a significant effect on shark sightability in the NSW drone trial research (Butcher et al., 2020). Wind direction also played an important role in the current study, with both the model containing all beaches and the model containing just NSI having wind direction as a significant predictor variable. Winds from westerly and northerly directions led to higher sightability, which would be expected because these are offshore winds coming from the land in the drone trial locations, thus causing lower disturbance to the water surface. Conversely, winds from easterly and southerly directions led to lower sightability because they would have had a larger fetch when blowing across the ocean, leading to increased disturbance on the water surface and greater swell.

Atmospheric pressure was another weather-related variable that had a significant effect on probability of shark sightings in both GLMs, with higher sightability during high pressure conditions. High pressure leads to calmer conditions with clear skies and light winds, therefore sea conditions would be expected to be more conducive to detecting sharks, as opposed to during low pressure systems, when wind speeds are typically higher, the amount of cloud is greater, and rain can occur.

Sharks were more likely to be seen during summer and autumn across all drone trial beaches, which would be expected as these seasons have higher water temperatures, which lead to greater activity levels of sharks (Taylor et al., 2011; Haig et al., 2018; Werry et al., 2018) and higher rainfall, which can lead to greater productivity and prey abundance in the coastal environment due to river outflows carrying nutrients (Loneragan, 1999; Meynecke et al., 2006). This was especially evident at Burleigh Beach, which is close to Tallebudgera Creek, as this location had much higher shark sighting probability during autumn and summer.

The sighting of other fauna had a positive relationship with shark sightings from drones, for both the combined and NSI GLMs, which may have occurred because some of those other fauna were potential prey species for sharks, thus attracting them to the area. Indeed, Colefax et al. (2020b) and Tucker et al. (2021) found that white shark behaviour close to surf beaches was markedly different when food sources were present, with shark swimming speed and track tortuosity (degree of twistedness, i.e. number of turns) increasing. This result therefore supports the Queensland Government SharkSmart behaviour recommendation: “If it looks fishy, it could be sharky. Leave the water if you see schools of bait fish or diving birds” as there could be a higher chance of sharks being present. For NSI in particular, sightings of other fauna occurred on the majority of flights, highlighting the productivity of this location and further supporting why it had by far the greatest sighting rate of sharks.

The sighting of other fauna may have also had a positive relationship in the GLM because it acted as a proxy for the sightability of sharks, i.e. if the water conditions were clear enough for other fauna to be sighted then they would also enable sharks to be sighted. This is supported by the fact that both GLMs contained turbidity as a significant predictor variable, which had a negative linear relationship with probability of shark sightings. Similarly, Cross et al. (2024) found a negative linear relationship between sightings of air-breathing marine megafauna and turbidity during this drone trial program. Butcher et al. (2020) also found a strong negative effect of turbidity on the likelihood of sighting shark models in NSW, and this variable has been widely acknowledged as being a critical limiting factor for aerial marine fauna surveys (Pollock et al., 2006; Hagihara et al., 2014).

Other variables linked to the ability of the drone to see into the water column were glare and cloud cover, which had a significant effect on the probability of shark sightings in the combined model and NSI model, respectively. Higher glare led to lower probability of sighting sharks as would be expected due to the fact it reduces the drone’s ability to see into the water column and detect contrast between a shark and seabed. For the NSI model, highest probability of sighting sharks occurred at intermediate levels of cloud cover, which is different to the result of Benavides et al. (2019), who reported a higher detection probability of shark models during non-cloudy days. This could potentially be explained by the fact that glare would be higher at lower levels of cloud cover and contrast between the shark and seabed would be lower at high levels of cloud cover, therefore intermediate levels of cloud cover led to highest probability of sightings. Localised factors at NSI could also explain this difference, as cloud cover did not have a significant effect in the combined model.

Interestingly, tidal state had a significant effect in both the combined model and the NSI model, with both showing higher probability of sharks during the falling tide and at high tide. During periods of slack water around high and low tide, when water movement is lowest, it would be expected that surface water conditions would be calmer and thus the ability of drones to see deeper into the water column and detect sharks would improve. So, it was unexpected that falling tides would lead to higher probability of sighting sharks than at low tide. However, these broader tidal categories do not consider localised differences in tidal flows or variations in spring and neap tidal cycles. The relationship between swell height and probability of shark sightings was also unexpected in the NSI model, with a positive linear relationship occurring rather than a negative linear relationship as would be expected, because larger swells lead to greater surface disturbance. Therefore, these unexpected results may be related to shark behaviour rather than drone effectiveness. For example, larger swells can increase turbidity in the surf zone by suspending sand as the waves break, and some fish species avoid the sediment laden water as it can irritate their gills. For this reason, perhaps sharks were more likely to swim beyond the breakers when the swell was higher, and were thus more likely to be detected by the drone in the clearer water behind the surf break. Lastly, flight number was used as an indicator of time of day, showing that the chance of sighting sharks was greatest on the first two flights of the day in the NSI, which typically occurred between 6:30am and 8:00am. This relationship may have occurred because some sharks are more active in the early morning, with increased levels of movement and foraging (Hammerschlag et al., 2017) and due to lower levels of disturbance from water users in the area at this time.

5.4 Shark movement tracks and behaviour

The detailed spatial data collected from drone sightings of sharks provides a unique opportunity to investigate their movement patterns and behaviour close to beaches. For example, the heatmap of shark movements for Burleigh Beach indicated that there was a zone close to the southern end of Burleigh Beach where many sharks spent a greater amount of time. This was especially the case for a large group (50-100 individuals) of juvenile scalloped hammerhead sharks that remained in this area for a period of 1 - 2 months in March - April 2023. This clustering may have occurred because this area of the beach was somewhat sheltered from swell and wind by the adjacent headland and is shallow, thus potentially providing a refuge from predators. There is also rocky habitat here that may have provided access to prey species for these sharks. Other species, including juvenile bull sharks and other whaler sharks were also seen swimming through this rocky habitat.

Movement patterns and space use of sharks at NSI were somewhat different to Burleigh, with sharks generally moving in a linear trajectory from south to north. There was some degree of clustering at the northern end of the beach, where the headland led to sharks moving further offshore. Other fauna were often seen close to this headland, possibly because water currents and eddies around the headland may generate higher productivity in this area, attracting prey species of sharks. The tracks mapped at Noosa were less numerous, but indicated that sharks were moving across the whole expanse of the beach, with some clustering at the western end of the beach, close to the mouth of the Noosa River. This zone would be expected to have higher productivity due to the river outflow carrying nutrients, so it would likely lead to higher concentration of prey species for sharks. Catches of sharks in the SCP net in the western section of Noosa Beach are also higher than in the other, more easterly, net (Cardno, 2020), supporting this theory. The movement track generated from the white shark sighted at Southport Main Beach showed when it was actively interacting with a school of fish, where its swim speed and turning rate increased, compared to when it was swimming steadily in a straight line.

With a larger dataset of shark movement tracks, it will be possible to generate a risk matrix for each beach where drones are operated, and even for different zones within each beach. This matrix can be based on factors including the species and size of sharks commonly sighted, their distance from shore and from water users, their direction and speed of movement and whether they were interacting with any potential prey in the area, such as bait fish schools. The matrix can then be used to determine how frequently higher risk shark movements are likely to occur and if they are clustered in certain areas of the beach covered by the drone transects. Refined flightpaths can then be developed, which prioritise spending more time in these higher risk areas. This information can also be applied by pilots to make more informed decisions about when to close the beach if certain factors on the risk matrix indicate a higher chance of a shark interacting with water users. Lastly, the findings can be summarised and communicated for the public to help them choose which beach to visit.

5.5 Comparison of shark sighting events versus SCP catch

Drones had a significantly higher overall number of shark sighting events than the numbers of sharks caught in the adjacent SCP gear (including both nets and drumlines), as well as a significantly higher number of large shark sighting events. This follows the same pattern observed during the first 12 months of the drone trial (Mitchell et al., 2022a,b). The higher number of sighting events occurred despite the markedly lower temporal coverage of drones. Drones were only operated during mornings, in relatively good weather and mostly only on weekends, equating to only 2.9% of the time that SCP nets were deployed and 5.1% of the time drumlines were active. However, drones did cover a larger spatial area (i.e. 400 m drone transect vs 186 m long net). Furthermore, the operation of drones is unlikely to impact on SCP catches; however, the operation of nets and drumlines may affect shark sightings by the drones, for example if a shark is caught before entering the area of operation of the drone.

Most shark sighting events on drones came from NSI, Burleigh Beach and Noosa, where drone sighting events were substantially higher than SCP catch. Three beaches (Alexandra Headland, Rainbow Beach and Alma Bay) showed the opposite result, with higher catches than drone sighting events. The higher numbers of catch at Rainbow Beach likely occurred because of the greater concentration of SCP gear, with three nets and 12 drumlines deployed at this location. For Alma Bay, the drumlines are set substantially further offshore from where the drones operate, so would likely catch sharks passing by Magnetic Island. Whereas the drone transects occurred within the small cove at Alma Bay, which sharks only rarely enter, based on the low number of sightings during the trial. When comparing SCP catch to drone sightings, the amount of SCP gear deployed at each beach, as well as its orientation and distance offshore, should be noted. The location of all SCP gear is available online on the Queensland Government website: (https://www.daf.qld.gov.au/news-media/campaigns/sharksmart/equipment/location).

The number of bull, tiger and white sharks caught by SCP gear was marginally higher than that sighted on drones at Noosa, NSI, Rainbow Beach and Alma Bay (other beaches had low number of sightings and catch of these species, with <5 individuals per beach), with different species composition caught on SCP gear compared to sighted on drones. Specifically, 59 tiger sharks were caught across these four beaches, but none were sighted on drones. Conversely, 19 bull sharks were caught in SCP gear vs 17 sighted on drones. This clear disparity for tiger sharks may be due to the fact that tiger sharks typically occur further offshore and are less likely to come in close to beaches, thus they are more susceptible to drumline or net capture than being seen by drones. Additionally, it is possible that the tiger sharks were more likely to be caught on drumlines than seen on drones because they were attracted to the bait on the drumlines, as they are known to be opportunistic, generalist feeders and scavenging represents an important part of their diet (Lowe et al., 1996; Dicken et al., 2017). Time of day may also have had an important effect, because the tiger sharks may have predominantly been caught at night, as found in Réunion Island (Guyomard et al., 2019), so they would not be detected by drones during the morning flights.

The number of white sharks caught or sighted by drones was low overall, with five being caught in SCP gear between Noosa and NSI and only a singular sighting at Southport Main Beach. This would be expected given the wide-ranging movements of this species and its relatively rare, seasonal presence in Queensland waters (Bruce et al., 2019). The similar number of bull sharks caught in SCP gear and sighted on drones supports previous research which has showed that they typically occupy waters further inshore than tiger sharks (Haig et al., 2018; Werry et al., 2018), potentially resulting in a higher risk to water users. This research therefore raises important questions about the behaviour of different shark species, the selectivity of fishing gear and the corresponding risk to water users. Research in NSW using drones, SMART drumlines and acoustic receivers showed there was no relationship between the detection/capture of sharks across the three different shark control methods (Colefax et al., 2020a), highlighting the complexity and variable nature of these approaches and the difficulty in making direct comparisons between them. Yet, the real-time monitoring capability of drones provides an extra level of safety compared to passive shark control gear, and the location of drone transects directly behind the surf break covers an area closer to where people are in the water, compared to the nets and drumlines which are typically 300-500m offshore.

The environmental impact of drones on aquatic wildlife was substantially less than SCP gear. Close approaches by drones are known to disturb some marine animals, such as dolphins (Ramos et al., 2018; Fettermann et al., 2019), but only sharks were approached and tracked closely in this trial. In contrast, 123 non-target animals which were caught in nets and drumlines during the trial period, 48% of which were dead on retrieval of the gear (total mortality rates would likely be higher due to some animals dying post-release). This number did also not include non-target shark species, so would be substantially higher if they were included. A large proportion of the catch also included species protected under the Environment Protection and Biodiversity Conservation Act 1999 especially loggerhead turtles manta and devil rays and cetaceans. Most of the non-target catch occurred in nets, with only a small number of non-target animals being caught on drumlines, many of which were able to be released alive. Other environmental impacts of using drones, such as loss of equipment in the marine environment, impacts associated with vessels and vehicles etc. were not quantified in this study. Drones also have the potential to impact upon seabirds, although research suggests that most seabird species have minimal detectable reactions to drones once they are >50 m away (Weimerskirch et al., 2018; Raoult et al., 2020). None of the drone trial locations are near any seabird nesting colonies, which are generally designated as restricted airspace by CASA. The impact of drones on seabirds was therefore expected to be low in this trial.

5.6 Other fauna sightings

A wide range of other marine fauna was observed during the drone trial, including protected and threatened species, and potential prey species for sharks. The most prevalent other fauna sighted were turtles and manta/eagle rays (which were grouped together due to difficulties in differentiating them at depth), particularly at NSI, where they were seen on >30% of flights. The location of NSI adjacent to Moreton Bay, coupled with the presence of extensive rocky reef habitat, makes it a hotspot for marine fauna compared to the other drone trial sites. Closer proximity to the continental shelf (~23 km versus >39 km for other drone trial beaches) also leads to greater presence of marine megafauna in this area, because the EAC and colder oceanic currents converge near shelf edges in this area, leading to upwelling and increased nutrient concentration (Roughan & Middleton, 2004). A range of marine megafauna, such as humpback whales (Bolin et al., 2020), manta rays (Jaine et al., 2014; Couturier et al., 2011), and sharks (Holmes et al., 2014) may use the EAC for navigation during migration, so would be more likely to be sighted at NSI, where the EAC passes closer.

Dolphins were also common at NSI, with groups of up to 45 Indo-Pacific bottlenose dolphins observed, sometimes with calves. Australian humpback dolphins were also sighted at NSI on four occasions. Stingrays were the third most sighted group across all beaches, with 7.2% sighting rate. This is likely to be an underestimate of overall stingray presence, given that they remain on the seabed so may be undetectable if they have buried themselves in the sand or during times of higher turbidity or greater glare. Likewise, whilst there were some sightings of jellyfish across the drone trial, many would have gone undetected due to their small size and translucent appearance. Large fish and bait balls were seen across all beaches, although were more prevalent at NSI. In combination with the greater abundance of other fauna, this could possibly lead to a higher risk for water users at this beach compared to the others in the trial, where all of the other fauna groups were seen on <10% of flights. Indeed, results from the GLMs confirmed that the sighting of other fauna was an important predictor of the probability of shark sightings.

The prevalence of some of these other fauna groups was lower than that recorded in the NSW drone trial, especially in the case of dolphins, which were seen on 25.5% of flights in the NSW trial (Kelaher et al., 2020), compared to only 3% in the current Queensland trial. Sighting rates of turtles were similar in Queensland compared to the previous NSW trial, with sighting rates of 7.7% and 7.4% of flights, respectively (Kelaher et al., 2020). Overall, however, the number of flights was also much higher in the current trial compared to the NSW study, with 17,954 vs 216 (Kelaher et al., 2020), preventing a robust comparison. The presence of different faunal groups will be influenced by local environmental conditions and certain species also displayed seasonal presence, such as manta rays and leopard sharks, which were seen predominantly during summer months, and dugong and humpback whales, which were only seen in winter months (Cross et al., in press). Other faunal groups were seen more uniformly across all months of the year, including large fish, stingrays, eagle rays and dolphins (Cross et al., in press). There were some other notable sightings that occurred during the drone trial, including that of a humpback dolphin at Coolum North, which was significant as sightings of this species on the Sunshine Coast are rare (J. Meager, pers. comm.). The first recorded instance of green turtles mating at NSI was also recorded during drone operations, highlighting the value of this research for understanding the presence, diversity and behaviour of other (non-shark) fauna.

It is important to note that the relationship between shark presence/absence and shark bite risk is not clearly understood. Indeed, it is likely that in the vast majority of cases where water users come into close proximity with sharks there are no adverse consequences. However, the most risk averse approach is to avoid being in the water when sharks are present or more likely to be present.

5.7 Future analyses

To increase understanding of the operational capabilities of drones and the influence of environmental factors on shark presence and sightability, a range of further analyses will be conducted on the drone trial data collected. Ground-truthing of drone capability to sight sharks in different environmental conditions specific to Queensland would improve understanding of the effectiveness of drones across varied ocean conditions. This could be achieved by deploying shark analogues at different depths and specifically in varying levels of turbidity and glare. It is recommended to follow the methodology used by Butcher et al. (2020), which found that depth of shark analogues and water visibility were the most important environmental factors influencing shark sightability. Specifically, detection rates were very low when the shark analogue was at depths greater than 2 m or when water visibility was less than 1.5 m (Butcher et al., 2020). Conducting this analogue testing will help to generate a more robust understanding of the abilities and limitations of drones for detecting sharks at Queensland beaches. Artificial intelligence (AI) machine-learning algorithms have the potential to assist SLSQ pilots and improve detection rates of sharks, by running in real time and providing identifying boxes around sharks and alerting the pilot. This may help to reduce the chance of pilots missing sharks, for example when they are not looking at the screen due to maintaining their line of sight with the drone or other aircraft in the area. Additionally, glare and low water visibility may result in them missing sharks, but AI may assist with detections in these conditions. Preliminary trials of AI solutions have recently been conducted in SEQ, to test their accuracy at detecting sharks and their practicality for use (KPMG, 2025). The AI systems tested showed potential for assisting drone pilots with detection of sharks, however further training of the AI algorithms is required for each specific location, to improve the success rate of detections. Improvements in the hardware are also required, to ensure the AI systems are rugged and practical for pilots to use in the beach environment (KPMG, 2025).

For beaches where higher turbidity occurs, including those in Central and North Queensland, current drone technology used during the trial was ineffective at detecting sharks (although it was unknown if there were any sharks present or not), as demonstrated by analysing flights conducted at Palm Cove in North Queensland during the first 12 months of the trial (Mitchell et al., 2022a). Advanced camera technologies (e.g. hyper or multispectral cameras (Colefax et al., 2023)) were recently trialled, to determine whether they can improve the detection rate of sharks in sub-optimal conditions, such as turbid water or when glare is high (KPMG, 2025). These trials established that the optimal wavelength for detecting sharks was 525-540 nm, however the conditions during the trial were not overly turbid, limiting the ability to assess whether the technology improved detection of sharks relative to the current drones used in the trial (KPMG, 2025). Additionally, further work would be needed to ensure the drones and hardware used are compatible with current operational requirements and budgets (KPMG, 2025).

Investigating shark presence at beaches is important for understanding the relative risk to water users. Bringing together different data sources can help to increase this understanding, so it is recommended that tracking data for tagged sharks should be analysed to determine presence/absence of tagged sharks at acoustic receivers deployed close to SCP gear and drone trial locations. There are now 41 bull and 163 tiger sharks which have been tagged by SCP contractors in the Great Barrier Reef Marine Park (as of 30/04/2024), as well as >500 tiger and white sharks in the NSW Shark Control Program and many more tagged by other researchers at the Australian Institute of Marine Science, James Cook University and University of the Sunshine Coast. These tagged animals will provide a wealth of data to investigate how shark detections compare to SCP catch and drone sightings at Queensland beaches. They also provide the opportunity to further investigate the environmental drivers behind when and why sharks are visiting particular beaches, and potentially identifying additional management options. The value of such interagency collaborations has been recently demonstrated for the Queensland acoustic telemetry array, highlighting the value of this program for improving our knowledge of the biology and ecology of key shark species and how this influences management and conservation (Barnett et al., 2024).

5.8 Criteria for future selection of beaches for drone operations

There is scope to expand the deployment of drones to other beaches in Queensland. However, before doing so, it is necessary to determine whether each beach meets the necessary criteria to ensure the use of drones is appropriate and will be effective. Firstly, environmental conditions need to be considered because some locations (particularly in North Queensland) may have high turbidity that makes detection of any sharks unlikely. Indeed, the trial flights conducted at North Queensland beaches did not detect any sharks, likely because the water turbidity was often high (mean value of 88% turbidity recorded by pilots, compared to 74% at South-East Queensland beaches) (Mitchell et al., 2022a). The use of advanced camera technologies, such as hyper and multispectral imaging, may be able to partially increase the detection capability of drones when turbidity is high, however further development and testing of these technologies is required to verify this and ensure they can be operationally viable (KPMG, 2025). The depth and seabed type must also be considered because this can influence the effectiveness for visually detecting sharks. For example, beaches with rocky and/or macroalgae dominated seabeds appear darker, therefore any sharks swimming above these seabeds would have lower contrast and be more difficult to detect, compared to above sandy seabeds. Advanced camera technologies may also be able to improve detection of sharks in these scenarios, due to the ability to use a wider range of wavelengths to improve contrast of sharks against the substrate (KPMG, 2025).

Airspace regulations are another key factor that govern where drones can be operated for shark detection. Civil Aviation Services Authority (CASA) regulations currently prohibit the operation of drones anywhere within a 5.5 km radius of controlled airports. Some beaches in Queensland fall within this 5.5 km radius, including those on the southern Gold Coast (near Gold Coast airport), mid and southern Sunshine coast (near Maroochydore and Caloundra airports), Cairns and Townsville. There are also limitations on the use of drones in other areas, such as important bird nesting sites at certain times of year. To maximise the usefulness of the drones, it is advised that they are used at beaches with relatively high year-round visitation rates which have on-duty lifesavers/lifeguards to operate the drones, and operational processes in place to respond to shark sightings.

Another consideration is the historical catch of sharks in SCP gear adjacent to the beach. Those beaches which have a higher catch rate of potentially dangerous sharks due to their biophysical setting (e.g. proximity to an estuary) and/or environmental conditions (e.g. a productive area with lots of baitfish and other potential prey for sharks), should be prioritised as there is a higher likelihood of sharks occurring in these areas. An example of such a location is Tannum Sands, which is close to an estuary and where there is a relatively higher catch of bull sharks compared to other locations. Similarly, Bundaberg and Agnes Water would be suitable locations to test whether drones can be effective at detecting sharks. Many of the factors influencing the suitability of using drones at different locations have been investigated in a previous report by Cardno (Cardno, 2020), and this report provides an important resource to guide the initial identification of suitable beaches for drone operations. Development of a risk matrix using a transparent and robust framework that helps prioritise suitable beaches for drone operations is also recommended.

5.9 Recommendations

Based on the findings presented here for the Queensland SharkSmart drone trial, the following recommendations are made:

1. Continue the deployment of drones at the beaches covered during the drone trial, because they have demonstrated successful capability to detect sharks and provide real time safety benefits to water users, with high levels of public support.
2. Extend the deployment of drones to other suitable beaches in Queensland, based on a set of rigorous scientific criteria, including, but not limited to, beach visitation and on-duty lifeguard presence, suitable environmental conditions, adherence to CASA regulations, proximity to river mouths and historical catch in the SCP.
3. Consider extending the flight periods to cover the whole day, rather than just mornings.
4. Monitor CASA regulations in relation to the ability to conduct flights in airport exclusion zones to see if operations may be possible in these areas in the future.
5. Conduct a robust assessment of the detection capability of drones in Queensland, using shark analogues deployed under a range of environmental conditions.
6. Continue testing the effectiveness of AI for detecting sharks in comparison to human observers under a range of environmental conditions, particularly when water visibility is lower, because pilots may be more likely to miss some sharks. Work with AI developers to improve the operational useability of AI systems, so that they are suitable for the beach environment.
7. Undertake further testing of advanced camera technologies (e.g. hyper or multispectral cameras) in locations where water turbidity is higher (e.g. North Queensland) and in rocky seabed habitats, to assess whether they are more effective at detecting sharks compared to standard cameras.
8. Conduct studies to improve understanding of the spatial and temporal use of the coastal zone by sharks, using acoustic and satellite telemetry and dedicated drone tracking flights in addition to regular SLSQ drone flights. Deploying hook timers on drumlines at beaches where drones are operating should also be undertaken to identify what time of day sharks are caught and how this influences their likelihood of being detected by drones.
9. Collaborate with other researchers to use footage of other non-shark fauna, for improving understanding of their seasonal abundance, movement patterns and behaviour and contributing to improved monitoring, management and conservation.
10. Progress extended and beyond visual line of sight flying protocols to increase capability of the program to monitor areas beyond the flags, which will increase real time safety for groups such as surfers, kayakers, paddle-boarders and ocean swimmers.
11. Investigate new developments in drone technology, including autonomous capabilities e.g. ‘drone in a box’ solutions.

12. Develop seamless data transfer and storage capability to reduce the labour burden of managing footage.
13. Investigate options to access live drone footage for use in real-time incident management.
14. Future communication activities for the SharkSmart drone trial should focus on promoting the days, times and locations drones are operating, to enable people to make an informed choice about where they undertake their chosen water-based activities. The results of the drone trial should also be incorporated into SharkSmart messaging recommendations, e.g. avoiding swimming near large schools of bait fish as drone footage has shown that large numbers of sharks can be present near bait balls. Furthermore, communication should also focus on the relative benefits of drones as a shark spotting tool, including their real-time monitoring capability and the negligible impact they have on the environment, as well as their limitations, such as their inability to fly during rain and high winds, operate in adverse sea conditions or cover all areas of the coastline.

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8. Appendices

8.1 Project timeline

- October 2019: Cardno report reviewing alternative shark control measures released (Cardno, 2019)
- December 2019: SCP Scientific Working Group consulted on possible trial locations
- January 2020: Detailed Cardno report delivered providing summary data to assist with beach selection for drone trial (Cardno, 2020)
- March 2020: Planning delayed due to impact of COVID-19 pandemic
- June 2020: Grant agreement finalised with SLSQ to deliver drone trial
- June 2020: Drone trial project team formally established
- July 2020: Operational demonstration of drones at Sunshine Coast
- 7 August 2020: Flights commenced at Coolum North and Alexandra Headland
- 19 September 2020: All five trial locations operational
- 18 February 2021: SCP Scientific Working Group consulted on preliminary results and potential expansion of the trial
- 26 June 2021: Palm Cove and Alma Bay (NQ) beaches operational
- 26 November 2021: Draft interim project report delivered
- 16 December 2021: Consultation with the SCP Scientific Working Group to discuss continuation of the drone trial at existing beaches and the addition of new beaches
- 20 June 2022 - new grant agreement established between DPI and SLSQ to continue the trial to 2025 and expand to additional locations
- 19 September 2022: First flight conducted at Rainbow Beach
- 24 September 2022: First flight conducted at Bribie Island
- 23 October 2022 – publication released - Mitchell, J.D.; Scott-Holland, T.B.; Butcher, P.A. Factors Affecting Shark Detection from Drone Patrols in Southeast Queensland, Eastern Australia. Biology 2022, 11, 1552. https://doi.org/10.3390/biology11111552
- 5 November 2022: First flight conducted at Kurrawa
- 6 November 2022: First flight conducted at Noosa
- 30 June 2024: Draft final report delivered for internal review

8.2 GLM outputs and diagnostics

A range of diagnostics were used to ensure the GLMs applied were robust and generated a good fit to the data. Firstly, continuous predictor variables were checked for high levels of correlation, with Pearson correlation coefficients of 0.5 being deemed as the threshold value. The results of the check for correlation are presented in Table A1.

Table A1 Pearson correlation coefficients for the continuous predictor variables used in GLMs.

Predictor variable						
Predictor variable	Wind speed	Temperature	Atmospheric pressure	Swell height	Turbidity	7-day rainfall
Wind speed	1.00	0.20	-0.03	0.07	0.15	0.04

Temperature	0.20	1.00	-0.49	-0.07	0.07	0.12
Atmospheric pressure	-0.03	-0.49	1.00	0.04	-0.03	-0.12
Swell height	0.06	-0.07	0.04	1.00	0.19	0.00
Turbidity	0.15	0.07	-0.04	0.19	1.00	0.19
7-day rainfall	0.04	0.12	-0.12	0.00	0.19	1.00

The distribution of predictor variables used in the GLMs was also checked to ensure they had an even distribution and those with uneven distributions were log +1 or square root transformed, which included turbidity and swell height (Figure A1).

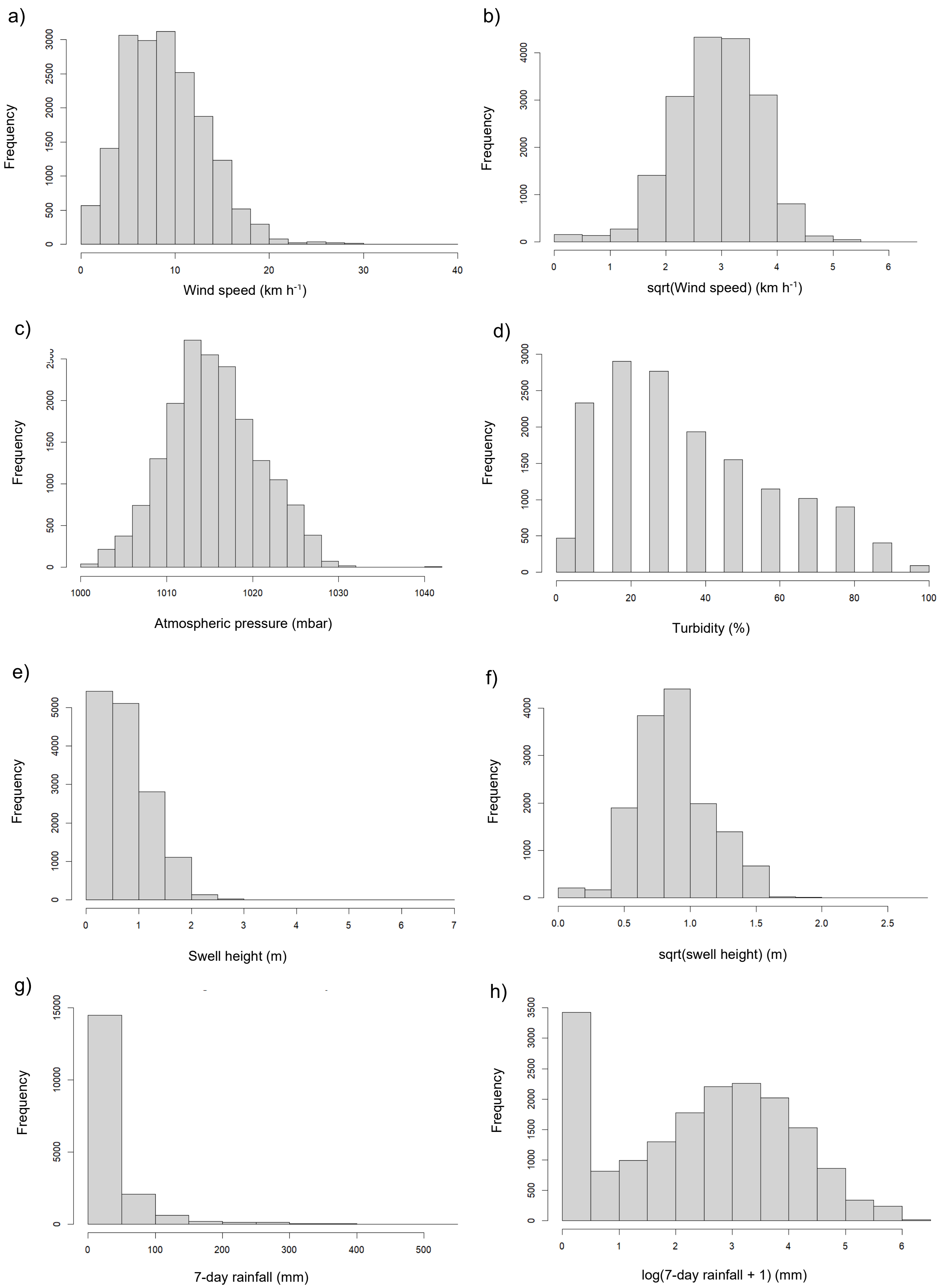
a)
Frequency
Wind speed (km h⁻¹)
b)
Frequency
sqrt(Wind speed) (km h⁻¹)
c)
Frequency
Atmospheric pressure (mbar)
d)
Frequency
Turbidity (%)
e)
Frequency
Swell height (m)
f)
Frequency
sqrt(swell height) (m)
g)
Frequency
7-day rainfall (mm)
h)
Frequency
log(7-day rainfall + 1) (mm)

Figure A1 Histograms showing the distribution of values for continuous predictor variables used in GLMs. a) wind speed, b) wind speed after square root transformation, c) atmospheric pressure, d) turbidity, e) swell height, f) swell height after square root transformation, g) 7-day rainfall, h) 7-day rainfall after log+1 transformation.

The best performing GLMs for the whole dataset and NSI were those which had the lowest AIC and only included significant predictor variables. The model outputs for these GLMs are provided below in Tables A2 and A3.

Table A2 Model output for the GLM run on the whole dataset.

Predictor variable	Chi-squared value	Degrees of Freedom	P-value
Location	371.51	9	<0.0001
sqrt(wind speed)	7.07	1	0.008
Tidal state	20.29	3	0.0001
Turbidity	48.37	1	<0.0001
Glare	22.96	4	0.0001
Season	43.79	3	<0.0001
Presence of other fauna	34.00	1	<0.0001
Wind direction	56.67	15	<0.0001
Atmospheric pressure	20.00	1	<0.0001

Table A3 Model output for the GLM run on the data for North Stradbroke Island.

Predictor variable	Chi-squared value	Degrees of Freedom	P-value
Flight number	18.26	5	0.003
Wind direction	37.97	15	0.0009
Cloud cover	32.27	8	<0.0001
Atmospheric pressure	36.42	1	<0.0001
Tidal state	11.56	3	0.009
Swell height	22.20	1	<0.0001
Turbidity	15.52	1	<0.0001
Presence of other fauna	7.13	1	0.008