Queensland SharkSmart Drone Trial

Final Report

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List of abbreviations

AI – Artificial Intelligence

CASA – Civil Aviation Safety Authority

DAF – Department of Agriculture and Fisheries

EPBC Act - Environment Protection and Biodiversity Conservation Act

GLMM – Generalised Linear Mixed 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

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 potentially dangerous sharks in real-time, whilst having a 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 beaches of South-East Queensland (SEQ) have relatively good water clarity and a high level of visitation, making them an ideal location to test drones for detecting sharks and improving the safety of water users (Cardno, 2019). North Queensland beaches typically have lower water clarity, although it is important to test drones under these conditions to assess whether they can be effective at detecting sharks.

The Queensland SharkSmart drone trial commenced on 19 September 2020, as a partnership between the Queensland Government Department of Agriculture and Fisheries (DAF) and Surf Life Saving Queensland (SLSQ). The trial was part of the Queensland Government's commitment to research and trialling alternatives to traditional shark control measures. 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) between 19 September 2020 and 4 October 2021. Additionally, to assess the effectiveness of drones at detecting sharks under the different environmental conditions found at North Queensland (NQ) beaches, drones were operated at Palm Cove, Cairns and Alma Bay, Magnetic Island, from 26 June 2021 to 31 October 2021. Drones were operated on weekends, public holidays and school holidays by SLSQ pilots, with two flights per hour from approximately 8am until midday. Flights lasted 15 - 20 minutes and followed a 400 m transect behind the surf break. All footage was collected in 4K and securely archived for later analysis with key operational and environmental data collected for every flight. When a shark was sighted, the drone pilot lowered the aircraft to determine the species and size while estimating distance of the animal from water users. Data analysis quantified the numbers of sharks sighted at each beach and the rate of sightings as a percentage across the whole trial from 19 September 2020 to 31 October 2021. Generalised Linear Mixed Models (GLMMs) were applied to quantify the influence of environmental and operational factors on the sightability (probability of a shark being sighted) of sharks. The movement tracks of sharks were mapped to analyse their behaviour and identify if there was clustering of movements in certain areas. Sighting rates from drones were also compared with shark catch in adjacent nets and drumlines deployed as part of the Queensland Shark Control Program (SCP).

Across the seven beaches, 3,669 drone flights were conducted (3,369 at SEQ beaches, 300 at NQ beaches), covering 1,468 km. Drones were able to operate in varying weather conditions, including up to 20 knot winds. A relatively low number of days (17%) were cancelled due to bad weather and there would likely be less people entering the water on these days anyway. A further 11% of days were also lost due to operational reasons, such as staff unavailability and events taking place on the beach. Drones used during the trial were mechanically reliable throughout, with few instances of failure.

In total, 174 sharks were sighted by drones across the trial, including 48 large sharks estimated to be >2 m in total length. Of these, eight bull sharks and one white shark were detected, leading to four beach evacuations. No tiger sharks were sighted during the trial. The shark sighting rate was 3% when averaged across all beaches, with NSI having the highest sighting rate (17.9%) and Coolum North, Palm Cove and Alma Bay the lowest (0%). Drone pilots were able to differentiate between key shark species, including white, bull and whaler sharks, and estimate total length of the sharks. The results of GLMM analysis indicated that location, the sighting of other fauna, season and flight number (a proxy for time of day) were the most important factors influencing shark sightability. 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) and the latter is close to the mouth of a creek which can lead to higher productivity in the local area. Indeed, the GLMM indicated that shark sightability was higher when other fauna were sighted. Summer was the season with the

highest probability of shark sightings, likely due to higher levels of rainfall leading to greater productivity in the coastal environment and the first flight of the day also had higher probability, possibly because sharks were more active at this time of day and there was less disturbance in the area. A separate GLMM was run for NSI specifically, indicating that the first two flights of the day, intermediate levels of cloud cover and higher atmospheric pressure led to the highest probability of shark sightings. At Burleigh Beach, shark sightability was higher during summer and autumn and when other fauna were sighted. Movement tracks generated for sharks were between 100 m and 400 m offshore and there was a clustering of four shark movements at the southern end of the drone transect at Burleigh Beach, possibly because this area is closest to the nearby creek mouth and thus supports higher productivity and more prey for sharks. A movement track was generated for the white shark sighted at Southport Main Beach, where it moved in a south-easterly direction and was observed interacting with fish, leading to increased tortuosity in its track.

The total number of sharks sighted by drones (174), as well as those larger than 2 m (48), was significantly higher than those caught in adjacent SCP gear (49 and 22, respectively), when all beaches were combined, despite drones operating for only ~2% of the time that SCP gear was deployed. NSI and Burleigh Beach had significantly higher shark sightings than catches, with 94 vs 8 and 73 vs 13, respectively. Numbers of large sharks >2 m were also significantly higher than that caught in nets and drumlines at NSI (22 vs 7) and Burleigh Beach (23 vs 3). However, the total number of sharks sighted on drones were slightly lower than the number caught in SCP gear at the other five beaches, although these differences were not statistically significant. Linear regression indicated that there was no significant relationship between the number of sharks sighted on drones and caught in SCP gear across the seven beaches, for either the total number of sharks or the number of large sharks >2 m in length. Drones detected more bull sharks (8) than were caught in SCP gear (5), yet 11 tiger sharks 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 inshore 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. 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, 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 when making comparisons between the two approaches.

SCP gear had a substantially higher environmental impact than drones due to the capture of 19 non-target animals at these seven beaches during the trial period, including marine mammals, turtles and manta rays. Conversely, drones observed a wide range of fauna in a non-invasive way, including turtles on 8% of flights and manta rays and eagle rays on 7% of flights. NSI had a very high prevalence of other fauna sightings, with marine animals seen on 82% of flights, whereas the other beaches had much lower prevalence. No fauna was seen at Palm Cove, likely due to high water turbidity levels. An important sighting of a humpback dolphin was recorded at Coolum North. This species is rarely recorded in the Sunshine Coast region. The first footage of green turtles mating at NSI was also collected during the drone trial. Footage of non-shark fauna is being analysed to understand how shark behaviour is influenced by the presence of potential prey and how this might translate into risk to water users at 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 has demonstrated that drones can be a reliable tool for detecting sharks at some Queensland beaches, operating across a range of environmental conditions. The real-time monitoring capability of drones provides an extra level of safety for water users in addition to the SCP gear. 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 the fact that drones were effective at operating across a range of environmental conditions, were successful at detecting a relatively large number of sharks given the short periods they were operating and provided a range of other safety benefits, it is recommended that they continue to be operated at the existing SEQ beaches. Drones should also be trialled at other beaches, which should be chosen based on a set of rigorous criteria, including CASA regulations, the suitability of environmental conditions (e.g. turbidity, depth, seabed type and proximity to river mouth), beach visitation rates, historical SCP catch and lifesaver/lifeguard presence. To further assess the capability of drones for detecting sharks across a range of environmental conditions, flights should be conducted with shark analogues (models) present and advanced camera technologies (e.g. hyper and multispectral cameras) should be trialled to determine whether they can improve shark detection rates in higher water turbidity levels. Artificial Intelligence (AI) technology should be utilised to improve shark detection rates in real-time whilst reducing pilot fatigue and for analysing existing archived footage. Incorporating these recommendations will improve the operational effectiveness of drones for detecting sharks at Queensland beaches and increase the safety and confidence of 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) to 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 key area 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 to automatically detect and identify sharks in development (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.

A large body of research has been conducted as part of a trial of drones for shark monitoring in New South Wales in recent years. 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 or the environment (Stokes et al., 2020). Yet, certain limitations of drones can reduce their effectiveness for detecting sharks, particularly their inability to operate during rain or when wind speeds are >20 knots, and their limited potential for detecting sharks in deeper and more turbid water. Overall, however, the success of trials in NSW, where drones have been tested at many beaches and were able to detect sharks and other marine fauna under a range of environmental conditions, has now led to the development of an operational drone program, where Surf Life Saving NSW operate drones at 50 beaches along the NSW coastline.

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 protected and/or endangered (Paterson, 1990; Gribble et al., 1998; McPhee et al., 2021). This can represent a threat to the localised 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); tagging research (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 protecting water users whilst significantly reducing the impact on non-target marine fauna (McPhee et al., 2021). DAF recently 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 key alternatives available, especially for 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.

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. Scientifically 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 and comply 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 of alternative approaches to shark control in Queensland (Cardno, 2019), advice from the SCP Scientific Working Group and Civil Aviation Safety Authority (CASA) regulations regarding restricted airspace close to airports and other no-fly areas, a range of locations were identified as potential sites for the drone trial. 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

1. Alexandra Headland (Sunshine Coast)
2. Coolum North (Sunshine Coast)
3. Burleigh Beach (Gold Coast)
4. Southport Main Beach (Gold Coast)
5. Ocean beach (North Stradbroke Island)

North Queensland

1. Palm Cove (Cairns)
2. Alma Bay (Magnetic Island, Townsville)

3.2 Flight schedule

To achieve optimal coverage of these seven beaches during times of highest 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 7-8am) and ending after a final flight at 12pm. 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 suspected 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 200m north and south of the ground control station, covering up to an 800m flight circuit (Fig. 1). Flights lasted between 15 and 20 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 never flown directly above water users or people on the beach. To protect privacy of beach users, the drone cameras were only turned on once the drone was above the water.

DJI Mavic Pro drones were used for the vast 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. Drones were set to record continuously in 4K video (Fig. 2) 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 accurately estimating its length, and then tracked the shark until a drone battery change was necessary or the shark moved in to deeper water. 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, with 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, i.e. it approached within 200m of a water user and/or was displaying fast and erratic swimming behaviour, standard SLSQ procedure for beach evacuation was followed.

3.5 Data collection

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

- 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)
- 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

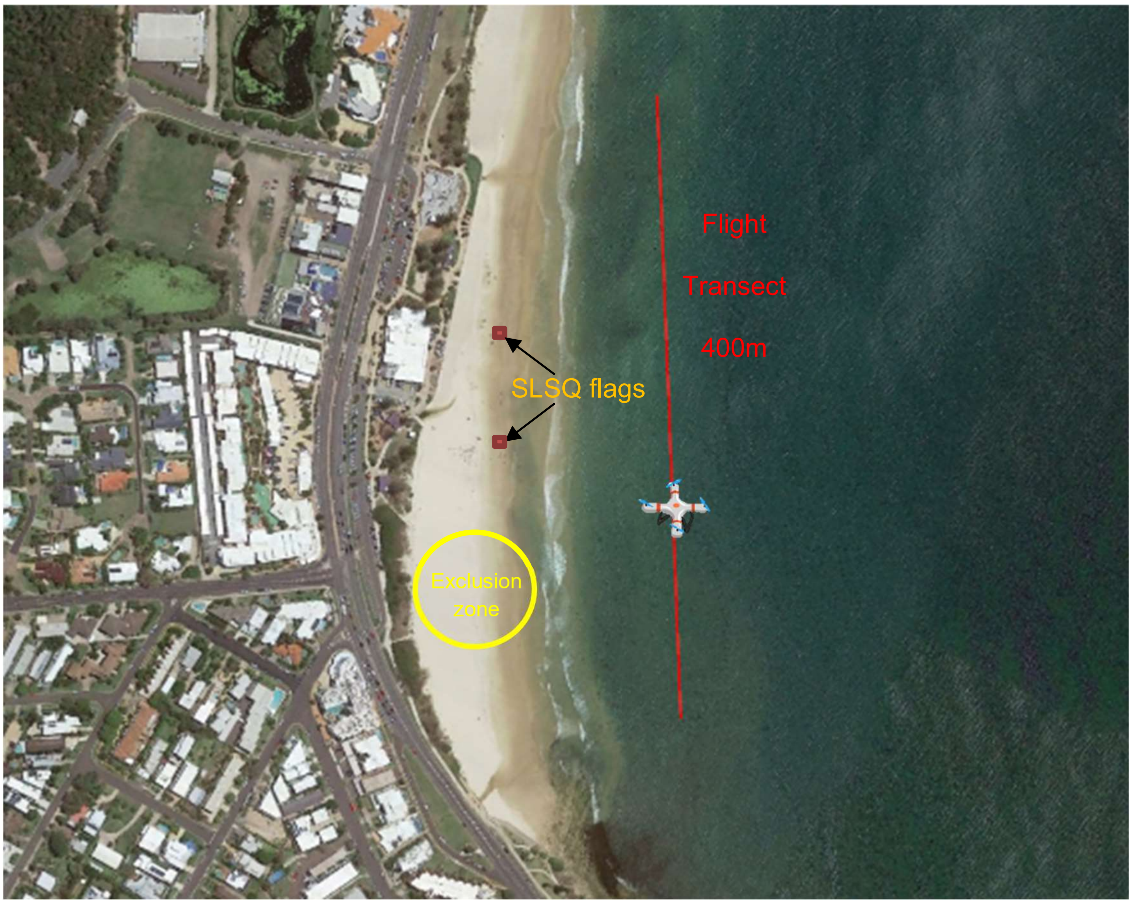

Fig. 1: Schematic showing the position of drone transects relative to the flagged area of the beach.

Fig. 2: 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.

3.6 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 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. One small whaler was missed by pilots at NSI, so it was added to the dataset.

A Generalised Linear Mixed Effects model (GLMM) was applied to determine how a range of environmental and operational factors (including location) influenced the sightability of sharks. Separate GLMMs were also run for the two beaches with highest numbers of shark sightings, to assess which specific factors were influencing the probability of sightings. The response variable of these GLMMs was modelled with a binomial distribution (presence/absence of sharks). Predictor variables were checked for correlation, which indicated all variable combinations had <0.5 Pearson correlation coefficients. The distribution of predictor variables were also visualised and a square root or log +1 transformation was applied to achieve more uniform distributions if necessary. Date in the form of Julian Day from the start of the trial was included as a random factor in the GLMMs to account for any random variation at the day level. 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) 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 sightings 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 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 number of shark sightings 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.

4 Results

4.1 Operational results

Between 19 September 2020 when all five SEQ beaches were operational and 4 October 2021, SLSQ operated 3,369 individual drone flights, representing a total minimum distance of 1,348 km (Table 1). For NQ, 300 flights were undertaken between 26 June 2021 and 31 October 2021. Mean flight time across this period was 17 minutes (± 3.3 minutes (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 knots or during rainfall. This resulted in 189 flight days being lost to bad weather across the seven trial beaches combined, which represented 17% of the total number of flight days (Table 1). The number of days lost to bad weather was variable across beaches, being equal highest (23%) at NSI and Coolum and lowest at Alexandra Headland and Alma Bay (10%). Importantly, only four days of flights were lost to bad weather (storms) throughout the whole 48-day school holiday period from 10 December 2020 to 26 January 2021. The drones operated by SLSQ were mechanically reliable, with few malfunctions 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. Some staffing issues also resulted in lost flying days, for example where pilots were unable to work due to being in isolation after taking a COVID-19 test, or other medical issues. In total, 123 days were lost to all of these non-weather related factors across the seven drone trial beaches combined, which represented 11% of the total number of flight days.

In addition to providing a platform to sight sharks and warn the public of the presence of any potentially dangerous sharks, drones offered an added safety benefit of being able to 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 Queensland Police with several search operations to find missing persons.

Table 1: Operational metrics for each beach covered by the Queensland SharkSmart drone trial. Data covers the time period 19 September 2020 – 4 October 2021 for South-East Queensland beaches and 26 June 2021 – 31 October 2021 for North Queensland beaches.

Location	Total number of flights	Distance covered (km)	No. of days lost to bad weather and percentage of total days	No. of days lost due to operational factors and percentage of total days
South-East Queensland (SEQ)				
Alexandra Headland	830	332	20 (10)	13 (6)
Coolum North	759	304	49 (23)	12 (6)
Burleigh Beach	705	282	22 (11)	27 (13)
Southport Main Beach	712	285	34 (16)	33 (16)
North Stradbroke Island	363	145	49 (23)	19 (9)
Sub-Total SEQ	**3,369**	**1,348**	**174 (17)**	**104 (10)**
North Queensland (NQ)				
Palm Cove	169	68	10 (21)	9 (19)
Alma Bay	131	52	5 (10)	10 (21)
Sub-Total NQ	**300**	**120**	**15 (16)**	**19 (20)**
TOTAL	**3,669**	**1,468**	**189 (17)**	**123 (11)**

4.2 Shark sighting rates

A total of 174 sharks were sighted during the Queensland SharkSmart drone trial, all of which were at SEQ beaches. 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 sightings were highly variable across beaches, ranging from zero shark sightings at Coolum North to 94 sightings at NSI (Table 2). The majority of these sightings were smaller whaler sharks <2 m in length, and therefore posed a lower risk to water users. However, 48 large sharks were seen, mostly at Burleigh Beach and NSI. For the three species most likely to be dangerous to humans (white, tiger and bull sharks), there were two sightings at Burleigh Beach, three at Southport Main Beach and four at NSI, which led to four beach evacuations. No large sharks were sighted at either of the Sunshine Coast beaches. Drone pilots were usually able to differentiate between the main groups of sharks, including white/tiger/bull and whaler sharks (Fig. 3), 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. In total, sharks were sighted on 3% of all flights, with the sightings rates varying from 0% at Coolum North to 17.9% at NSI (Table 3).

Table 2: Number of sharks sighted at Queensland SharkSmart drone trial beaches. Data covers the time period 19 September 2020 – 4 October 2021 for South-East Queensland beaches and 26 June 2021 – 31 October 2021 for North Queensland beaches.

Location	Total number of sharks*	No. of large (>2 m) sharks	No. of white, bull, tiger	No. of beach evacuations
South-East Queensland				
Alexandra Headland	3	1	0	0
Coolum North	0	0	0	0
Burleigh Beach	73	23	2	2
Southport Main Beach	4	2	3	0
North Stradbroke Island	94	22	4	2
North Queensland				
Palm Cove	0	0	0	0
Alma Bay	0	0	0	0
TOTAL	**174**	**48**	**9**	**4**

***total does not include leopard sharks**

Table 3: Percentage of flights where sharks were sighted at Queensland SharkSmart drone trial beaches. Data covers the time period 19 September 2020 – 4 October 2021 for South-East Queensland beaches and 26 June 2021 – 31 October 2021 for North Queensland beaches.

Location	Percentage of flights where sharks were sighted
South-East Queensland (SEQ)	
Alexandra Headland	0.2%
Coolum North	0%
Burleigh Beach	5.1%
Southport Main Beach	0.6%
North Stradbroke Island	17.9%
North Queensland (NQ)	
Palm Cove	0%
Alma Bay	0%
All SEQ and NQ locations combined	**3%**

***total does not include leopard sharks**

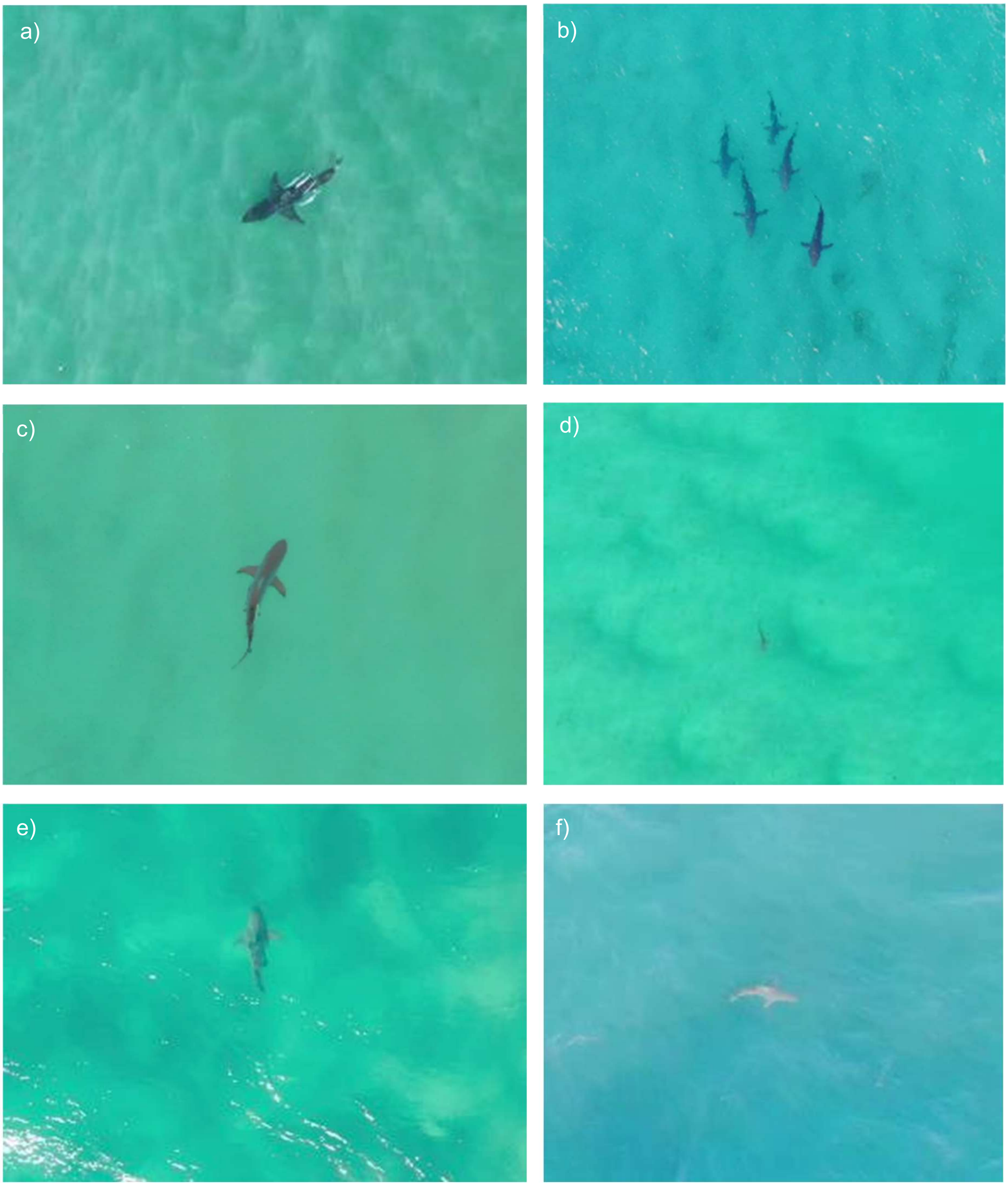

Fig. 3: Example images of sharks recorded during the Queensland SharkSmart drone trial. a) white shark recorded at Southport Main Beach, Gold Coast in September 2020, b) a group of five large whaler sharks observed at Ocean beach, North Stradbroke Island in November 2020, c) a whaler shark from the blacktip complex recorded at North Stradbroke Island in December 2020, d) a small whaler shark seen at North Stradbroke Island in January 2021, e) a bull shark recorded at Burleigh Beach in June 2021 and f) whaler shark at North Stradbroke Island in December 2020.

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 may affect shark sightings. For example, wind speed varied between 0 and 20 knots (mean = 8.4 km h^{-1}) and was recorded from all compass directions, most commonly from the southeast and least often from the west-southwest. Glare and turbidity (which were estimated by the pilot) varied substantially from 1-5 (mean = 3) and 0-100% (mean = 75%), respectively (Table 4). Notably, mean turbidity was substantially higher for the two NQ beaches (88% ± 8% (SD)), compared to the SEQ beaches (74% ± 5% (SD)). Other environmental parameters that were likely to influence the sightings of sharks were cloud cover, which ranged from 0 – 8 oktas and sea state, spanning 1 – 10 on the Beaufort scale (Table 4).

Table 4: Ranges of data recorded for environmental variables included in Generalised Linear Mixed Modelling analysis.

Variable	Data range
Temperature	5.6 – 37 °C (mean = 23.1 °C)
Swell height	0 – 2 m (mean = 0.7 m)
Wind speed	0 – 30 km h^{-1} (mean = 8.4 km h^{-1})
Wind direction	All 16 directions (max = SE 431 flights, min = WSW 145 flights)
Cloud cover	0 – 8 oktas (mean = 3 oktas)
Glare	1 – 5 scale (mean = 3)
Turbidity	0 – 100% (mean = 75%)
Atmospheric pressure	1001 – 1063 mbar (mean = 1016.6 mbar)
Sea state	Beaufort 1 – 5 (mean = 3)
Humidity	36 – 100% (mean = 62.3%)

GLMM outputs indicated that location, the sighting of other fauna, season and flight number were the most important factors that had a significant influence on the sightability of sharks, explaining 57% 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 (0.02), followed by Burleigh Beach (0.008), with Alma Bay, Coolum North and Palm Cove all having zero values due to no sharks being sighted at these locations (Fig. 4a). The sighting of other fauna increased the likelihood of a shark being sighted (0.008), compared to if other fauna were not sighted (0.003) (Fig. 4b). Season also had a variable impact on shark sightability, with the highest probability of shark sightings occurring in summer (0.02), which was more than double the likelihood for sightings in spring (0.008) (Fig. 4c). Sharks were most likely to be sighted on the first flight of the day (0.04) and least likely on flights 3 (0.008) and 5 (0.007) (Fig. 4d).

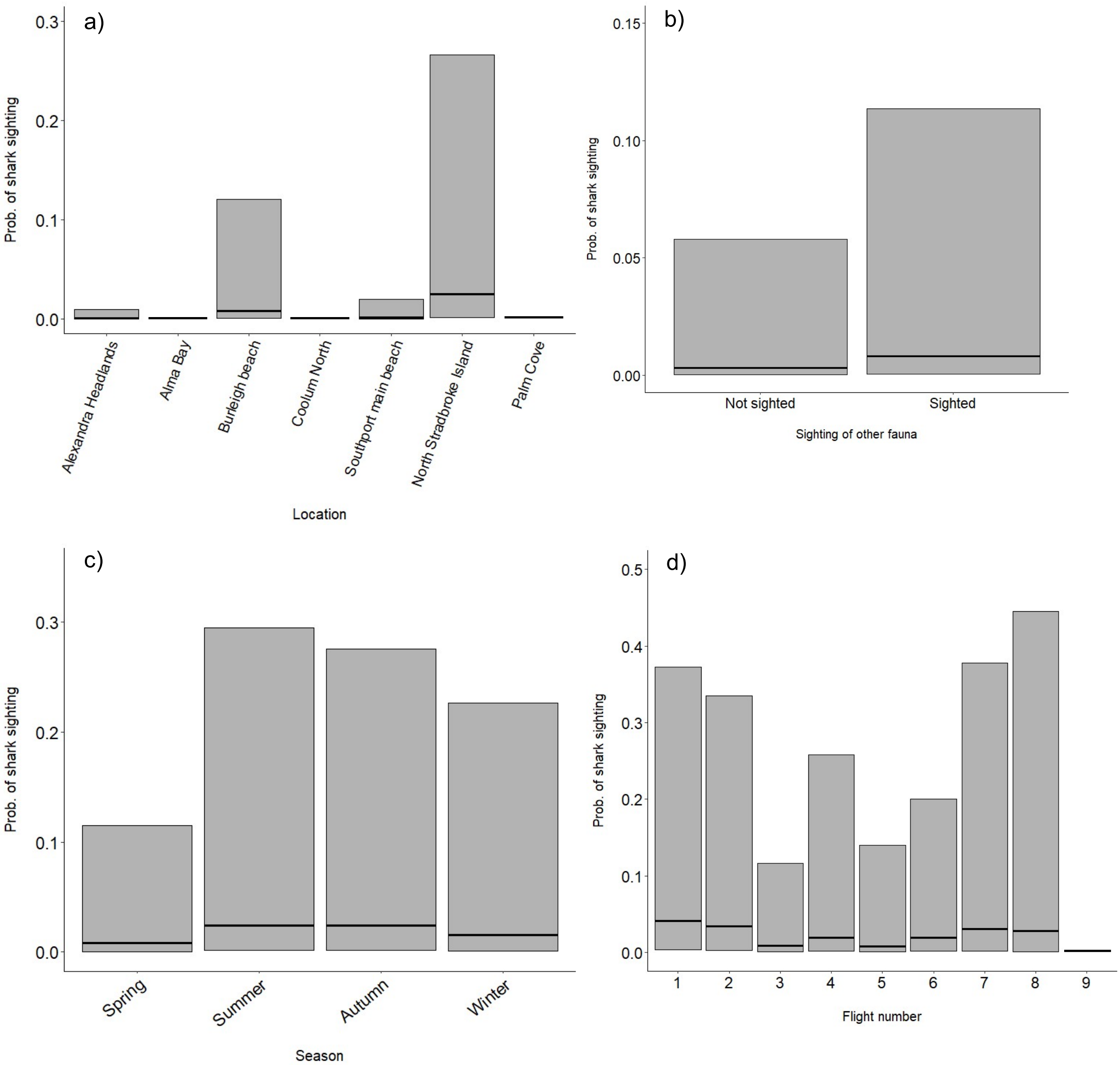

Fig. 4: Influence of significant predictor variables on the probability of sighting sharks, across all beaches combined. a) location, b) sighting of other fauna, c) season, d) flight number. Solid black lines indicate model fitted values. Grey shaded areas indicate 95% confidence intervals.

In addition to the overall GLMM including all beaches, separate GLMMs were run for NSI and Burleigh Beach, because they had the most sightings. For NSI, the predictors variables flight number, cloud cover and atmospheric pressure had a significant influence on the presence of sharks, explaining 47% of the deviance in the response. The probability of sighting sharks was highest in the first two flights of the day (0.07 for flight 1 and 0.08 for flight 2) before declining to 0.01 for flight 3 and remaining lower for the rest of flights (Fig. 5a). Cloud cover had a variable effect on probability of shark sightings, with highest probability occurring at cloud cover values of 5 (0.59) and 6 (0.36) and lowest probability at cloud cover levels 7 (0.07) and 1 (0.08) (Fig. 5b). Atmospheric pressure had a positive linear effect on probability of shark sightings, increasing from 0.03 at 1006 hPa to 0.15 at 1027 hPa, although the confidence intervals were larger for higher pressure values (Fig. 5c).

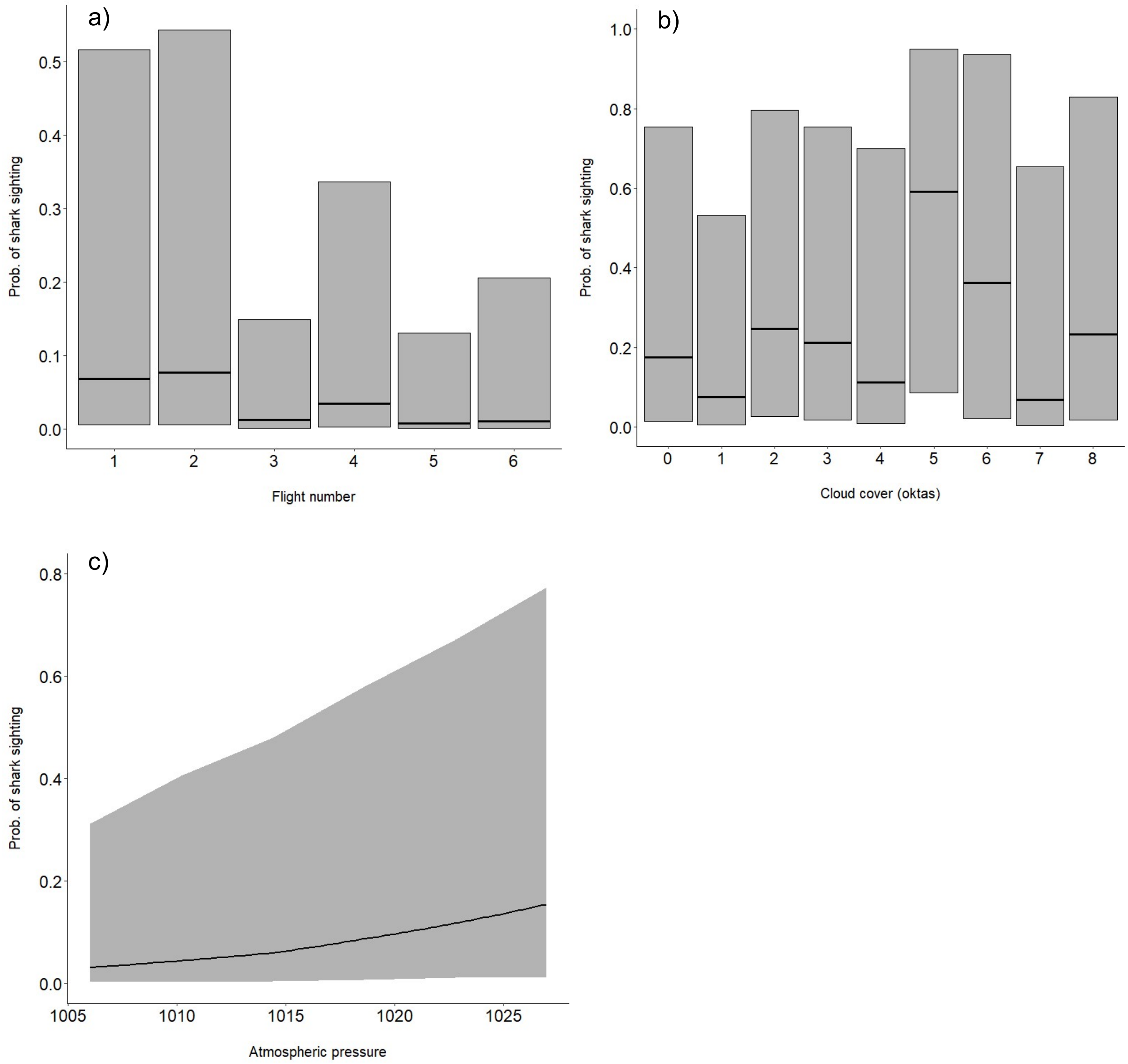

Fig. 5: Influence of significant predictor variables on the probability of sighting sharks at North Stradbroke Island. a) flight number, b) cloud cover in oktas, c) atmospheric pressure (hPa). Solid black lines indicate model fitted values. Grey shaded areas indicate 95% confidence intervals.

For Burleigh Beach, GLMM results indicated that only season and the sighting of other non-shark fauna had a significant influence on the probability of sighting sharks, explaining 54% of the response deviance. Autumn and summer had a substantially higher probability of sharks being sighted, with model fitted values of 0.27 and 0.20, respectively. The probabilities were much lower for spring and winter, at 0.03 (Fig. 6a). Sharks were more likely to be sighted when other fauna were sighted (0.19) versus not sighted (0.08) (Fig. 6b).

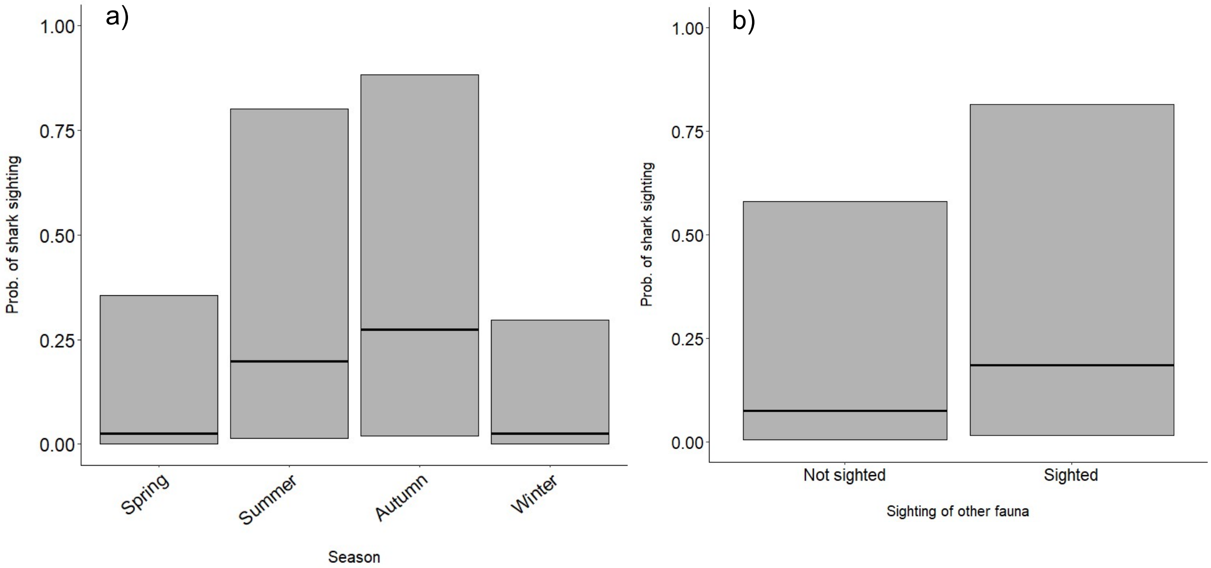

Fig. 6: Influence of significant predictor variables on the probability of sighting sharks at Burleigh Beach. a) season, b) sighting of other fauna. Solid black lines indicate model fitted values. Grey shaded areas indicate 95% confidence intervals.

4.4 Shark movement tracks and behaviour

Preliminary analysis has been undertaken to map shark movement tracks at drone trial beaches and classify their behaviour. Tracks were generated for small whaler sharks, one bull shark and one white shark. Mean track length was 2 minutes 47 seconds (± 1 minutes and 41 seconds (SD)) (sharks were tracked until drones were beyond visual line of sight, battery was low or the shark was determined to be moving offshore), with most sharks travelling in a northerly direction at NSI and Burleigh Beach. The distance of shark tracks offshore varied from approximately 100 – 400 m and there were cases where small (<2 m) whaler sharks moved to within ~100 m of water users at Burleigh Beach. From the small number of shark tracks mapped at Burleigh Beach, four were clustered close together at the southern end of this beach and between 220 – 350 m offshore (Fig. 7). 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 (Fig. 8). There were two instances where sharks were observed interacting with schools of fish, which lead to an increased tortuosity in their tracks, including where the white shark at Southport Main Beach consumed a fish.

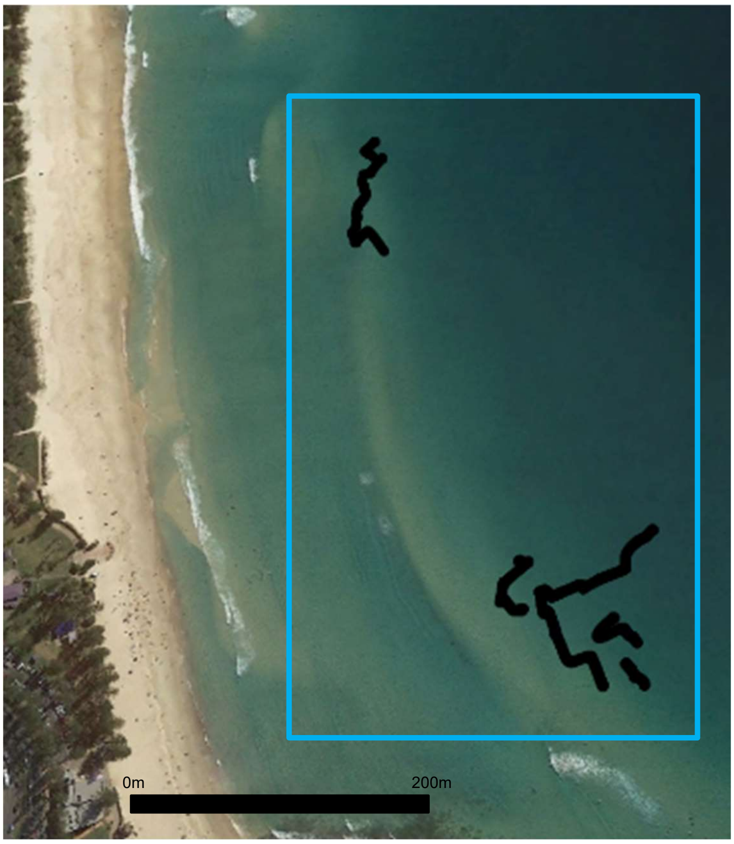

Fig. 7: Movement tracks of five whaler sharks at Burleigh Beach, as indicated by black lines. The blue box outlines the total area over which drones patrolled.

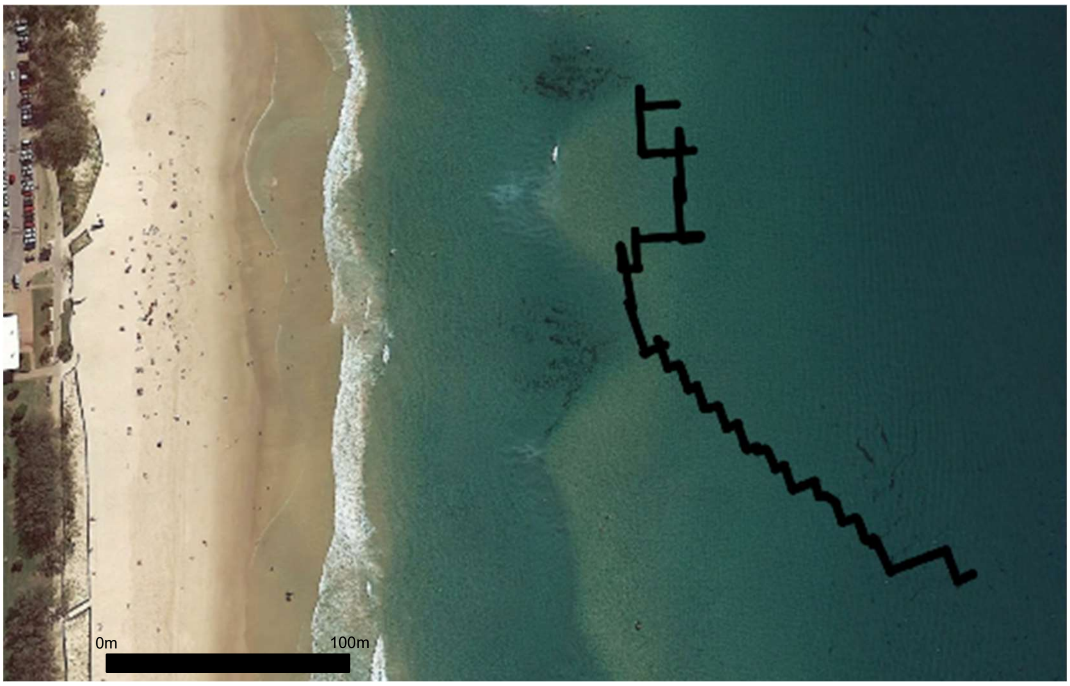

Fig. 8: Movement track of a white shark sighted at Southport Main Beach, as indicated by the black line.

4.5 Comparison of drone sightings vs catch in SCP gear

There was a significantly higher ($p = <0.001$, binomial test) number of sharks sighted on drones (174) compared to caught in SCP nets and drumlines (49), at the seven trial beaches (Table 5). NSI and Burleigh Beach had significantly higher shark sightings than catches, with 94 vs 8 ($p = <0.001$) and 73 vs 13 ($p = <0.001$), respectively. Although there were less sharks sighted than caught Alexandra Headland (3 vs 5) and Southport Main Beach (4 vs 8), these differences were non-significant (p values of 0.73 and 0.39, respectively) (Table 5). Yet, there were a significantly higher ($p = 0.03$) number of sharks caught at Coolum North (6) compared to the number sighted (0). Additionally, no sharks were sighted at Palm Cove or Alma Bay, but low numbers were caught (four at Palm Cove and five at Alma Bay), resulting in a non-significant difference (p values of 0.13 and 0.06, respectively) (Table 5). Results of a linear regression indicated that there was no significant relationship between the number of sharks sighted on drones and caught in SCP gear across the seven beaches ($r^2 = 0.41$, t value = 2.27, $p = 0.07$).

In terms of large sharks >2 m, there was also a significantly higher ($p = 0.003$) number of sightings on drones (48) compared to the number caught in SCP gear (22) (Table 5). At an individual beach level, there were a significantly higher number of large sharks seen at NSI ($p = 0.008$) and Burleigh Beach ($p = <0.001$), compared to the number caught in nets and drumlines (Table 5). Conversely, there was no significant difference for the other five beaches (all p-values >0.05). 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 ($r^2 = 0.24$, t value = 1.7, $p = 0.15$).

Numbers of bull, tiger and white sharks sighted by drones or caught by SCP gear were low overall, with no significant differences (all p-values >0.05) at an overall level or for individual beaches. NSI had the highest number sighted (4 bull sharks) and caught (5 tiger sharks, 2 white sharks). At the other six beaches, between one and three bull/tiger/white sharks were caught in SCP gear, although these species were only sighted on drones at Southport Main Beach (1 white shark, 2 bull sharks) and Burleigh Beach (2 bull sharks) (Table 5). Tiger sharks were not sighted during the drone trial, although 11 were caught by SCP gear across the same beaches.

When comparing the shark sighting rate of drones compared 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 four beaches where nets were deployed 24 hours per day (Alexandra Headland, Coolum North, Burleigh Beach and Southport Main Beach), drones were operational for only 2.3% of the time that nets were operational (852 hours for drones based on 3,006 flights averaging 17 mins vs 36,480 hours for nets based on 9,120 hours (24 hours x 380 days) multiplied by the four beaches). For the three beaches where only drumlines were present (NSI, Palm Cove and Alma Bay), drones operated for 188 hours (based on 663 flights running for 17 mins), which equates to 2.5% of the total time that drumlines were operational (7,608 hours, based on 9,120 hours (24 x 380 days) for NSI plus 6,096 hours (24 x 127 days x 2) for two NQ beaches, divided by two. This is based on the assumption that drumlines are operational for 50% of the time. Drumlines are operational while bait remains on the hook. For the purpose of this analysis, an assumption was made that baits are depredated or fall off 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, but it is possible that it could cover an area larger than 400 m at times.

Table 5: Number of sharks sighted by drones and caught by Queensland Shark Control Program fishing gear (nets and drumlines) at each of the beach locations. Data covers the time period 19 September 2020 – 4 October 2021 for South-East Queensland beaches and 26 June 2021 – 31 October 2021 for North Queensland beaches.

Location	**Total number of sharks sighted***	**No. of large (>2 m) sharks**	**No. of white, bull, tiger sighted**	**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	3	1	0	5 (net)	1	2 (bull)
Coolum North	0	0	0	6 (net)	1	1 (bull)
Burleigh Beach	73	23	2 (bull)	13 (net)	3	1 (tiger)
Southport Main Beach	4	2	3 (1 white, 2 bull)	8 (net)	3	2 (tiger, bull)
North Stradbroke Island	94	22	4 (bull)	8 (drumlines)	7	7 (5 tiger, 2 white)
North Queensland						
Palm Cove	0	0	0	4 (drumlines)	3	2 (tiger)
Alma Bay	0	0	0	5 (drumlines)	4	3 (2 tiger, 1 bull)
TOTAL	**174**	**48**	**9 (8 bull, 1 white)**	**49**	**22**	**18 (11 tiger, 5 bull, 2 white)**

***dataset excludes leopard sharks**

In addition to the generally higher detection rate of sharks by drones than that caught by SCP nets and drumlines, the drones also had very minimal impact on non-target species, whereas SCP apparatus caught 19 non-target animals, including a number of marine mammals, rays and turtles (Table 6). These animals included two species listed as endangered in Queensland (leatherback and loggerhead turtles) by the *Nature Conservation Act 1992* (Qld, *NCA*) and manta ray, which are listed as migratory under the Convention of Migratory Species. Non-target catch was highest at Burleigh Beach (6 animals caught) and North Stradbroke Island (4 animals caught). SCP gear at Coolum North and Alma Bay caught one non-target animal each and no non-target animals were caught at Palm Cove.

Table 6: Catch of non-target animals at each beach by Queensland Shark Control Program nets and drumlines, including species and size (total length or disc width for rays). Data covers the time period 19 September 2020 – 4 October 2021 for South-East Queensland beaches and 26 June 2021 – 31 October 2021 for North Queensland beaches.

Beach	**Non-target animals caught, size and number**
South-East Queensland	
Alexandra Headland	1 manta ray (1.2 m), 2 cownose rays (0.3 m, 0.55 m), 1 devil ray (1.32 m)
Coolum North	1 eagle ray (0.8 m)
Burleigh Beach	2 common dolphins (1.86 m, 2.12 m), 1 eastern shovelnose ray (1.8 m), 2 devil rays (0.55 m, 0.6 m), 1 cownose ray (0.46 m)
Southport Main Beach	1 common dolphin (1.2 m), 1 cownose ray (0.34 m), 1 manta ray (0.9 m)
North Stradbroke Island	3 leatherback turtles (1.34 m, 1.69 m, 2.09 m), 1 loggerhead turtle (0.78 m)
North Queensland	
Palm Cove	None
Alma Bay	1 cod (0.9 m)
TOTAL	**19 non-target marine animals**

4.6 Sightings of other fauna

Similar to the shark sightings, the numbers of other marine fauna varied widely between beaches, with NSI having by far the highest number of sightings (fauna sighted on 82% of flights) and the greatest diversity of fauna; and Southport Main Beach (10% of flights) and Alexandra Headland (13% of flights) the lowest. No fauna were sighted at Palm Cove, likely due to the high water turbidity levels. A wide range of non-shark fauna were sighted during the drone trial, the most prevalent of which were green turtles, which were seen at all drone trial locations apart from Palm Cove and were most prevalent at NSI, where they were sighted on 40% of flights (Table 7, Fig. 9). The first recorded occurrence of green turtles mating at NSI was also observed during the trial (Fig. 9e). Manta rays and eagle rays (Fig. 9c,f) were also sighted regularly across all locations apart from Palm Cove, as well as stingrays (Table 7). Important prey species for sharks, including large fish and bait balls, were also observed during the trial, occurring on 2-16% of flights across the drone trial locations. Dolphins were only rarely observed (≤1% of flights) at most drone trial locations, apart from at NSI, where they were seen on 21% of flights (Table 7) and were mostly Indo-Pacific bottlenose dolphins (Fig. 9b,c). Groups of Australian humpback dolphins were also observed at NSI and a single adult was observed at Coolum North (Fig. 9a). 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. Humpback whales were observed during five flights at NSI and Burleigh Beach (Fig. 9d).

Table 7: Number and percentage 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**	**Whales**	**Stingrays**	**Manta/ eagle rays**	**Shovel nose rays**	**Large fish**	**Bait balls**
South-East Queensland								
Alexandra Headland	42 (5%)	0 (0%)	0 (0%)	8 (1%)	13 (2%)	0 (0%)	26 (3%)	36 (4%)
Coolum North	43 (6%)	6 (1%)	0 (0%)	30 (4%)	40 (5%)	0 (0%)	50 (7%)	21 (3%)
Burleigh Beach	8 (1%)	1 (0.1%)	1 (0.1%)	75 (11%)	39 (6%)	0 (0%)	32 (5%)	14 (2%)
Southport Main Beach	7 (1%)	3 (0.4%)	0 (0%)	30 (4%)	15 (2%)	0 (0%)	17 (2%)	0 (0%)
North Stradbroke Island	147 (40%)	76 (21%)	4 (1%)	85 (23%)	139 (38%)	37 (10%)	59 (16%)	18 (5%)
North Queensland								
Palm Cove	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Alma Bay	36 (27%)	1 (1%)	0 (0%)	1 (1%)	1 (1%)	0 (0%)	3 (2%)	0 (0%)
TOTAL	**283 (8%)**	**87 (2%)**	**5 (0.1%)**	**229 (6%)**	**257 (7%)**	**37 (1%)**	**187 (5%)**	**89 (2%)**

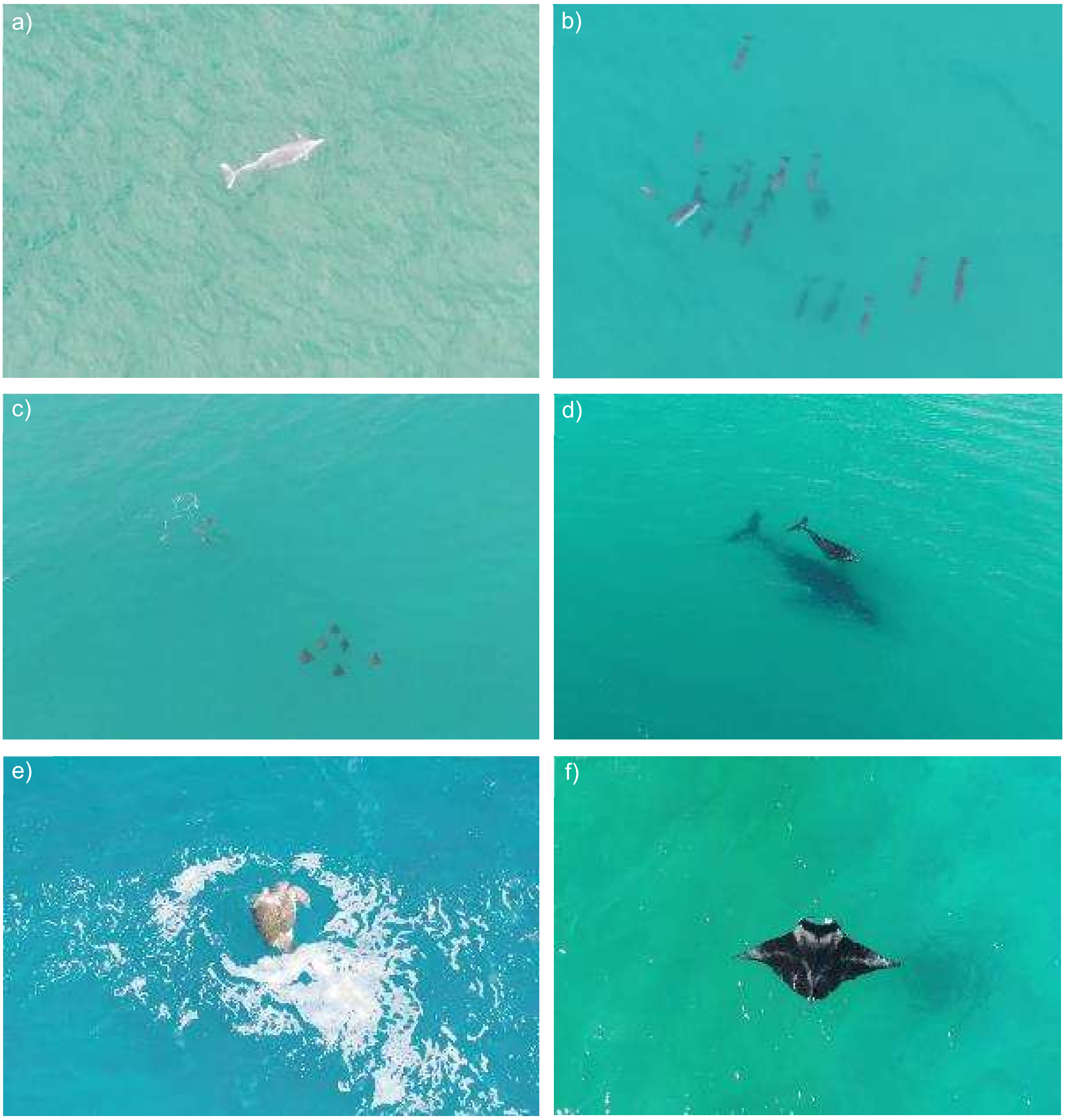

Fig. 9: Examples of other marine fauna detected during the Queensland SharkSmart drone trial. a) an Australian humpback dolphin sighted at Coolum North, b) a pod of Indo-Pacific bottlenose dolphins sighted at North Stradbroke Island (NSI), c) Indo-Pacific bottlenose dolphins and eagle rays at NSI, d) humpback whale and calf at NSI, e) first recorded sighting of green turtles mating at NSI, f) a manta ray 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

5 Discussion

5.1 Operational results

The Queensland SharkSmart drone trial demonstrated the capability for operating drones as a public safety tool to detect sharks, running 3,669 flights across seven beaches and covering a minimum of 1,468 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 and warn water users and close the beach if a shark was presenting a threat. As such, the research demonstrated the utility of drones for improving public safety. A range of operational factors affected the ability to operate drones at beaches, including poor weather, malfunctioning drones, high beach usage and staff availability. The main loss of flights was due to poor weather, which ranged from 10 – 23% of days lost across trial beaches. This was expected given the unpredictable and variable weather that occurs in Queensland, 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 Alexandra Headland and Burleigh Beach, had the lowest loss of flights, compared to those that were more exposed, which included NSI and Coolum North.

Modifications to the program could reduce the number of lost days to non-weather related issues, such as technical problems with the drones and staff availability. Extra back-up drones can be purchased to build redundancy into the program and enable flights to continue if there is a malfunction or drone loss. More permanent staff can also be hired to prevent loss of shifts due to staff availability issues and it is anticipated that Queensland Government regulations relating to the COVID-19 pandemic will cause less disruption in the future.

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, 174 sharks were sighted, 48 of which were large sharks (>2 m). Overall, the prevalence of shark sightings was low, with sharks detected on only 3% of flights when all beaches were combined. This result is similar to, albeit slightly higher than, 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 nine sightings of bull or white sharks during the current trial, with only four beach evacuations, highlighting that occurrences of these shark species close to beaches are rare.

The level of sightings varied substantially between beaches, however, likely due to the prevailing environmental conditions at each location. In particular, the higher number of sightings 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. Higher catches of sharks in nets and drumlines also occurs at Queensland beaches close to river mouths and after rainfall, especially for bull sharks (Haig et al., 2018; Werry et al., 2018). Higher numbers of fauna sightings were 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). NSI had very high prevalence of other marine fauna, including turtles, rays, large fish and bait balls, all of which can be important prey species for sharks, which may explain the higher prevalence of shark sightings at this location as well.

The very low level of sightings that occurred at the two Sunshine Coast beaches 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.

5.3 Environmental and operational influences on shark sightability

Environmental factors exerted an important influence on the sightability of sharks, particularly season, time of day (flight number) and the sighting of other fauna. Sharks were more likely to be seen during summer and autumn, which would be expected as these seasons have higher water temperatures, which lead to greater abundance and 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. 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, which typically occurred between 7am and 8:30am. This relationship may have occurred due to higher activity levels of sharks in the early morning and lower levels of disturbance from water users and boats in the area at this time.

The sighting of other fauna had a positive effect on shark sightings from drones, which likely 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. The sighting of other fauna may have also had a positive effect in the GLMM 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. Interestingly, turbidity did not have a significant influence on sightings of sharks according to the GLMM results, unlike a recent study in NSW, where it had a strong negative impact on sighting rates (Butcher et al., 2020). However, the high turbidity at the two NQ beaches may have prevented sharks from being sighted from drones.

Atmospheric pressure had a positive linear relationship with probability of shark sightings at NSI, likely because higher atmospheric pressures typically leads to lower windspeeds and a lower sea state, making it easier to sight sharks. The relationship between cloud cover and shark sightability was variable, with highest probability of sighting sharks at intermediate levels of cloud cover at NSI. 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. Wind speed has been found to affect shark sighting rates in other drone based studies, with lower sightability at higher windspeeds (Benavides et al., 2019), however it did not have a significant effect on shark sightability in the current study and the NSW drone trial research also found minimal or no effect of wind on sighting rates (Butcher et al., 2020). Ultimately, environmental conditions will vary at a local level for each beach where drones are used, therefore it will be necessary to conduct robust analyses of the local environmental conditions and their effects on shark sightability at any new beach where drones are trialled.

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, from the limited analysis conducted so far, it was evident that there is a certain zone close to the southern end of Burleigh Beach where multiple sharks were sighted on different days. This clustering may have occurred because this southern portion of the beach is closest to the mouth of Tallebudgera Creek, where there is likely to be higher productivity and greater prey abundance. Additionally, 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. This 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. This information can be used 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. Likewise, this information can be summarised and communicated for the public to help them choose which beach to visit. To build this risk matrix approach, further analyses will be conducted to map the tracks of all sharks sighted during the drone trial and generate movement metrics such as swimming speed and path tortuosity.

5.5 Comparison of shark sightings versus SCP catch

Drones sighted a significantly higher overall number of sharks than were caught in the adjacent SCP gear (including both nets and drumlines) at the SEQ beaches, as well as a significantly higher number of large sharks >2 m in length. This is despite the markedly lower temporal coverage of drones, which only operated during mornings, in relatively good weather and mostly only on weekends, equating to only ~2% of the time that SCP gear was deployed for, although drones did cover a larger spatial area. The majority of shark sightings on drones came from NSI and Burleigh Beach, whereas sighting rates at the other five beaches were similar to, or lower than, SCP catch, although these differences were non-significant. No sharks were sighted at Coolum North, Palm Cove or Alma Bay, whereas small numbers were caught on the SCP gear at these locations. This could have occurred because sharks were relatively rare in these areas, therefore the chance of sighting them on a drone was very low due to the small amount of time drones were operating, compared to SCP gear. Alternatively, the sharks could have been swimming further offshore and were attracted to and hooked by baited drumlines or trapped in nets before they had chance to reach the beach at these locations.

The number of bull, tiger and white sharks caught by SCP gear was marginally higher than that sighted on drones (although there was no significant difference), however this was solely caused by the fact that 11 tiger sharks were caught on SCP gear with none being sighted by drones. This 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 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. Hook timers could be deployed on drumlines in future, to collect data on the time of capture of tiger sharks and other species to investigate this question. The sighting of six bull sharks on drones with none being caught in SCP gear at NSI and Burleigh Beach further emphasises the difference in selectivity between drones and SCP gear. The higher sighting rate of bull sharks 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 from this species. 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 the passive shark control apparatus, 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 at the seven beaches covered by the trial.

The environmental impact of drones 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, 19 non-target animals which were caught in nets and drumlines during the trial period, the majority of which died. This non-target catch included the endangered loggerhead and leatherback turtles (NCA 1992) and species listed as migratory under the Convention of Migratory Species (manta ray). Other threatened species such as the grey nurse shark, dugong, Australian humpback dolphin and Australian snubfin dolphin are also occasionally caught in the SCP.

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 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 40% and 38% of flights, respectively. 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. Dolphins were common at NSI, with groups of up to 45 Indo-Pacific bottlenose dolphins observed, sometimes with calves and Australian humpback dolphins were observed at NSI on four occasions. Large fish and bait balls were also more prevalent at NSI, which, in combination with the greater abundance of other fauna, could possibly lead to a higher risk for water users at this beach compared to the others covered in the drone trial, where all of the other fauna groups were seen on <10% of flights. Indeed, results from the GLMMs in this study confirmed that the sighting of other fauna was an important predictor influencing the probability of shark sightings. However, it is important to note that just because sharks are present it does not necessarily lead to higher risk to water users.

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 2% in the current Queensland trial. However, turtles were more prevalent in Queensland compared to the previous NSW trial, with sightings on 8% and 7.4% of flights, respectively (Kelaher et al., 2020). Overall, the number of flights was also much higher in the current trial compared to the NSW study, with 3,669 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 display seasonal movement patterns, such as manta rays which were only observed in summer months at NSI, which is a known aggregation site for the species due to the presence of cleaning stations (Couturier et al., 2011). 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.

5.7 Community sentiment towards drones as a shark spotting tool

The results of a market research survey conducted by Kantar Public for DAF in February 2021 , as well as results of a community survey conducted by DAF in March and April 2021, indicate strong community support for drones as a shark spotting tool (DAF, 2021). These surveys recorded that 83% of market research respondents (n=751) and 96% of community survey respondents (n=233) support drones as a shark spotting tool (DAF, 2021). Additionally, 75% of community survey respondents (n=233) said they were likely to choose a beach with a shark spotting drone (DAF, 2021). This indicates that if people are aware of where drones are operating, they may favour choosing a location monitored by drones for their chosen water-based activity. The environmental impact of shark management measures is a key concern for many community members, with 49% of community survey respondents (n=233) saying they supported drones as they do not harm sharks and are a better option than nets and drumlines (DAF, 2021).

Future communication activities for the SharkSmart drone trial could 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. Communication should focus on the benefits of drones as a shark spotting tool, including that they do not harm sharks or other marine animals.

5.8 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, will be undertaken by deploying shark analogues at different depths and specifically in varying levels of turbidity and glare, to improve understanding of the effectiveness of drones across varied ocean conditions. This will 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. AI technology will also be trialled to assess its ability to detect sharks from footage relative to a human observer, particularly when water visibility is lower. It is expected that pilots will miss some sharks (as was found in the review of 5% of the footage, where one shark was not seen by the pilot) because they are also required to look at the position of the drone and activity occurring on the beach, which means they are not looking at the video screen on the drone controller at all times. Additionally, glare and low water visibility may result in them missing sharks. If AI is found to be successful at detecting sharks at a level similar to, or better than, human observers, this technology will be used to analyse existing archived footage to detect any sharks that may have been missed by pilots. The AI should also be incorporated into the operation of drones so that it runs in real time, allowing automated detection and flagging of sharks to assist the pilots. This will increase the capability of the drones to detect sharks and reduce pilot fatigue. For beaches where higher turbidity occurs, including Alexandra Headland and Palm Cove, advanced camera technologies (e.g. hyper or multispectral cameras (Colefax et al., in press)) should also be trialled when the shark analogues are deployed, to determine whether they can improve the detection rate of sharks in turbid water. These future analyses will all contribute towards increased effectiveness of drones as a tool for detecting sharks at Queensland beaches and improving public safety.

5.9 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 individual beach meets criteria designed to ensure they 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 sharks (if present) 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). While the use of advanced camera technologies such as hyper and multispectral cameras may be able to partially increase the detection capability of drones at beaches with higher water turbidity, this is not expected to markedly increase this to a point where the drones are economically viable. The depth and seabed type must also be considered because this will influence the effectiveness for 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.

Airspace regulations are another key factor that will govern where drones can be operated to detect sharks, because 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 Sunshine coast (near Maroochydore airport), Cairns and Townsville. There are also limitations on the use of drones in some 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 and which have on-duty lifeguards to operate the drones and with 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. Examples of such locations include Noosa main beach which is close to an estuary and where there is a relatively higher catch of bull sharks compared to other locations and beaches around Cairns and Townsville, which typically have higher catch rates of sharks than any other location in the SCP due to the localised productivity of the ecosystem. However, many beaches in North Queensland already have stinger nets deployed during summer, which will likely prevent sharks coming into contact with water users, therefore operation of drones in these locations could be restricted to winter months, as occurred during the current trial.

All of these factors influencing the suitability of using drones at different locations have been investigated in a previous report by Cardno (Cardno, 2020), with the creation of an interactive GIS map for viewing the information. This should be used as an important resource to guide the identification of suitable beaches for drone operations. It is also recommended that a matrix scoring system be created with these factors incorporated, to create a clear and robust approach for identifying suitable beaches for drone operations.

5.10 Recommendations

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

- To continue the deployment of drones at the SEQ beaches covered during the drone trial, because they have enabled detection of sharks at some beaches and improved public safety, and have high levels of public support
- Develop a set of decision criteria to determine whether drones should continue to be used at beaches after a trial period has been completed
- Extend the deployment of drones to other suitable beaches in Queensland, based on a set of rigorous scientific criteria, including beach visitation and on-duty lifeguard presence, suitable environmental conditions, adherence to CASA regulations, proximity to river mouths and historical catch in the SCP
- Build extra redundancy in the event of loss or malfunctioning of equipment
- Increase the number of trained pilots throughout Queensland to enable new locations to become operational and to provide more back-up coverage of existing trial locations in the event of staff availability issues
- Conduct a robust assessment of the detection capability of drones in Queensland, using shark analogues deployed under a range of environmental conditions
- Test AI to assess its effectiveness for detecting sharks in comparison to human observers, under a range of environmental conditions, particularly when water visibility is lower, because pilots are likely to miss some sharks. If found to be effective, AI should be incorporated into real-time drone operations to aid with the detection of sharks and reduce pilot fatigue
- Test advanced camera technologies (e.g. hyper or multispectral cameras) in locations where water turbidity is higher (e.g. North Queensland), to assess whether they are more effective at detecting sharks compared to standard cameras
- Deploy hook timers on drumlines at beaches where drones are operating to identify what time of day sharks are caught and how this influences their likelihood of being detected by drones
- Conduct further analyses to learn about the movement patterns of sharks near beaches and how environmental conditions influence the presence and sightability of sharks
- Collaborate with other researchers to utilise footage of other non-shark fauna, for improving understanding of their seasonal abundance, movement patterns and behaviour and contributing to improved management and conservation

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7 References

Benavides, M. T., Fodrie, F. J., & Johnston, D. W. (2019). Shark detection probability from aerial drone surveys within a temperate estuary. *Journal of Unmanned Vehicle Systems,* **8**, 44-56.

Bloom, D., Butcher, P. A., Colefax, A. P., Provost, E. J., Cullis, B. R., & Kelaher, B. P. (2019). Drones detect illegal and derelict crab traps in a shallow water estuary. *Fisheries Management and Ecology,* **26**, 311-318.

Butcher, P. A., Colefax, A. P., Gorkin, R. A., Kajiura, S. M., López, N. A., Mourier, J., Purcell, C. R., Skomal, G. B., Tucker, J. P., & Walsh, A. J. (2021). The drone revolution of shark science: a review. *Drones,* **5**, 8.

Butcher, P. A., Piddocke, T. P., Colefax, A. P., Hoade, B., Peddemors, V. M., Borg, L., & Cullis, B. R. (2020). Beach safety: can drones provide a platform for sighting sharks? *Wildlife Research,* **46**, 701-712.

Cardno. (2019). *Queensland Shark Control Program: Review of Alternative Approaches*. Queensland Department of Agriculture and Fisheries, Brisbane.

Cardno. (2020). *Data Review for Queensland Shark Control Program Regions & The Whitsundays*. Cardno (NSW/ACT) Pty Ltd, Brisbane.

Colefax, A. P. (2020). *Developing the use of drones for non-destructive shark management and beach safety. PhD Thesis.* Southern Cross University, Coffs Harbour.

Colefax, A. P., Butcher, P. A., & Kelaher, B. P. (2018). The potential for unmanned aerial vehicles (UAVs) to conduct marine fauna surveys in place of manned aircraft. *ICES Journal of Marine Science,* **75**, 1-8.

Colefax, A. P., Butcher, P. A., Pagendam, D. E., & Kelaher, B. P. (2019). Reliability of marine faunal detections in drone-based monitoring. *Ocean & Coastal Management,* **174**, 108-115.

Colefax, A. P., Butcher, P. A., Pagendam, D. E., & Kelaher, B. P. (2020a). Comparing distributions of white, bull, and tiger sharks near and away from the surf break using three tech-based methods. *Ocean & Coastal Management,* **198**, 105366.

Colefax, A. P., Kelaher, B. P., Pagendam, D. E., & Butcher, P. A. (2020b). Assessing white shark (*Carcharodon carcharias*) behavior along coastal beaches for conservation-focused shark mitigation. *Frontiers in Marine Science,* **7**, 268.

Colefax, A. P., Kelaher, B. P., Walsh, A. J., Purcell, C. R., Pagendam, D. E., Cagnazzi, D. D. B., & Butcher, P. A. (in press). Utility of spectral band selection from drone-based hyperspectral imagery for improving detectability of submerged marine fauna. *Biological Conservation,* https://doi.org/10.1016/j.biocon.2021.109102.

Couturier, L. I., Jaine, F. R., Townsend, K. A., Weeks, S. J., Richardson, A. J., & Bennett, M. B. (2011). Distribution, site affinity and regional movements of the manta ray, *Manta alfredi* (Krefft, 1868), along the east coast of Australia. *Marine and Freshwater Research,* **62**, 628-637.

DAF. (2021). *SharkSmart drone trial community sentiment report*. Queensland Government Department of Agriculture and Fisheries, Brisbane.

Dicken, M. L., Hussey, N. E., Christiansen, H. M., Smale, M. J., Nkabi, N., Cliff, G., & Wintner, S. P. (2017). Diet and trophic ecology of the tiger shark (*Galeocerdo cuvier*) from South African waters. *PloS one,* **12**, e0177897.

Engelbrecht, T., Kock, A., Waries, S., & O'Riain, M. J. (2017). Shark spotters: successfully reducing spatial overlap between white sharks (*Carcharodon carcharias*) and recreational water users in False Bay, South Africa. *PloS one,* **12**, e0185335.

Fettermann, T., Fiori, L., Bader, M., Doshi, A., Breen, D., Stockin, K. A., & Bollard, B. (2019). Behaviour reactions of bottlenose dolphins (Tursiops truncatus) to multirotor Unmanned Aerial Vehicles (UAVs). *Scientific reports,* **9**, 1-9.

Gribble, N., McPherson, G., & Lane, B. (1998). Effect of the Queensland Shark Control Program on non-target species: whale, dugong, turtle and dolphin: a review. *Marine and Freshwater Research,* **49**, 645-651.

Guyomard, D., Perry, C., Tournoux, P. U., Cliff, G., Peddemors, V., & Jaquemet, S. (2019). An innovative fishing gear to enhance the release of non-target species in coastal shark-control programs: the SMART (shark management alert in real-time) drumline. *Fisheries Research,* **216**, 6-17.

Haig, J. A., Lambert, G. I., Sumpton, W. D., Mayer, D. G., & Werry, J. M. (2018). Habitat features influence catch rates of near-shore bull shark (*Carcharhinus leucas*) in the Queensland Shark Control Program, Australia 1996–2012. *Estuarine, Coastal and Shelf Science,* **200**, 289-300.

Huveneers, C., Whitmarsh, S., Thiele, M., Meyer, L., Fox, A., & Bradshaw, C. J. (2018). Effectiveness of five personal shark-bite deterrents for surfers. *PeerJ,* **6**, e5554.

Kelaher, B. P., Colefax, A. P., Tagliafico, A., Bishop, M. J., Giles, A., & Butcher, P. A. (2020). Assessing variation in assemblages of large marine fauna off ocean beaches using drones. *Marine and Freshwater Research,* **71**, 68-77.

Kelaher, B. P., Peddemors, V. M., Hoade, B., Colefax, A. P., & Butcher, P. A. (2019). Comparison of sampling precision for nearshore marine wildlife using unmanned and manned aerial surveys. *Journal of Unmanned Vehicle Systems,* **8**, 30-43.

Lipscombe, R. S., Spaet, J. L., Scott, A., Lam, C. H., Brand, C. P., & Butcher, P. A. (2020). Habitat use and movement patterns of tiger sharks (*Galeocerdo cuvier*) in eastern Australian waters. *ICES Journal of Marine Science,* **77**, 3127-3137.

Loneragan, N. R. (1999). River flows and estuarine ecosystems: implications for coastal fisheries from a review and a case study of the Logan River, southeast Queensland. *Australian Journal of Ecology,* **24**, 431-440.

Lowe, C. G., Wetherbee, B. M., Crow, G. L., & Tester, A. L. (1996). Ontogenetic dietary shifts and feeding behavior of the tiger shark, *Galeocerdo cuvier*, in Hawaiian waters. *Environmental Biology of Fishes,* **47**, 203-211.

McPhee, D. P., Blount, C., Smith, M. P. L., & Peddemors, V. M. (2021). A comparison of alternative systems to catch and kill for mitigating unprovoked shark bite on bathers or surfers at ocean beaches. *Ocean & Coastal Management,* **201**, 105492.

Meynecke, J.-O., Lee, S. Y., Duke, N. C., & Warnken, J. (2006). Effect of rainfall as a component of climate change on estuarine fish production in Queensland, Australia. *Estuarine, Coastal and Shelf Science,* **69**, 491-504.

O'Connell, C., Andreotti, S., Rutzen, M., Meÿer, M., & Matthee, C. (2018). Testing the exclusion capabilities and durability of the Sharksafe Barrier to determine its viability as an eco-friendly alternative to current shark culling methodologies. *Aquatic Conservation: Marine and Freshwater Ecosystems,* **28**, 252-258.

Paterson, R. (1990). Effects of long-term anti-shark measures on target and non-target species in Queensland, Australia. *Biological Conservation,* **52**, 147-159.

Provost, E. J., Butcher, P. A., Colefax, A. P., Coleman, M. A., Curley, B. G., & Kelaher, B. P. (2019). Using drones to quantify beach users across a range of environmental conditions. *Journal of Coastal Conservation,* **23**, 633-642.

Provost, E. J., Butcher, P. A., Coleman, M. A., Bloom, D., & Kelaher, B. P. (2020). Aerial drone technology can assist compliance of trap fisheries. *Fisheries Management and Ecology,* **27**, 381-388.

Ramos, E. A., Maloney, B., Magnasco, M. O., & Reiss, D. (2018). Bottlenose dolphins and Antillean manatees respond to small multi-rotor unmanned aerial systems. *Frontiers in Marine Science,* **5**, 316.

Raoult, V., Tosetto, L., & Williamson, J. E. (2018). Drone-based high-resolution tracking of aquatic vertebrates. *Drones,* **2**, 37.

Saqib, M., Khan, S. D., Sharma, N., & Blumenstein, M. (2017). *A study on detecting drones using deep convolutional neural networks.* Paper presented at the 2017 14th IEEE International Conference on Advanced Video and Signal Based Surveillance (AVSS), Lecce.

Schlacher, T. A., & Connolly, R. M. (2009). Land–ocean coupling of carbon and nitrogen fluxes on sandy beaches. *Ecosystems,* **12**, 311-321.

Schofield, G., Esteban, N., Katselidis, K. A., & Hays, G. C. (2019). Drones for research on sea turtles and other marine vertebrates–A review. *Biological Conservation,* **238**, 108214.

Sharma, N., Scully-Power, P., & Blumenstein, M. (2018). *Shark detection from aerial imagery using region-based CNN, a study.* Paper presented at the Australasian Joint Conference on Artificial Intelligence, Wellington.

Spaet, J. L., Patterson, T. A., Bradford, R. W., & Butcher, P. A. (2020). Spatiotemporal distribution patterns of immature Australasian white sharks (*Carcharodon carcharias*). *Scientific reports,* **10**, 1-13.

Stokes, D., Apps, K., Butcher, P. A., Weiler, B., Luke, H., & Colefax, A. P. (2020). Beach-user perceptions and attitudes towards drone surveillance as a shark-bite mitigation tool. *Marine Policy,* **120**, 104127.

Tagliafico, A., Butcher, P. A., Colefax, A. P., Clark, G. F., & Kelaher, B. P. (2020). Variation in cownose ray *Rhinoptera neglecta* abundance and group size on the central east coast of Australia. *Journal of Fish Biology,* **96**, 427-433.

Taylor, S., Sumpton, W., & Ham, T. (2011). Fine-scale spatial and seasonal partitioning among large sharks and other elasmobranchs in south-eastern Queensland, Australia. *Marine and Freshwater Research,* **62**, 638-647.

Torres, L. G., Nieukirk, S. L., Lemos, L., & Chandler, T. E. (2018). Drone up! Quantifying whale behavior from a new perspective improves observational capacity. *Frontiers in Marine Science,* **5**, 319.

Tucker, J. P., Colefax, A. P., Santos, I. R., Kelaher, B. P., Pagendam, D. E., & Butcher, P. A. (2021). White shark behaviour altered by stranded whale carcasses: Insights from drones and implications for beach management. *Ocean & Coastal Management,* **200**, 105477.

Werry, J. M., Sumpton, W., Otway, N. M., Lee, S. Y., Haig, J. A., & Mayer, D. G. (2018). Rainfall and sea surface temperature: key drivers for occurrence of bull shark, *Carcharhinus leucas*, in beach areas. *Global Ecology and Conservation,* **15**, e00430.

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
- 10 December 2020 – 26 January 2021: Drone flights running every day across the summer school holidays
- 18 February 2021: SCP Scientific Working Group consulted on preliminary results and potential expansion of the trial
- 31 March 2021: Interim progress report delivered
- 26 June 2021: Palm Cove and Alma Bay (NQ) beaches operational
- 4 October 2021: Drone trial concludes at SEQ beaches
- 31 October 2021: Drone trial concludes at NQ beaches
- 26 November 2021: Draft final project report delivered

8.2 GLMM outputs and diagnostics

A range of diagnostics were used to ensure the GLMMs 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 GLMMs.

Predictor variable	Wind speed	Temperature	Atmospheric pressure	Swell height	Turbidity
Wind speed	N/A	0.21	-0.04	-0.03	0.06
Temperature	0.21	N/A	-0.44	0.15	0.11
Atmospheric pressure	-0.04	-0.44	N/A	0.13	0.01
Swell height	-0.03	0.15	0.13	N/A	0.09
Turbidity	0.06	0.11	0.01	0.09	N/A

The distribution of predictor variables used in the GLMMs 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 (Fig. A1).

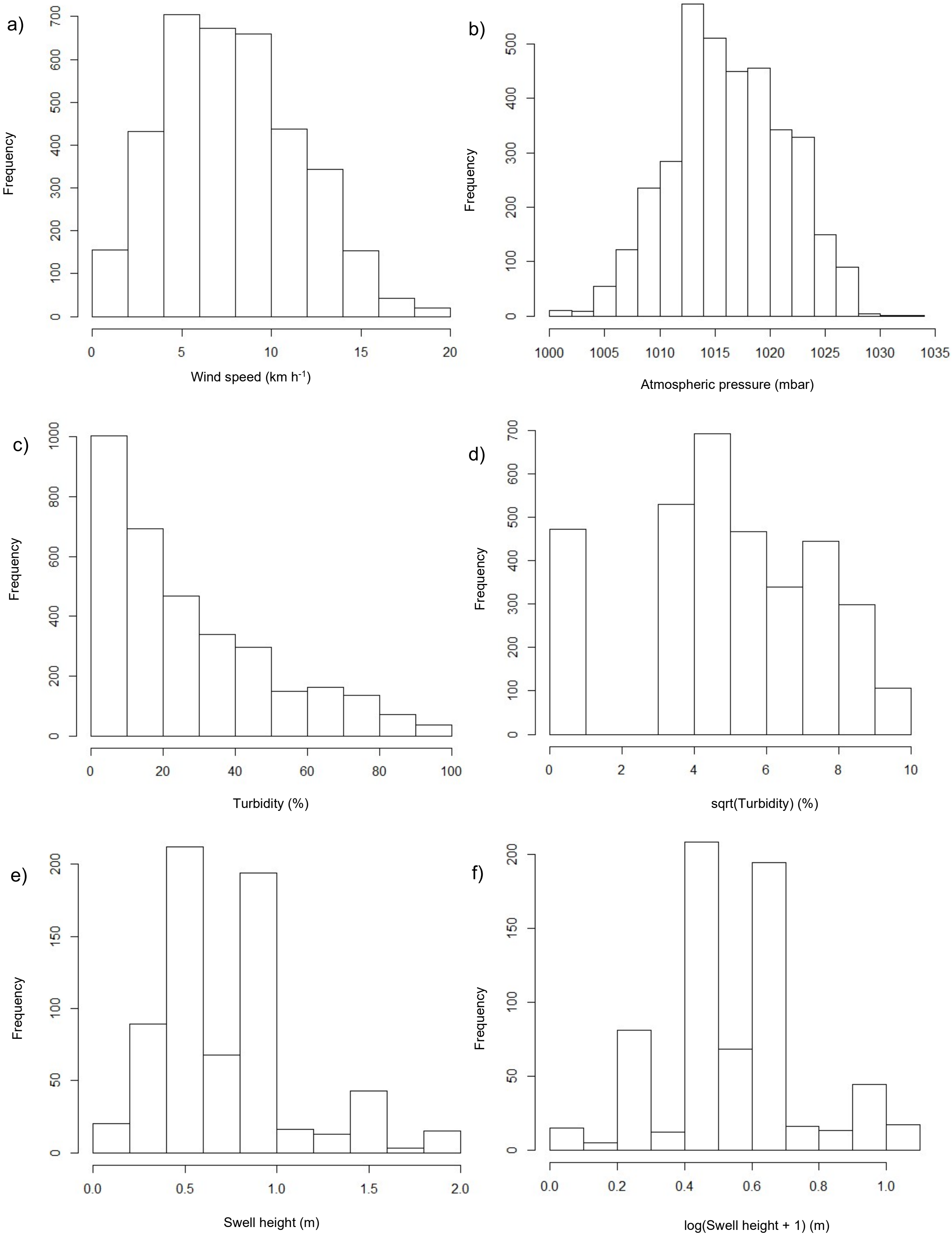

Fig. A1: Histograms showing the distribution of values for continuous predictor variables used in GLMMs. a) wind speed, b) atmospheric pressure, c) turbidity, d) turbidity after square root transformation, e) swell height, f) swell height after log +1 transformation.

The best performing GLMMs for the whole dataset, NSI and Burleigh Beach were those which had the lowest AIC and only included significant predictor variables. The model outputs for these GLMMs are provided below in Tables A2, A3 and A4.

Table A2: Model output for the GLMM run on the whole dataset.

Predictor variable	Chi-squared value	Degrees of Freedom	P-value
Location	46.98	6	<0.001
Flight number	21.22	8	0.007
Season	8.63	3	0.03
Sighting of other fauna	9.85	1	0.002

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

Predictor variable	Chi-squared value	Degrees of Freedom	P-value
Flight number	20.96	5	<0.001
Cloud cover	17.46	8	0.03
Atmospheric pressure	15.13	1	<0.001

Table A4: Model output for the GLMM run on the data for Burleigh Beach.

Predictor variable	Chi-squared value	Degrees of Freedom	P-value
Season	7.88	3	0.04
Sighting of other fauna	4.41	1	0.03