



Drone monitoring of endangered scalloped hammerhead shark *Sphyrna lewini* movements and habitat use on a dynamic urbanised coastline in Australia

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Abstract

Many elasmobranch species face increasing pressures from overfishing, habitat degradation, and coastal development, highlighting the need to identify and protect habitats used during critical life stages. Unmanned Aerial Vehicles or drones offer a non-invasive method to study the distribution and habitat use of species frequenting inshore areas. Scalloped hammerhead sharks (*Sphyrna lewini*), listed as Critically Endangered on the International Union for the Conservation of Nature (IUCN) Red List, have experienced global population declines prompting the need for research that identifies key habitats, including nursery and aggregation sites. This study analysed archived footage from the Queensland SharkSmart drone program at nine beaches in southeast Queensland between September 2020 and December 2024. The frequency of scalloped hammerhead sightings was quantified, along with the influence of environmental, biotic, and operational variables on detectability. Eighty-four sightings were recorded, primarily between April and June. Sightings were significantly influenced by turbidity, presence of other fauna, time of day, month, and location. Aggregations of up to 80 juvenile sharks (mean ± SD: 109 ± 25 cm) were observed at Burleigh Beach, with additional sightings at Noosa Main Beach. These findings provide the first detailed description of seasonal juvenile scalloped hammerhead aggregations in southeast Queensland, Australia, and highlight the value of drone monitoring for identifying habitats of conservation importance and informing targeted spatial management.

Keywords Aerial surveys · Spatial ecology · Critical habitat · Juvenile sharks · Elasmobranchs

Introduction

Understanding the movements and habitat use of endangered marine species is fundamental to their conservation, as it informs spatial management and the protection of habitats used by critical life stages such as breeding, nursery and aggregation sites. However, monitoring marine megafauna in dynamic coastal environments remains a significant challenge due to factors such as turbidity, complex bathymetry, and the logistical and cost constraints of traditional survey methods limiting data availability (Butcher et al. 2019; Cross et al. 2024). Elasmobranchs (sharks and rays) can be particularly vulnerable to anthropogenic pressures in these coastal areas, including overfishing, habitat degradation, and rapid urban development (Dulvy et al. 2014; Pacoureau et al. 2021). Urban-driven alterations to these habitats can disrupt key behaviours in elasmobranchs, including foraging,

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migration, and parturition (Heupel et al. 2007; Todd et al. 2019). Given their proximity to these areas, many coastal species are facing significant global population declines, and key aspects of their movement ecology and habitat use remain poorly understood, complicating efforts to develop targeted conservation and management strategies.

Among the more imperilled species, scalloped hammerhead sharks (*Sphyrna lewini*) have undergone steep population declines worldwide, with loss estimates exceeding 80% (Pacoureau et al. 2021; Lopez et al. 2023). As a result, the International Union for Conservation of Nature (IUCN) classified the species as Critically Endangered under criterion A2bd (Rigby et al. 2019), which reflects an estimated median global population reduction of 76.9–97.3% over three generation lengths (72.3 years). They are also listed in Appendix II of the Convention on the Conservation of Migratory Species of Wild Animals (CMS) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES).

While global populations of scalloped hammerhead sharks continue to decline, Australia represents an important region for research due to ongoing management measures and continued observations of the species in coastal waters. Within Australia, scalloped hammerheads are listed as ‘Conservation Dependent’ under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC ACT 2018) and they have been a no-take species in Queensland waters since 2024 (Queensland Government 2025). Despite these protections, national assessments continue to highlight conservation concern for the species, with Australian populations considered Endangered and depleted (Kyne et al. 2021; FRDC 2023). To support effective conservation strategies, there is an urgent need to identify critical habitats, including breeding, parturition, nursery, and aggregation sites, particularly in regions like Australia, where the species remains accessible for study (Gustafson 2020; Lopez et al. 2022). Such information is essential for improving management in Australia and informing conservation strategies in areas where populations have been severely depleted or extirpated (Kyne et al. 2021; Pacoureau et al. 2021).

Scalloped hammerheads have a circumglobal distribution, inhabiting tropical and warm temperate waters (Compagno 1984). This species is highly mobile, capable of migrating over 1,000 km (Bessudo et al. 2011; Spaet et al. 2017), and occurs across a mosaic of ecosystems, including, estuaries, bays, continental shelves, and offshore pelagic waters (Wells et al. 2018). Despite their migratory capacity, studies have found that most scalloped hammerheads have relatively small home ranges and display aggregative behaviours around bathymetric features, such as seamounts, likely influenced by environmental factors (Klimley et al. 1988; Holland et al. 1993; Hearn et al. 2010; Bessudo et

al. 2011; Lopez et al. 2023). These aggregations are subject to sexual segregation, with adult males and females typically occupying different spatial regions within their overall distribution (Klimley 1987; Stevens and Lyle 1989; Harry et al. 2011). Mature females, although rarely observed, are believed to primarily inhabit offshore, pelagic waters, whereas males tend to remain closer to coastal areas (Harry et al. 2011; Hoyos-Padilla et al. 2014; Wells et al. 2018). During warmer summer months, pregnant females are thought to migrate inshore to give birth, typically producing litters of 12 to 41 pups in Australian waters (Stevens and Lyle 1989; Harry et al. 2011). Neonates and juveniles are predominantly found in shallow, turbid coastal nursery areas, where they remain for several months (Simpfendorfer and Milward 1993; Yates et al. 2015; Brown et al. 2016; Zanella et al. 2019). Scalloped hammerhead pups are born at sizes ranging from approximately 31 to 57 cm in total length, with sexual maturity attained at lengths of around 140–198 cm for males and 200–250 cm for females, and maximum sizes reaching up to 430 cm (Ebert et al. 2021). However, knowledge gaps remain in Australia regarding their seasonal habitat preferences, the duration of their stay in nursery areas, and their subsequent movements after leaving these regions (Simpfendorfer and Milward 1993; Duncan and Holland 2006; Hutchinson et al. 2023).

Unmanned Aerial Vehicles (UAVs; hereafter referred to as ‘drones’) offer a unique vantage point for observing marine megafauna and have been increasingly used in recent years to identify important habitats for elasmobranchs (Raoult et al. 2018; Ayres et al. 2021). Drones are especially advantageous for shark research, providing non-invasive monitoring with minimal disturbance to the species, a critical consideration for understanding natural behaviour and movements (Butcher et al. 2021; McIvor et al. 2022; Cross et al. 2025). Studies have demonstrated the utility of drones in detecting sharks off coastal beaches (Kelaher et al. 2019; Mitchell et al. 2022b; Cross et al. 2024), highlighting their potential for detecting the presence of scalloped hammerhead sharks. This is emphasised in a recent study by Lopez et al. (2022), which used drones to monitor a seasonal scalloped hammerhead aggregation in Western Australia. The study documented aggregation size and structure, behavioural interactions, and environmental drivers influencing the timing and presence (Lopez et al. 2022). This aggregation extended the southern range of the species in Australia, and the findings were used to make recommendations for improved coastal zone management and marine park planning, supporting the need for protection of this aggregation site (Lopez et al. 2023).

Since September 2020, the Queensland SharkSmart drone program has monitored sharks for public safety purposes at up to nine beaches in southeast Queensland,

Australia (Mitchell et al. 2022a, 2025). The program has recorded a total of 4,959 sharks from September 2020 to April 2024, across 16,601 flights (Mitchell et al. 2025). A range of environmental and biotic factors were found to influence shark detectability, including the sighting of other fauna, season, wind speed and direction, turbidity, tidal state, glare, and atmospheric pressure (Mitchell et al. 2025). The archived footage represents an important resource for documenting marine megafauna biodiversity, abundance, and behaviour. This study used the archived footage from the Queensland SharkSmart drone program to assess sightings of scalloped hammerhead sharks off coastal beaches of southeast Queensland between September 2020 to December 2024. Specifically, the objectives of this study were to identify how frequently scalloped hammerhead sharks were sighted off these coastal beaches and quantify the influence of environmental, biotic, and operational factors on their detectability. Additionally, this study aimed to determine the presence of important habitats for the species, such as those supporting aggregations and juveniles.

Materials and methods

Study site and drone flights

From 2020 to 2024, the Queensland SharkSmart drone program operated at nine beach locations in southeast Queensland (Fig. 1), as described in Mitchell et al. (2025). Pilots from Surf Life Saving Queensland flew drone surveys on weekends, public holidays, and school holidays when

weather permitted, completing 8–10 flights per day between 07:00 and 12:00. Flight transects were 400 m long behind the surf break (~200 m offshore), with multiple passes of the transect occurring (Fig. 2; Cross et al. 2024). Drone footage was recorded in 4k high definition and archived for later analysis. Shark sightings were recorded, including an estimate of total length, direction of movement, and proximity to the beach. A range of environmental variables were also recorded for each flight (Table 1; Mitchell et al. 2022a, 2025).

Species identification followed the standardised Queensland SharkSmart drone protocol (Mitchell et al. 2025), whereby species were assigned only when individuals displayed clear morphological features in drone footage (e.g., pigmentation, head and body shape). Initial classifications were assigned to broad taxonomic groups where species-level identification was not possible, including hammerhead sharks (*Sphyrna* spp.). The hammerhead species complex could therefore include scalloped (*Sphyrna lewini*), great (*S. mokarran*) or smooth (*S. zygaena*) hammerheads based on their distribution (Compagno 1984). Species-level identification for hammerheads was confirmed using high-resolution stills extracted from the footage, focusing on individuals swimming near the surface that displayed distinctive morphological features, including a scalloped cephalofoil (head shape) and central indentation (Fig. 3). All confirmed hammerhead sightings were identified as scalloped hammerheads, and other hammerhead species were omitted from the dataset based on these clear morphological distinctions.

Fig. 1 Map of the nine southeast Queensland locations where the Queensland SharkSmart drone program operated from 2020 to 2024, as indicated by red points

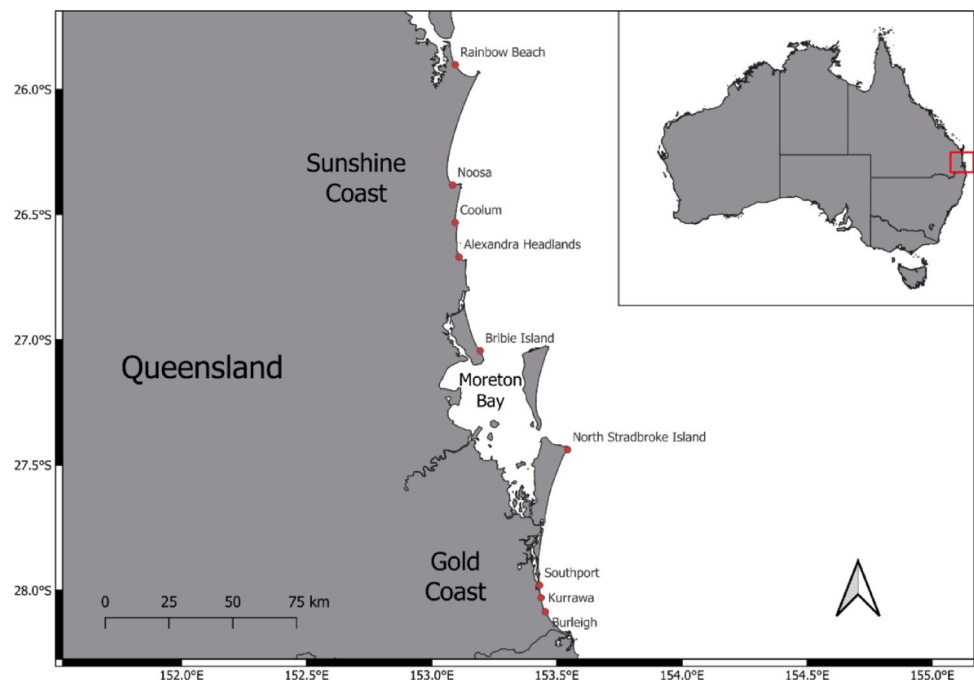
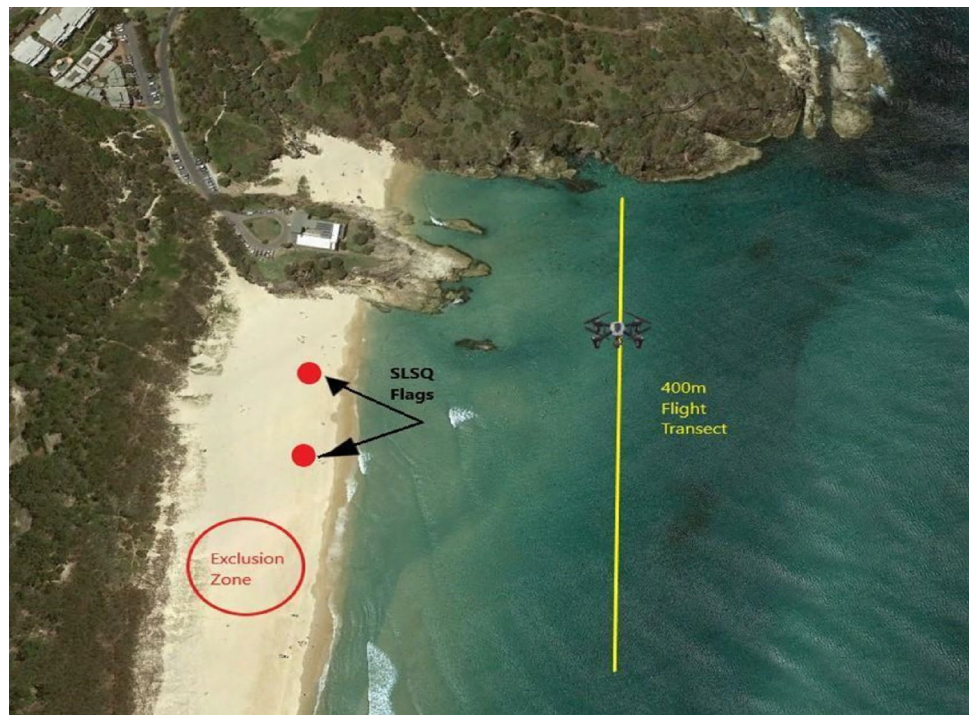


Fig. 2 Diagram illustrating the drone transect route behind the surf break at Main Beach, North Stradbroke Island, Queensland. The red circle highlights the 30 m public exclusion zone, from which drones were launched and retrieved



Data collection for scalloped hammerhead sharks

For each sighting, species, number of animals present, presence of other fauna, and the sharks' movement track were recorded. Movement tracks were generated using QGIS (v3.32.2-Lima; QGIS.org 2023; see Cross et al. 2025 for track methods). Movement tracks represented the drone flight path rather than the precise movements of the sharks. To ensure accuracy, only instances where the drone remained closely aligned directly above the shark were included in analyses. Tracking was terminated when the drone could no longer remain directly above the shark or the individual could no longer be followed. Previous research by Raoult et al. (2018) demonstrated that drones flown directly overhead can provide highly precise trajectory data for sharks. However, in cases involving pairs or large schools of sharks, individuals could not be reliably distinguished and a single track representing the overall movement was generated. Consequently, these tracks reflected general activity and fine-scale habitat use patterns of multiple sharks or the aggregation rather than the directional movements of individual sharks.

To account for differences in survey effort among locations, the total number of flights at each site was converted into effort hours (two flights per hour), and sighting rates were calculated as the number of hammerhead shark events or individuals per flight hour.

Total length of each scalloped hammerhead shark was estimated by comparing the shark's size to nearby reference objects visible in the footage, such as swimmers, surfboards, paddleboards, and other marine animals (Fig. 4).

For paddleboards, an average length of 3.15 m (range: 2.8–3.5 m) was used based on standard dimensions. Shark length was estimated by assessing the relative size of the shark to the reference object within the same frame (Graham and Roberts 2007). In instances where no reliable scale objects were present, footage from the same area and day when reference objects were available, was used to approximate scale. If no suitable reference could be established, the shark was excluded from length analysis.

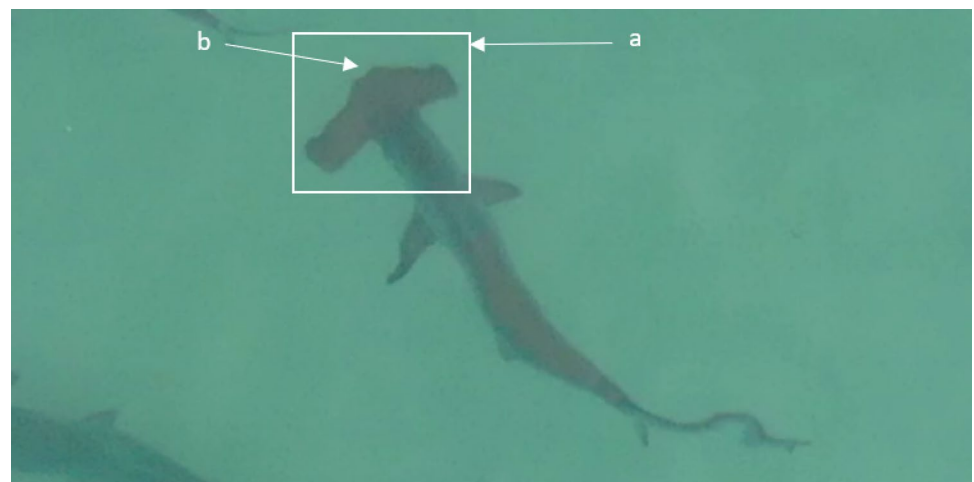
Statistical analysis

Kernel Density Estimation (KDE) heatmaps were generated using QGIS from all available movement tracks, with aggregations represented by a single group track. Only Burleigh Beach and Noosa Main Beach were selected due to high hammerhead shark sighting frequencies and clear recurring patterns of use. KDE analysis was conducted by interpolating shark track points into a heatmap using a 10 m cell size, following methods outlined in Cross et al. (2025).

A Generalised Additive Model (GAM) was fitted using the `gam()` function in the *mgcv* package (v1.9.4; Wood 2017) to quantify the influence of environmental, biotic, and operational factors on the probability of detecting scalloped hammerhead sharks during drone surveys (Table 1). Shark detection was modelled as a binary response variable, representing the presence (1) or absence (0) of scalloped hammerheads recorded per survey flight. A binomial error distribution with a logit link function was used to model detection probability. Continuous predictors were initially

Table 1 Summary of predictor variables included in the Generalised Additive Model (GAM), including data type, units, data source, and model treatment

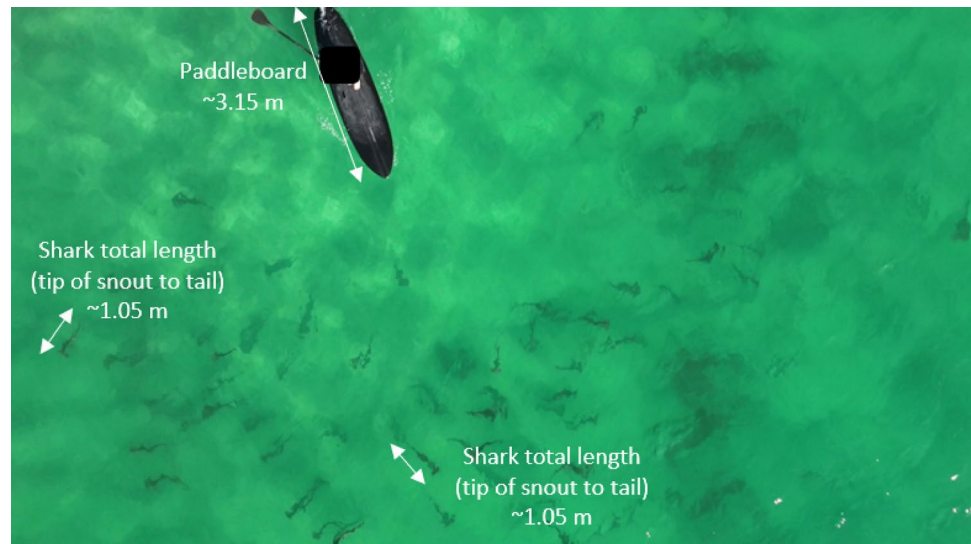
Category	Predictor	Type	Unit / Scale	Data Source	Model treatment
Environmental	Month	Categorical (ordered cyclic)	January–December	Pilot recorded	Cyclic cubic regression spline ($k=12$)
Environmental	Rainfall	Continuous	mm day ⁻¹	Bureau of Meteorology (BOM)	Smooth term (thin plate regression spline, $k=5$)
Environmental	Air temperature	Continuous	°C	BOM	Smooth term (thin plate regression spline, $k=5$)
Environmental	Turbidity	Continuous	% (0–100)	Pilot estimated	Smooth term (thin plate regression spline, $k=5$)
Environmental	Sea state	Categorical	Beaufort scale (1–6)	BOM	Parametric factor
Environmental	Cloud cover	Continuous / ordinal	oktas (0–8)	Pilot estimated	Parametric linear effect
Environmental	Glare	Ordinal	1 (low) – 5 (high)	Pilot estimated	Parametric linear effect
Environmental	Atmospheric pressure	Continuous	hPa	BOM	Smooth term (thin plate regression spline, $k=5$)
Environmental	Tidal state	Categorical	rising / falling / high / low	BOM	Parametric factor
Environmental	Lunar illumination	Continuous	0–1	BOM / derived	Thin plate regression spline
Biotic	Presence of other fauna	Categorical	presence/absence of bait balls, fish, rays, marine mammals	Pilot recorded	Parametric binary factor
Operational	Location	Categorical	beach/site	Pilot recorded	Parametric fixed effect
Operational	Flight number	Categorical (ordered)	1–8 (time of day proxy)	Pilot recorded	Parametric factor

Fig. 3 Scalloped hammerhead sharks (*Sphyrna lewini*) observed during drone flights at Burleigh Beach, southeast Queensland. The image shows an individual swimming near the surface, with arrows highlighting the (a) distinctive scalloped cephalofoil and (b) central indentation used to confirm species identification

fitted as smooth terms to allow potential non-linear relationships with detection probability. Month was modelled as a cyclic cubic regression spline to account for seasonal periodicity, whereas other continuous predictors were fitted using thin plate regression splines with a basis dimension of five ($k=5$). Categorical predictors were included as fixed

effects (Online Resource 1). Prior to model fitting, multicollinearity among predictors was assessed using variance inflation factors (VIF) calculated with the `vif()` function in the *car* package (v3.1.5; Fox and Weisberg 2019) from a linear model containing all candidate predictor variables (Online Resource 2).

Fig. 4 Estimation of total length using a visible reference object. For paddleboards, an average length of 3.15 m was used based on standard dimensions (range: 2.8–3.5 m). In this example, the sharks were approximately one-third the length of the paddleboard, indicating an estimated total length of approximately 1.05 m



Model selection followed an information-theoretic approach. A global GAM containing all candidate predictors was fitted initially, and competing models representing ecologically plausible combinations of predictors were compared using Akaike's Information Criterion (AIC; Akaike 1974). To evaluate whether modelling non-linear relationships improved model performance, an equivalent Generalised Linear Model (GLM) containing the same predictors as linear terms was also fitted and compared using AIC. As the GAM provided the best fit (lowest AIC), all subsequent inference was based on the GAM (Online Resource 3). Generalised Additive Models were fitted using restricted maximum likelihood (REML), which optimises the estimation of smoothing parameters and reduces the risk of overfitting. Estimated degrees of freedom (EDF) were examined to assess smooth-term complexity, with EDF values close to one interpreted as approximately linear relationships.

To investigate whether anthropogenic activity influenced scalloped hammerhead aggregation size, an exploratory analysis was conducted using the number of nearby people and vessels recorded during each sighting event. Aggregation size (number of sharks per sighting event) was modelled using negative binomial GLMs to account for overdispersion. Aggregation size was selected as the response variable because the duration of shark presence could not be reliably quantified from drone survey flights, whereas the number of sharks observed per sighting event provided a consistent measure of aggregation. The number of nearby people and vessels was log-transformed using $\log(x+1)$, and competing models including anthropogenic activity, location, and their combination were compared using AIC (Online Resource 4). All statistical analyses were conducted in RStudio (R v4.5.1; RStudio v1.4.1711; R Core Team 2023). The *tidyverse* package (v2.0.0; Wickham et al. 2019) was used for data organisation and visualisation.

Results

Scalloped hammerhead sightings

A total of 84 scalloped hammerhead shark sighting events were recorded across the nine southeast Queensland beaches monitored by the SharkSmart drone program between September 2020 to December 2024. Collectively, these sightings comprised 2,696 individual scalloped hammerhead sharks. The majority of sightings occurred at Burleigh Beach (Gold Coast) and Noosa Main Beach (Sunshine Coast), where sighting rates were highest (0.026 and 0.032 events/hr, and 1.105 and 1.015 individuals/hr, respectively; Table 2). Many sharks at these locations were likely resighted across multiple flights, and as such, this figure does not represent the total number of unique individuals. Sightings at Burleigh and Noosa almost exclusively involved groups of multiple scalloped hammerhead sharks, whereas other beaches generally involved solitary individuals or pairs (Table 2). Group size ranged from one to 100 individuals, with the largest aggregations observed between April and June, when median group sizes were 55, 45 and 32.5 individuals, respectively, compared with ≤ 2 individuals during all other months (Fig. 5; Online Resource 5). Estimated total lengths varied from <0.80 m to 3 m (mean $\pm$ SD: 109 ± 25 cm; $n=2,696$; Online Resource 6). Juveniles dominated sightings at Burleigh and Noosa, while larger individuals were more frequently observed off North Stradbroke Island (Table 2).

Movement patterns and space use

Scalloped hammerhead sharks displayed variable movement patterns and space use off the surveyed coastal beaches. At North Stradbroke Island (Fig. 6a), 13 of the 14

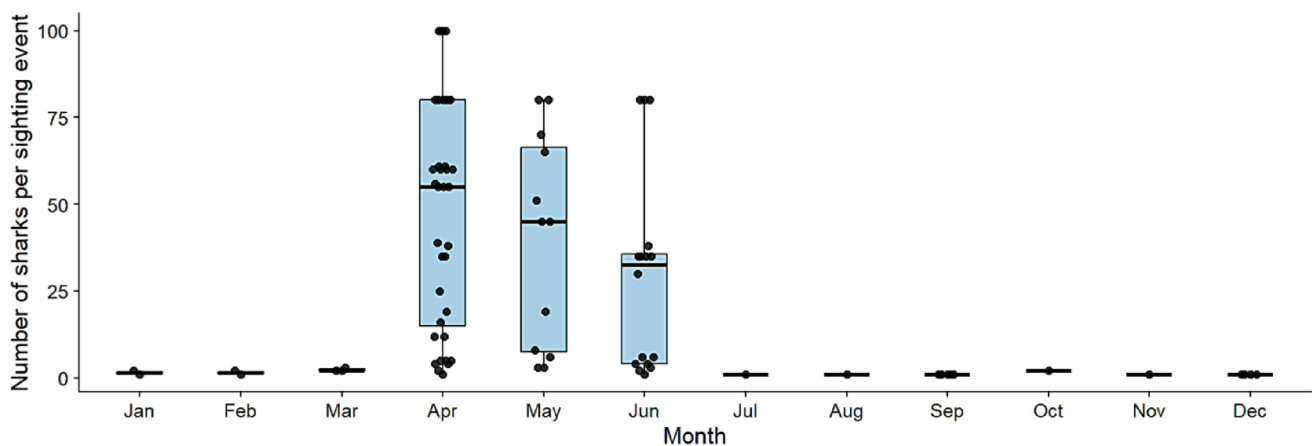


Fig. 5 Monthly variation in the number of scalloped hammerhead sharks detected per sighting event during drone surveys. Boxes represent the interquartile range (IQR), horizontal lines indicate the median, whiskers extend to 1.5 x IQR, and points represent a sighting event

Table 2 Summary of scalloped hammerhead shark sightings across nine southeast Queensland beach locations covered by the SharkSmart drone program, including standardised sighting events

Beach location	No. of flights	No. of hammerhead sighting events	No. of individuals ^a	Sighting rate (events/hr)	Individuals/hr	Total length (TL) range (cm)	Group size range
Alexandra Headlands	3,277	1	1	0.001	0.001	<100	1
Bribie Island	1,183	2	2	0.003	0.003	100–200	1
Burleigh	3,091	39	1,708	0.026	1.105	0.80–150	1–80
Coolum	3,008	0	0	0	0	-	-
Kurrawa	1,730	0	0	0	0	-	-
Noosa	1,907	28	968	0.032	1.015	<100	1–100
North Stradbroke Island	1,885	12	14	0.015	0.015	150–300	1–2
Rainbow Beach	1,787	0	0	0	0	-	-
Southport	3,043	2	3	0.001	0.002	100–250	1–2
Total	20,911	84	2,696	0.009	0.258	0.80–300	1–100

^a Includes repeated sightings of the same individuals.

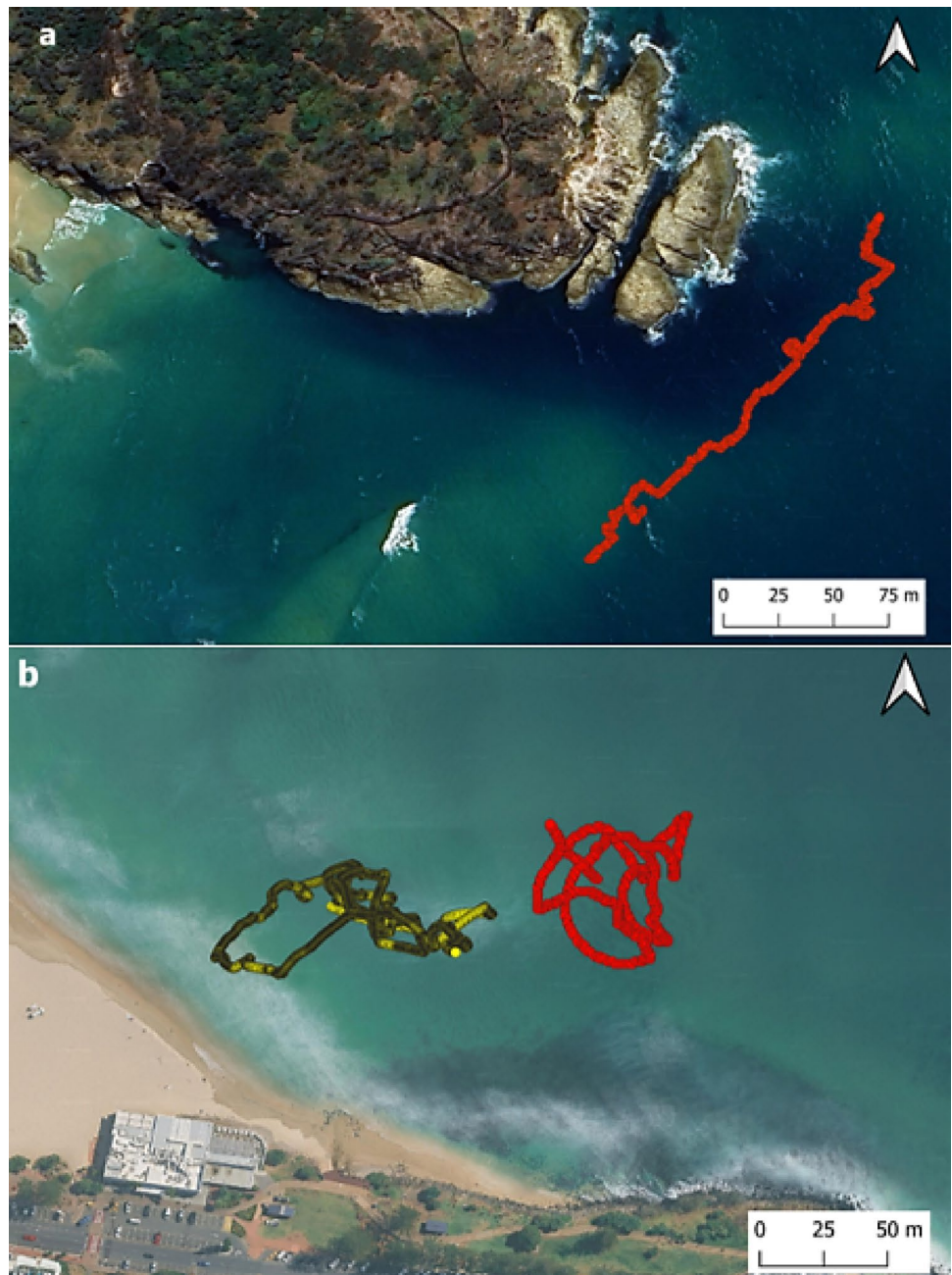
sharks moved northeast parallel to the shoreline, following linear trajectories with minimal deviation in direction. Most individuals were tracked for approximately 100 m, although one shark was tracked for approximately 250 m. The remaining individual also exhibited a linear trajectory but travelled eastward. In contrast, observations at Burleigh Beach revealed more clustered movement patterns, particularly during aggregations between March and early June (Fig. 6b). Tracks from 1 April 2023 (yellow) and 3 April 2024 (red) showed frequent overlap and repeated use of the same coastal areas, with each track representing movements of multiple scalloped hammerheads observed on a single drone flight during the aggregation period. Kernel density heatmaps revealed consistent spatial hotspots at Burleigh across both years (Fig. 7a and b), with sightings concentrated near the southern end of Burleigh Beach near Burleigh Headland. A similar pattern of localised space use was evident at Noosa Beach from 6 April to 30 June 2023 (Fig. 7c). However, scalloped hammerheads were not observed at Noosa during the same period in 2024, unlike the persistent

aggregations observed at Burleigh Beach. During the 2023 aggregation season, shark presence was documented in three main areas. The central hotspot, adjacent to Noosa Main Beach, showed the highest sighting density, with two additional zones of moderate activity extending to the east and west.

Factors influencing hammerhead shark presence

The final GAM, selected based on the lowest AIC value, identified turbidity, presence of other fauna, sea state, flight number (proxy for time of day), month and location as significant predictors of hammerhead shark detectability. Inspection of smooth terms indicated that month exhibited a non-linear seasonal relationship with detection probability (EDF = 4.61), whereas continuous predictors showed approximately linear relationships (EDF $\approx$ 1; Online Resource 7). The final GAM explained 33.7% of the deviance in the response variable (Tjur's R^2 = 0.1). Sightings were negatively associated with increasing turbidity (Fig.

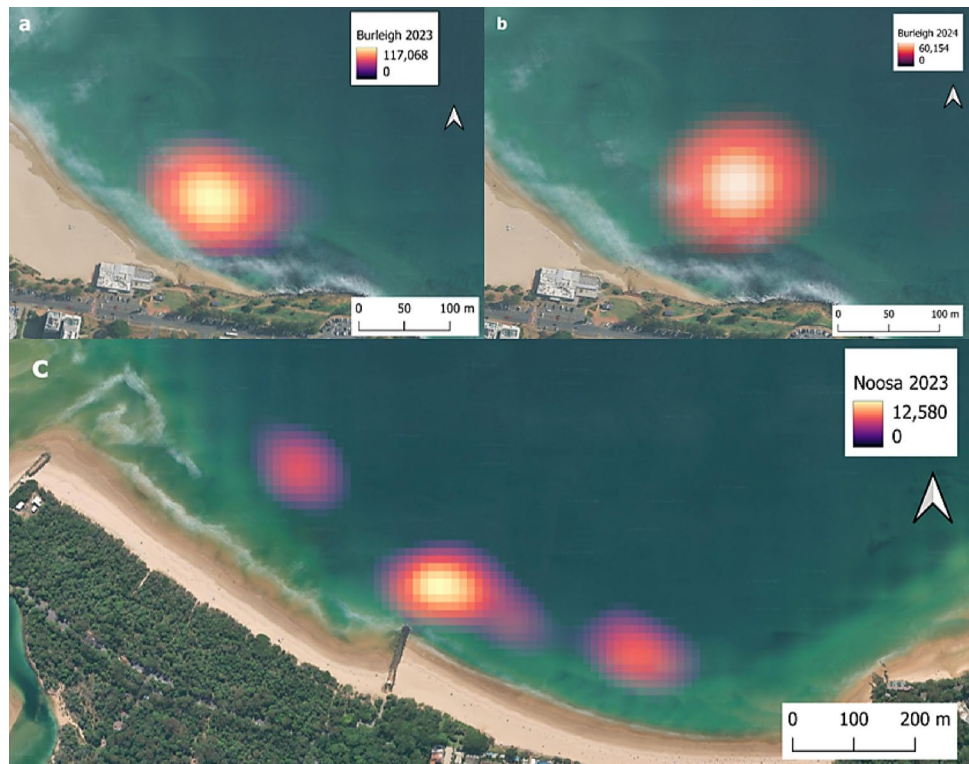
Fig. 6 Raw movement tracks of scalloped hammerhead sharks recorded from drone observations. (a) Linear movement track of an individual shark at North Stradbroke Island in 2023. (b) Aggregated movement patterns at Burleigh Beach in 2023 (yellow) and 2024 (red), illustrating increased localised space use



8a), with the highest probability of sightings occurring under clear water conditions (0.06 ± 0.02). The relationship between sightings and sea state was non-linear, with the highest probability of sightings observed during calm conditions (sea state 1; 0.02 ± 0.01), although a similarly high probability was also predicted at sea state 5 (0.02 ± 0.008 ; Fig. 8b). The presence of other fauna significantly increased the likelihood of hammerhead sightings (0.08 ± 0.03 ; Fig. 8c). Within the morning survey period, sighting probability was highest during early flights (0.02 ± 0.01) and generally declined across the survey period, although probabilities increased slightly during later flights (Fig. 8d).

Temporal analysis revealed a seasonal pattern, with peak sighting probabilities occurring between April (0.04 ± 0.01) and June (0.02 ± 0.01), and lower probabilities recorded during the summer months (0.003 ± 0.002 ; Fig. 8e). Spatial variation in sightings was evident, with the highest probabilities of hammerhead presence observed at Burleigh (0.02 ± 0.008) and Noosa (0.02 ± 0.008) beaches (Fig. 8f).

Fig. 7 Spatial distribution of scalloped hammerhead shark sightings recorded by drones at Burleigh Beach and Noosa Main Beach, respectively. (a) Kernel density heatmap of shark tracks from 2023; (b) Kernel density heatmap from 2024, (c) Kernel density heatmap from 2023 at Noosa Main Beach. Yellow areas indicate higher sightings densities, while purple areas indicate lower densities. Heatmap scales (a: 0–117,068; b: 0–60,154; c: 0–12,580) represent relative intensity of overlap derived from kernel density estimation, not absolute sighting counts



Discussion

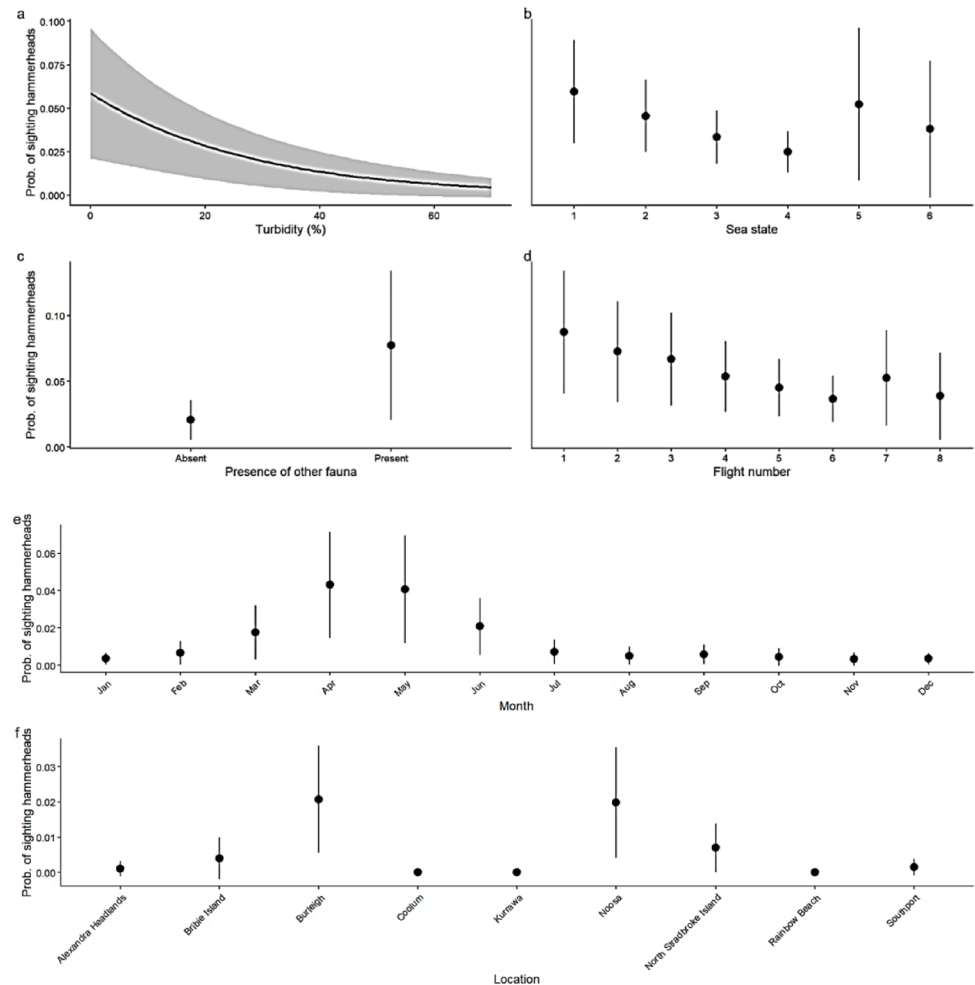
This study highlights drones as a highly effective, non-invasive tool for detecting fine-scale habitat use of scalloped hammerhead sharks (*Sphyrna lewini*). Here, we demonstrate the successful detection of spatio-temporal hammerhead aggregations at popular urbanised beach sites that serve as important habitat for these juveniles at this critical life history stage. Further, these sharks were previously undetected at these same locations through traditional monitoring programs (Queensland Department of Agriculture and Fisheries 2025), indicating the viability of deploying UAVs as an emerging tool for research on critically endangered elasmobranchs.

The repeated detection of juvenile scalloped hammerheads, particularly in large aggregations at Burleigh and Noosa, suggests that these sites may provide critical habitat features that enhance survival and growth, such as structural complexity associated with headlands and nearshore habitats, prey availability, and potential refuge from predators (Brown et al. 2016). In contrast, the predominance of solitary individuals at Bribie Island, North Stradbroke Island, and Southport Main Beach highlights fine-scale spatial heterogeneity in habitat suitability, indicating that juveniles may actively partition space to balance resource acquisition with predator avoidance (Heupel et al. 2007; Zanella et al. 2019). These spatial patterns align with observations from the Eastern Tropical Pacific (including Colombia and the Galapagos

Islands) and Central Pacific (Hawaii), where scalloped hammerheads exhibit strong site selectivity (Hearn et al. 2010; Bessudo et al. 2011) and occupy small core areas during daylight hours (Klimley et al. 1988; Holland et al. 1993). Collectively, these findings suggest that juvenile scalloped hammerheads are not randomly distributed but instead exhibit strategic habitat selection influenced by a combination of biotic and abiotic factors, including prey availability, refugia, and local environmental conditions.

Although the observed individuals comprised a mix of young-of-the-year and older juveniles (1–2 years old; Harry et al. 2011; Lubitz et al. 2025) rather than neonates, the repeated occurrence of similar sized sharks across multiple months and years suggests seasonal and interannual use of these areas. While these coastal zones may not meet the criteria for nursery areas as defined by Heupel et al. (2007), they likely serve as important juvenile aggregation areas that warrant precautionary management consideration given repeated use and the presence of multiple juvenile age classes. This interpretation aligns with precautionary approaches to nursery designation that support early management intervention under uncertainty while longer-term demographic and movement data are collected, as well as more recent adaptive, tiered frameworks that incorporate varying levels of evidence in nursery designation (Hlavin et al. 2026). Notably, the sampled beaches are located within 20–60 km of several estuarine and embayment systems, including Moreton Bay, Broadwater, and associated river

Fig. 8 Predicted relationships between significant predictor variables and the probability of sighting scalloped hammerhead sharks across southeast Queensland beaches: (a) turbidity, (b) sea state, (c) presence of other fauna, (d) flight number (time of day), (e) month, and (f) location. Solid black lines represent model-fitted values for continuous predictors, with grey shaded areas indicating 95% confidence intervals. For categorical predictors, points represent predicted probabilities of shark sightings and error bars indicate 95% confidence intervals



mouths, which have been proposed as potential nursery grounds for scalloped hammerheads in this region (Gustafson 2020). The presence of older juveniles at coastal beach sites may therefore reflect an ontogenetic shift in habitat use, with individuals dispersing from sheltered nursery areas as their energetic requirements and prey preferences change with development (Hoyos-Padilla et al. 2014; Rosende-Pereiro et al. 2020).

Aggregations occurred consistently between March and June, which overlaps with the known regional pupping season for scalloped hammerhead sharks (Stevens and Lyle 1989; Harry et al. 2011; Gustafson 2020), although the individuals observed during this period were likely born in previous years. This seasonal timing may still be ecologically significant, as warmer water temperatures during these months can increase prey availability and support elevated metabolic and growth rates in juveniles (Simpfendorfer and Milward 1993; Duncan and Holland 2006; Niella et al. 2020). These conditions may make adjacent coastal habitats particularly favourable for older juveniles during this time of year. Together, these findings support the hypothesis that coastal zones act as transitional developmental habitats and

underscore the need for long-term monitoring, particularly through acoustic telemetry, to confirm connectivity with nearby nurseries and identify the environmental drivers shaping juvenile distribution.

Consistent with their repeated seasonal occurrence, juveniles at Burleigh Beach and Noosa Main Beach exhibited highly localised movements in shallow nearshore areas. At Burleigh, a rocky headland habitat appears to be a focal congregation point, suggesting that site use may be driven by structural complexity that supports diverse prey communities and provides shelter and foraging opportunities for lower trophic levels (Ketchum et al. 2014; Yates et al. 2015; Brown et al. 2016). While aggregations of juvenile scalloped hammerheads have been rarely documented in Australian waters (Klimley 1983; Lopez et al. 2023; Lubitz et al. 2025), the repeated overlap of movement tracks at Burleigh across multiple years underscores its importance as an aggregation site. However, because individual sharks could not be reliably identified from drone imagery, these repeated observations cannot confirm individual residency or site fidelity, and future integration with photo-identification or telemetry will be required to determine the

persistence of individual use of this habitat. Such behaviour may reflect schooling for predator avoidance or improved foraging efficiency. Notably, core use areas ranged from 0.2 km² to 0.4 km², closely matching the 0.2 km² core aggregation area reported in scalloped hammerhead sharks in Western Australia (Lopez et al. 2023), highlighting the critical role of small, localised habitats in supporting juveniles. These aggregations resemble those documented in the eastern Pacific, where juveniles display site-specific behaviours including resting and repeated co-occurrence, which may suggest social interactions (Klimley 1983, 1985; Ketchum et al. 2014; Papastamatiou et al. 2022). In contrast, a comparable aggregation was not observed at Noosa in 2024. This may reflect interannual variability in habitat use or reduced detectability associated with local environmental conditions, such as increased turbidity or freshwater influence from Noosa River rather than a true absence of juveniles. Continued long-term monitoring will be required to distinguish between these possibilities.

In contrast to the highly localised movements observed at Burleigh Beach and Noosa Main Beach, scalloped hammerheads at North Stradbroke Island displayed linear, directed trajectories consistent with transitory movements by larger individuals (Harry et al. 2011; Wells et al. 2018). Given its proximity to the continental shelf (~23 km; Cross et al. 2024), this location may serve as a navigational aid during seasonal migrations (Klimley 1993; Holmes et al. 2014), particularly for mature scalloped hammerhead females moving towards the coast in summer and autumn. While these inshore movements coincide with periods of reproductive activity reported in eastern Australia and the broader Indo-Pacific (Stevens and Lyle 1989; Harry et al. 2011), the absence of long-term tracking data limits their interpretation as definitive reproductive migrations. Additionally, North Stradbroke Island lies within the influence of the East Australian Current (EAC), which brings warmer tropical waters during summer months (Suthers et al. 2011). The combination of reef-associated habitats, proximity to Moreton Bay and deeper offshore environments, and seasonal oceanographic influences may contribute to the use of this area by larger individuals undertaking broader movements. This temperature variation may further influence seasonal movement patterns, with larger sharks potentially following thermal gradients for energetic efficiency or reproductive cues (Niella et al. 2020). The use of adjacent shallow areas may also provide thermal benefits or protection during these transits, although further research is needed to confirm the drivers of these movements (Holland et al. 1993; Klimley 1993).

Scalloped hammerhead detectability was significantly influenced by environmental and operational variables. Visibility factors such as turbidity and sea state affected sighting

probability, consistent with previous drone-based elasmobranch studies (Raoult et al. 2018; Butcher et al. 2019; Cross et al. 2024; Mitchell et al. 2025). These conditions not only limit aerial visibility but may influence shark behaviour, possibly reducing surface time or nearshore presence under certain sea conditions. Nonetheless, sharks may still be present under such conditions but remain undetected. In contrast, sightings increased when bait balls and teleosts were present, suggesting shared habitat use or foraging in productive zones, although reduced detectability under conditions of high turbidity or variable sea state may also have contributed. It is noted that the 'other fauna' covariate also included occasional larger megafauna, however, given the predominantly juvenile size class observed (109 ± 25 cm), these are unlikely to represent consistent predator-driven interactions and are more appropriately interpreted as indicators of broader habitat conditions. Given their diet of benthic teleosts and cephalopods (Rosende-Pereiro et al. 2020; Galloway et al. 2024; Páez-Rosas et al. 2024), this likely reflects prey-driven habitat selection. Estuarine outflows from nearby Tallebudgera Creek (Burleigh Beach) and the Noosa River (Noosa Main Beach) may enhance local productivity and prey abundance, contributing to consistently high hammerhead sightings (Meynecke et al. 2006; Connolly et al. 2009). Additionally, the presence of nearby reefs such as Burleigh Reef and Palm Beach Reef, both adjacent to Burleigh Beach, may provide structurally complex habitats that support diverse prey communities, further attracting scalloped hammerheads to this area (Henderson et al. 2022).

Diel activity patterns were also observed, with sightings more frequent during early morning flights, consistent with crepuscular activity in juveniles (Klimley et al. 1988; Bush 2003). However, surveys were restricted to morning hours, leaving much of the diel cycle unsampled and limiting broader inference. The observed patterns are likely primarily driven by crepuscular foraging and movement behaviours, which are widely documented in scalloped hammerhead sharks (Klimley et al. 1988; Bush 2003; Ketchum et al. 2014; Lopez et al. 2023). Increasing human activity later in the morning may also contribute to variation in sighting probability; however, the relationship with flight number was not strictly monotonic, suggesting that multiple factors may influence shark detectability. Exploratory analysis of anthropogenic activity during scalloped hammerhead sightings indicated that aggregation size was better explained by location than by the number of nearby people and vessels, suggesting that the apparent relationship between human activity and aggregation size reflected spatial overlap between aggregation sites and popular recreational beaches. Sharks were occasionally observed altering their behaviour when approached by snorkellers

and paddleboarders, including temporary fragmentation of aggregations; however, these observations were opportunistic and not systematically quantified. Similar behavioural responses to anthropogenic activity have been reported in elasmobranchs (Barker et al. 2011; Trave et al. 2017; Cattano et al. 2021). Further research incorporating standardised measurements of human activity and behavioural responses would be required to quantify disturbance effects.

Implications for conservation and monitoring

Findings reported herein support the use of drones for targeted monitoring of endangered elasmobranchs. Importantly, no escape or erratic responses were observed during surveys conducted at the standard operational flight altitude (≥ 20 m), indicating minimal disturbance to these sharks from the drones and supporting the reliability and ongoing use of drones for behavioural monitoring (Butcher et al. 2021; Mitchell et al. 2022b). Drone-derived data offer a pathway for adaptive management, enabling dynamic, seasonally informed mitigation strategies that enhance both public safety and conservation outcomes. These insights can support marine spatial protections by identifying areas of repeated juvenile occurrence, which can inform the designation and refinement of Essential Fish Habitat (EFH) under national legislation and contribute to evidence-based spatial conservation planning. Importantly, these findings are consistent with the criteria used in the identification of Important Shark and Ray Areas (ISRAs; Hyde et al. 2022; <https://sharkrayareas.org/about-isras/>). This region has subsequently been designated as the Burleigh-Kirra ISRA, recognising it as an aggregation area for scalloped hammerheads (IUCN SSC Shark Specialist Group 2025). Moreover, drone observations can engage the public by presenting sharks in a natural context, potentially shifting perceptions and building support for conservation (Stokes et al. 2020; Cross et al. 2025). These data can also inform the development and promotion of codes of practice aimed at minimising human disturbance during shark interactions. Given the predictable seasonal occurrence of aggregations at specific urbanised beaches, management actions could include public education on responsible shark encounters, maintaining minimum approach distances, avoiding deliberate pursuit or encirclement of aggregating sharks, and promoting awareness of aggregation periods among recreational users (Lopez et al. 2023).

While drones improve our ability to monitor these populations and inform management, existing human activities continue to impact these species. The high juvenile presence at Burleigh Beach and Noosa Main Beach highlights the need for seasonal spatial protections, as juvenile occurrence is temporally variable and may not align with periods of

highest interaction risk. Both sites are part of the Queensland Government's Shark Control Program (QSCP), which aims to reduce the risk of shark bites using a combination of operational equipment (shark nets, baited drumlines, drones), research, trials and education. At Noosa, both shark nets and baited drumlines are operated, while Burleigh is equipped with shark nets only, which are located 300–500 m offshore. Between 2001 and 2024, the QSCP recorded 65 captures of scalloped hammerheads at Burleigh and Noosa combined, 63 in nets and two on drumlines, comprising both juveniles and adults (Queensland Department of Agriculture and Fisheries 2025). Statewide, 675 scalloped hammerheads were captured over the same period, including 512 in nets and 163 on drumlines. Although not a target species, scalloped hammerheads are particularly susceptible to fishing mortality, and all but 10 individuals caught under the QSCP were deceased.

Juvenile captures (< 120 cm) peak from September to February, coinciding with presumed nursery use, whereas drone surveys documented aggregations from March to June, revealing a temporal mismatch. This discrepancy likely reflects ontogenetic habitat transitions, whereby neonates and young-of-the-year are associated with more sheltered nursery areas during early development before moving into more exposed coastal habitats as their energetic and dietary requirements change (Hoyos-Padilla et al. 2014; Rosende-Pereiro et al. 2020). As juveniles transition into these coastal environments, their spatial overlap with QSCP gear may vary seasonally, resulting in periods of elevated interaction risk during movement between habitat types. This pattern may also reflect seasonal variation in depth and habitat use, with juveniles typically occupying surface waters and adults occurring closer to the seafloor (Lopez et al. 2023). The QSCP's surface-set nets, which feature relatively large mesh sizes (~ 500 mm), likely influence the size classes caught. Most scalloped hammerheads recorded are < 200 cm in total length, indicating that juveniles and sub-adults are more susceptible to entanglement. Together, this suggests that QSCP captures primarily reflect individuals encountered during a transitional movement phase between nursery areas and more exposed coastal habitats.

Conclusion

This study demonstrates the value of drone-based surveys for revealing previously undocumented habitat use of juvenile scalloped hammerhead sharks (*Sphyrna lewini*) in coastal environments. Across southeast Queensland, drones identified repeated juvenile aggregations at urbanised beaches, including sites where traditional monitoring approaches had not previously detected this species. These observations

suggest that nearshore coastal habitats provide important developmental areas for juvenile scalloped hammerheads, potentially representing transitional habitats between sheltered nursery environments and broader coastal ecosystems. By identifying fine-scale patterns of habitat use, movement, and environmental drivers of detectability, this study highlights how drone-derived observations can complement existing monitoring approaches and support evidence-based conservation planning. The designation of the Burleigh-Kirra Important Shark and Ray Area demonstrates the value of targeted observations for identifying habitats of conservation importance for threatened chondrichthyans. Continued integration of drone surveys with acoustic telemetry, environmental DNA, and individual identification methods will be critical to confirm habitat connectivity, residency patterns, and population-level importance. Together, these findings demonstrate the potential of drones as a scalable tool for improving conservation outcomes while supporting coexistence in increasingly urbanised marine environments.

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Data availability Corresponding author can provide the datasets used in this study upon reasonable request, although footage which contains

images of people is considered confidential and cannot be made publicly available.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

Ethics approval This is an observational study. The Queensland Government has confirmed that no ethical approval is required.

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