

Review

Drone-Based Surveillance Methods for Non-Lethal Shark Mitigation in Nearshore Environments: Current Applications, Challenges, and Future Directions

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Highlights

What are the main findings?

- Drones are a valuable non-lethal mitigation tool for monitoring shark presence in nearshore areas; however, challenges remain for real-time detection and species misidentification.
- Drone-based monitoring can provide beach authorities with valuable insights into coastal shark ecology, supporting informed management decisions.

What are the implications of the main findings?

- The effectiveness of drone-based shark surveillance programs is dependent on efficient operational procedures that support rapid response and appropriate safety measures.
- Integrating advanced technologies (e.g., remotely operated drone systems, artificial intelligence (AI)-based detection software) has the potential to improve real-time detection and identification, expanding the application of drones in shark science.

Abstract

Unprovoked shark bites are one of the most recognised human–wildlife conflicts and present a significant concern for beach safety. Lethal methods of shark mitigation have previously been implemented to reduce the risk of such incidents; however, due to their destructive impacts on vulnerable marine wildlife, non-lethal approaches are increasingly preferred. In recent years, drones have emerged as an effective, minimally invasive tool for real-time shark surveillance in surf zones. Drones are also used to collect valuable data on shark ecology and behaviour in nearshore environments, which can inform evidence-based policies. This review examines the utility of drones for shark surveillance programs by identifying key operational parameters and associated challenges of drone-based methods. We investigate emerging technologies, including long-range drones, remotely operated or autonomous flight missions, and the use of artificial intelligence for shark detection and species identification. We also outline current drone licensing, laws, and regulations, noting that these vary across administrative regions (i.e., countries and states). Overall, this review provides insight into the expansion of drone-based shark surveillance in nearshore areas and its potential to enhance beach safety, support management decisions, and advance scientific knowledge without negatively impacting shark populations.



Academic Editors: Humberto Perotto-Baldivieso and Aaron M. Foley

Received: 6 May 2026

Revised: 25 June 2026

Accepted: 7 July 2026

Published: 22 July 2026

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Keywords: aerial surveillance; artificial intelligence; coastal; drone; unmanned aerial vehicle; remotely piloted aircraft; shark; shark management; shark mitigation

1. Introduction

Sharks play a key role in maintaining the structure, function, and resilience of many marine and estuarine ecosystems [1–3]. Despite their ecological importance, worldwide shark populations are declining, primarily due to overfishing [4–6]. It is estimated that 31.2% of shark species are currently threatened [7], with coastal sharks particularly vulnerable due to their frequent use of nearshore areas [8–10].

Nearshore areas are highly productive habitats that are heavily used by humans for recreational and commercial activities [11,12]. These habitats are also critical for many coastal shark species, supporting key biological processes such as feeding, reproduction, and nursery sites [8,13]. The spatial overlap between humans and sharks in nearshore areas increases the likelihood of human–shark interactions [14,15], highlighting the need for effective risk management strategies [16].

While unprovoked shark bites remain rare, they can result in severe injury or fatality, raising safety concerns among coastal communities [17–19]. Unprovoked shark bites primarily occur in ocean beaches, estuaries, harbours, and reefs [20,21]. The United States, Australia, South Africa, Brazil, Réunion Island, and the Bahamas are recognised as global shark bite hotspots, where the majority of incidents are recorded [22,23]. White (*Carcharodon carcharias*), tiger (*Galeocerdo cuvier*), and bull (*Carcharhinus leucas*) sharks are the most dangerous species as they are involved in most unprovoked shark bites worldwide [24,25]. However, global assessments by the International Union for the Conservation of Nature (IUCN) currently list white sharks and bull sharks as Vulnerable, and tiger sharks as Near Threatened [26–28].

Lethal methods of shark mitigation, including shark nets, baited drumlines, and longlines, have previously been implemented to minimise the risk of shark bites [29–31]. These methods negatively impact non-target marine wildlife and vulnerable shark populations [32,33], with their effectiveness also routinely debated [34,35]. Culling strategies implemented to decrease shark density are also recognised as ineffective for reducing unprovoked shark bites [29], with such incidents more likely to reflect behavioural variability among individual sharks within species [36–38]. This has prompted a re-evaluation of lethal methods in shark management, highlighting the need for strategies that incorporate human safety with conservation and environmental implications [39,40]. Consequently, minimally invasive approaches, including aerial or land-based surveillance [41–44], exclusion zones (e.g., SharkSafe Barriers [45,46]), Shark-Management-Alert-in-Real-Time (SMART) drumlines [47], and tagged shark listening stations [48], are increasingly being developed and implemented in regions where shark bites are more prevalent [49]. These methods are often used in combination [50,51] and are complemented by scientific research, public education, and the development of personal deterrents [52–54].

Drones have emerged as a practical, non-lethal tool for monitoring shark presence along coastal beaches [43,55]. Drone surveillance offers a clear aerial perspective, facilitating real-time detection of sharks. These methods can be used to enhance beach safety through the implementation of countermeasures when an observed shark is perceived as a potential threat to water users [49,56]. In addition, drone-based surveys enable data collection that can improve our understanding of coastal sharks [57,58] and other marine fauna [59,60]. Compared to crewed aircraft (e.g., planes and helicopters), small drones are easier to

operate and provide a more cost-effective alternative that requires less training, fewer personnel, and is considerably safer [61,62].

Here, we reviewed the utility of drones for real-time shark surveillance by examining operational considerations while also identifying the challenges and limitations of current methods. We investigated emerging technologies being developed, trialled, or implemented to enhance their effectiveness. We also explored drone-based shark research in nearshore areas, which can improve our overall understanding of coastal sharks. Finally, we provided an overview of current drone rules and regulations in global shark hotspots. As well as researchers, this review can also inform beach management authorities and guide the development of effective drone-based shark mitigation programs.

2. An Overview of Drone Operations for Shark Surveillance

A standard drone operation typically requires a drone and a ground control station connected through a communications link [61]. The pilot operates the drone from the ground control station, which receives a live video feed directly from the camera (Figure 1). Small multirotor drones (<2 kg) are commonly used in shark surveillance programs due to their manoeuvrability, hovering capability, and ability to take off, perform altitude adjustments, and land vertically, offering greater versatility than fixed-wing drones [63]. The capacity of multirotor drones for quick height changes, slow speeds, and hovering is particularly useful for shark identification.

Drone surveys are generally conducted during rain-free periods, with calm to moderate wind speeds (≤ 16 knots; refs. [43,55]). Although schedules vary among surveillance programs, all flights are undertaken during daylight hours, typically between 9:00 and 16:00 during peak beach attendance periods [49]. Multiple surveys can be completed per hour, with individual missions mostly ranging from 15 to 25 min and surveying distances of 1–2 km [57]; however, this is dependent on the drone platform.

Pilots typically operate the drone manually, as this allows adaptable flight paths in response to daily tidal variations. Drones are usually flown along transects behind the surf break at an altitude of 60 m and flight speeds between 6 and 12 m/s, enabling effective monitoring of the surf zone [64,65]. Drone cameras are oriented directly downward, providing a field of view width of approximately 110 m, with the inside edge of the observable area aligning with the backline of the surf break [66,67]. Pilots may manually adjust the camera angle during flight to optimise visibility depending on environmental conditions. Image resolution can vary among drone platforms due to differences in camera systems, flight altitude, and sensor specifications, which may influence detectability. Automated missions using preprogrammed waypoint flight paths with grid-based patterns can be designed in flight-planning software to comprehensively survey the surf zone despite tidal changes [68]. However, when a shark is detected, the mission must be paused and the drone manually controlled to facilitate tracking and species identification.

When a shark is detected, the drone can be flown at lower altitudes (often 10–25 m), depending on the conditions, to facilitate tracking [69,70] and species identification [71,72]. In-water noise generated by drones operated at these lower altitudes remains minimal and is unlikely to disturb submerged animals [73,74]. In contrast, drones can trigger behavioural responses in air-breathing marine fauna (e.g., cetaceans, pinnipeds, reptiles, sirenians) at varying altitudes across faunal groups [75–78]. Pilots should, therefore, ensure compliance with regulations that specify minimum flight altitudes and separation distances from wildlife.

If a shark is observed during a flight, the drone pilot can perform a risk assessment based on the species and size of the shark, as well as its proximity to water users. Beach authorities are alerted and, if appropriate, countermeasures can be implemented to reduce

the risk of a human–shark interaction. While beach procedures may differ, countermeasures are typically triggered by the presence of a potentially dangerous shark (i.e., bull, white, tiger) or when a shark is estimated to be ≥ 2 m in total length [79]. Drones used for shark surveillance are often equipped with a siren that can warn water users, while activated beach sirens can alert all beachgoers to a nearby shark [67]. Watercraft may also be deployed to guide the shark further offshore, and water evacuations or beach closures may be implemented, based on a risk assessment [56]. Sharks are continually monitored until they are no longer considered a potential risk, usually after swimming further offshore or away from the area, or until a drone battery swap is required [64]. Despite being part of a broader risk mitigation framework, drone surveillance plays an important role in real-time monitoring of the surf zone [50] and supports countermeasure implementation to reduce the probability of human–shark interactions, with no unprovoked shark bites reported on days when drone surveillance has occurred [56].

While the primary objective of drone-based shark surveillance is to increase beach safety through the detection of shark presence, this information can also improve understanding of species-specific shark behaviour and movement patterns, informing beach management in regions where unprovoked shark bites are likely to occur. Additional documentation of operational (e.g., date, time, location, flight duration) and environmental (e.g., wind speed, cloud cover, glare, water turbidity, sea state) factors can complement shark observation data (e.g., species- or group-level identification, number of individuals), and high-resolution recorded footage (FHD or higher) assists with post-flight analysis.

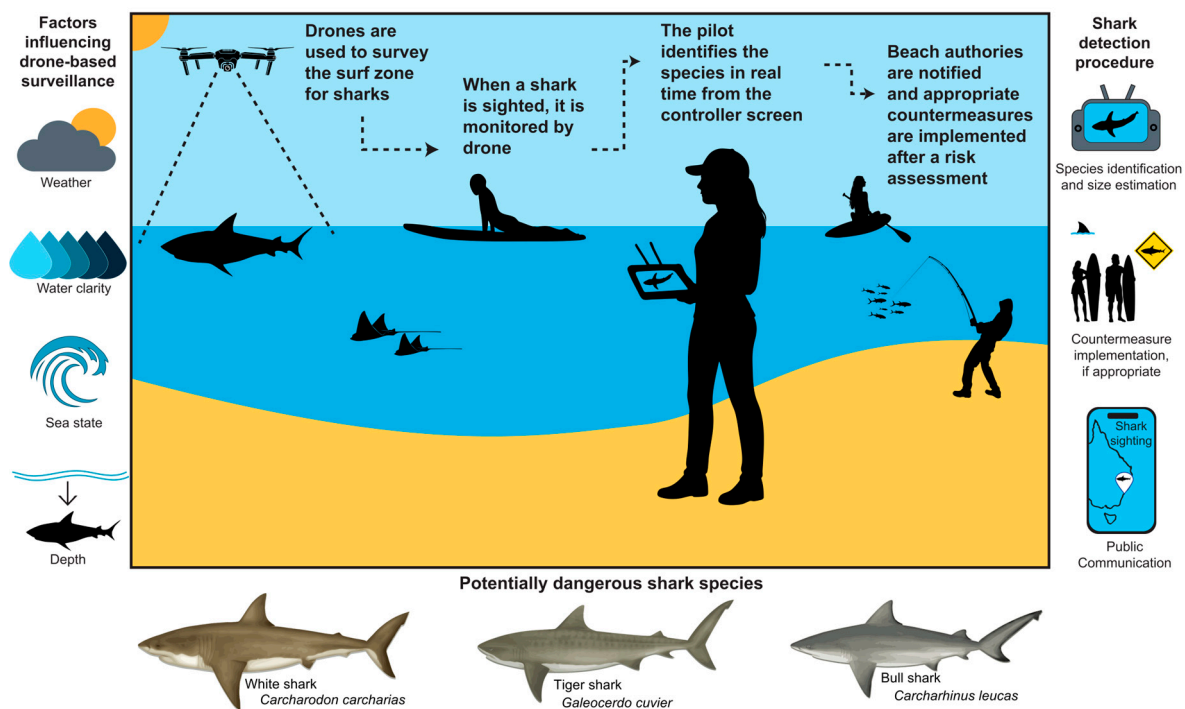


Figure 1. Workflow of drone-based shark surveillance, including factors that influence flight operations and detection probability (left), procedure that may be taken once a shark has been detected (right), and potentially dangerous sharks (i.e., white [*Carcharodon carcharias*], tiger [*Galeocerdo cuvier*], and bull [*Carcharhinus leucas*]), which are the primary focus for shark mitigation efforts in nearshore areas (bottom).

2.1. Challenges in Drone-Based Shark Surveillance

The efficacy of drones for detection using shark analogues has been evaluated across diverse marine environments, demonstrating their effectiveness while highlighting their limitations. Fixed-wing drones were used to test real-time detection using shark analogues placed on the ocean surface [80], whereas post-flight analysis of drone footage assessed the detectability of analogues at varying depths in a temperate estuary [81]. Multirotor drones have also been evaluated for spotting sharks in surf zones, with post-flight analyses reporting significantly higher detection rates than real-time surveillance [65].

Detectability is influenced by environmental factors, including water conditions (e.g., turbidity, clarity, sea state) and weather (e.g., wind speed, sun glare, cloud cover). Swimming depth also affects detection probability, with sharks in the top metre of the water column most likely to be observed, while the likelihood of detection decreases with increasing depth and water turbidity [81,82]. Sharks are more likely to be observed over light coloured sand than over reefs due to the higher contrast between the animal and the habitat. The integration of advanced camera technologies (e.g., multi- or hyperspectral sensors) may enhance shark detectability when ocean conditions are suboptimal [61]. Colefax, et al. [83] demonstrated that wavelengths in the band of 514–554 nm provide maximum contrast between submerged fauna and their surrounding environment when using a drone-based hyperspectral sensor. Nevertheless, these sensors can be expensive, and post-analysis of footage requires additional equipment, resources, and time; therefore, cost-effectiveness should be evaluated on a case-by-case basis [84].

While glare is less prominent during morning and afternoon flights, the effects can increase around midday, particularly under clearer skies and during elevated wind speeds, when wavelets are more prevalent [85,86]. However, midday flights with fewer clouds provide greater light availability, which may improve visibility within the water column [81]. In contrast, increased cloud cover can reduce sun glint and reflection off the ocean's surface but also decreases available natural light [87]. Applying a polarising filter may improve detectability by minimising the effects of glare, while the use of larger screens with attachable sun hoods may enhance visibility during real-time surveillance [88–91]. Furthermore, manual adjustments to camera angles can also help mitigate visibility challenges caused by glare or sea surface reflection [86]. Overall, real-time drone-based shark detection is most effective in shallow nearshore habitats (≤ 3.5 m in depth), particularly under relatively calm conditions (Beaufort sea state ≤ 4 ; wind speeds ≤ 12 knots), where water turbidity is low, and visibility extends to or near the seafloor [65,92,93]. As operational capabilities vary among drone platforms, it is important to remain within the limitations of each type of drone to ensure safe operations.

Challenges also remain in accurately identifying species and estimating shark size during drone surveillance. In addition to suboptimal environmental conditions, observing a shark at a distance or at an oblique angle can complicate identification [94]. Positioning the drone directly above the animal with the gimbal pointing downward can improve real-time species identification while also enabling the collection of high-quality data for post-flight analysis [95,96]. This provides a clear, direct view of the shark, allowing the pilot to observe key distinguishing features, such as snout and tail shape, body size, dorsal fin placement, and swimming style [97,98]. While specialised training can improve shark identification, distinguishing among some species (e.g., whaler sharks) by observation alone is difficult due to morphological similarities [99] and may result in accurate classification only to the genus level.

Shark length measurements are a key factor for real-time surveillance, as the presence of a shark ≥ 2 m in length is generally perceived as a higher risk, triggering further beach countermeasures (e.g., water evacuations; refs. [64,79,100]). Drone-based shark size estimation relies on several operational factors, including an accurate drone altitude above the water, field of view, animal depth, camera equipment, and image resolution [70,101,102]. In addition, sea surface distortion, water refraction, and poor water clarity can also complicate shark size estimates, as morphological features (e.g., snout, caudal fin) may not be fully visible, particularly at greater depths [102]. Accordingly, size estimations are more accurate when sharks are near the ocean's surface under calm conditions. While shark size estimations are significantly improved when drone altitude and the shark's swim depth are accounted for [101,102], accurately performing these assessments in real time is challenging. Size estimations are often based on visual assessment during real-time surveillance, and predetermined reference scales specific to the drone platform used can assist pilots in estimating shark size [67].

2.2. Community Opinion on Drone-Based Shark Surveillance

Public perception and community opinion strongly influence shark management policies. Beach user preferences for shark mitigation techniques were assessed through social media, information sessions, and online surveys [16,103–107]. Most participants approved the use of drones for shark monitoring in surf zones, highlighting their cost-effectiveness and minimal impact on marine life, while expressing optimism about future technological advancements [104,105]. Some respondents were concerned that shark-spotting drones may heighten awareness of sharks, potentially increasing fear among water users [106]. Current drone limitations, including flight time and restrictions due to unsuitable weather conditions, were also acknowledged [105,106]. Overall, there is a preference for minimally invasive shark mitigation, indicating strong support for drone surveillance, community education, and scientific research [16,103,107].

3. Drone-Based Shark Research: Implications for Beach Safety

Drones are increasingly used to study coastal sharks, primarily focusing on abundance and density estimates [88,108,109], behaviour [110,111], occurrence and distribution [112–114], feeding [115,116], and localised movement patterns [69].

Coastal aggregation sites provide opportunities to investigate shark presence and population dynamics [117,118], while analysing key spatial and temporal parameters can help identify areas where sharks are more likely to occur at the local beach scale [58,117]. Drones have also provided insights into the complex relationship between white sharks and humans, documenting daily co-occurrence [15] and revealing behavioural changes by sharks in response to humans, highlighting their cautious yet inquisitive nature [14]. This information offers beach authorities valuable insights into shark behaviour in nearshore environments, enabling effective management.

Localised shark tracks have also been documented using drones, revealing energy-conserving movements, with increases in swim speed and more sinuous patterns observed near food sources, such as fish schools, large marine mammals, or floating carcasses [70,119,120]. The presence of whale carcasses, which typically coincides with seasonal migrations and the natural mortality of some individuals [121], can attract larger shark species over long distances, causing temporary increases in shark activity and changes in behaviour [122–124]. Monitoring seasonal migrations and prey presence can improve predictions of shark occurrence, informing strategies to minimise human–shark interactions. Long-term shark monitoring is also recommended to capture species-specific intra-annual variability [117]; however, this requires a sustained campaign of drone operations.

Alternative approaches can complement drone monitoring programs by including data that cannot be collected by drones, such as during periods of adverse weather, in low-light conditions, or when sharks are deep in the water column [82,118]. Incorporating data collected using multiple methods (e.g., eDNA, electronic tagging, fishing methods, baited remote underwater video cameras [BRUVs]) can offer valuable insights into variation in shark presence across temporal and spatial scales [116,118,125].

4. Emerging Technologies and Future Directions

Despite the effectiveness of drone-based shark surveillance, the current generation of small quadcopters (<2 kg) commonly used have limitations in flight operations. Recent technological developments are, however, addressing these challenges and expanding their application.

4.1. Drone Advancements

Advancements in operating systems and battery development are extending flight duration, increasing spatial coverage, and permitting operations across a wider range of environmental conditions [63]. For example, small petrol-electric multirotor drones (Figure 2f; ref. [126]) and petrol-powered fixed-wing drones [127] can achieve flight times exceeding 90 min and 18 h, respectively, enabling more continuous monitoring.

Hybrid vertical take-off and landing (VTOL) drones improve operational flexibility and efficiency by combining vertical take-off and landing capabilities with horizontal flight [128]. These drones often use tilt mechanisms to facilitate the transition between multirotor and fixed-wing flight modes [129]. This transition is increasingly standardised as a third 'hybrid' mode, which reduces energy consumption and improves stability through advanced control systems [128,129]. Several models of VTOL drones (<25 kg) were trialled for their capacity to detect and identify sharks in a beyond-visual line of sight trial on the eastern Australian coast, demonstrating long-range capabilities that can support beach safety programs (Figure 2a–d; refs. [130,131]).

Remotely operated drone-in-a-box (DIAB) technology also has the potential to enhance shark surveillance programs and sustained research projects in localised areas. These drone and docking systems include landing platforms and self-charging stations that allow drones to land and recharge after a mission, enabling fully remote operations [132–134]. DIAB technology has proven successful for marine megafauna detection, performing autonomous, pre-programmed flight missions under the supervision of an off-site pilot [68]. These methods were particularly effective with the addition of post-flight analysis.

Despite their advantages, long-range, remotely operated drone technologies remain considerably more expensive than the drones currently used for shark surveillance. DIAB docking stations are also relatively heavy and require on-site installation, which presents logistical challenges during the initial setup phase. While technological advancements are expected to improve cost efficiency, operations beyond visual line of sight (BVLOS) require additional personnel, training, licensing, and regulatory approvals.



Figure 2. Examples of advanced drone systems with long-range capabilities that have been trialled for shark spotting (a) Elbit Systems of Australia, Skylark I-LEX drone, (b) Flight Technologies, DeltaQuad Pro VTOL fixed-wing drone (c) Swoop Aero Kite VTOL fixed-wing drone, (d) FreeSpace Operations, Calisto 50 heavy lift multirotor drone and (e) DJI Drone-in-a-Box technologies. (f) A Quaternium HYBRiX 2.0 hybrid petrol-electric drone, which has a long flight time (>90 min) for a multi-rotor drone and has been used for coral reef research (Image Credit: (a,b,d,e) Surf Life Saving NSW / Australian UAV Service, (c) K. Monteforte and (f) B. Kelaher).

4.2. Artificial Intelligence for Detection and Identification

Accurate identification of sharks poses a challenge for drone-based shark surveillance, particularly without specialised training or experience. While post-flight video analysis provides greater accuracy, surveillance programs often rely on drone pilots to identify sharks in real time, which can result in misclassifications and unnecessary safety measures for non-dangerous animals [91,94].

The use of artificial intelligence (AI) has the potential to increase efficiency in wildlife monitoring [135]. Several operational systems have successfully demonstrated the application of AI in shark detection. In Australia, the SharkSpotter system, integrated into Little Ripper Lifesaver drones (rippercorp.com), classifies objects from live video feeds, providing visual and audible alerts to pilots for verification. The system achieves 90% accuracy in shark detection, distinguishing sharks from 15 other classes, including marine life (e.g., dolphins, whales, rays), humans (e.g., swimmers, surfers), and human-related equipment (e.g., boats; ref. [136]). In California, SharkEye (sharkeye.org) uses machine learning models to analyse drone footage and automatically detect white sharks as part of a long-term shark monitoring program. Shark detections are subsequently reported to beach authorities and communicated to the wider community, while footage is used to study shark behaviour.

A separate project, also named Sharkeye, is an autonomous shark-alert platform that integrates live drone feed with cloud-based inference to provide real-time alerts to beachgoers via smart devices [137]. While Sharkeye achieved 91.7% accuracy in shark detection during trials, these results are based on a limited dataset, which may limit its utility across locations or environmental conditions [55]. In another study, two RetinaNet models with ResNet-50 and MobileNet V1 backbones were trialled for detecting and identifying potentially dangerous sharks in drone-collected video footage, achieving accuracies of 80% and 78%, respectively [138]. ResNet-50 is a deeper network that generally requires greater computational resources and has slower inference speeds [139]. In contrast, MobileNet networks are lightweight and specifically designed for devices with limited computational

resources; however, they generally achieve lower detection performance than ResNet-based models [140].

More recently, Frame-Level Alignment and Tracking (FLAIR) leveraged a zero-shot approach for shark detection, tracking, and biometric analysis using drone imagery, reducing human effort compared to traditional machine learning workflows [141]. This approach leveraged pre-trained foundation models (e.g., deep learning models trained on large-scale datasets), demonstrating potential for generalisation to other species without requiring labelled data, training a new model, or task-specific fine-tuning [142,143]; however, it may require higher-performance computational resources [141].

Overall, this review highlights the potential of AI-based image analysis for drone-based shark monitoring, while demonstrating performance differences across architectures. Standard real-time detection models typically require substantial computational resources, as well as large, high-quality training datasets across diverse marine habitats and environmental conditions to ensure reliable performance in real-world applications [137,144]. In addition, the use of AI-based detection software for shark surveillance may be constrained by limited onboard or local processing capacity, or a reliance on network connectivity for cloud-based analysis, which can affect scalability and real-time operational performance in coastal environments [137,138]. Challenges also remain when water turbidity is high or when animals are deeper in the water column [138,141]. Nevertheless, ongoing technological advancements are likely to improve performance and efficiency [145]. Incorporating AI as a support tool to assist shark-spotting pilots with real-time detection and species identification could enhance surveillance programs by enabling faster and more reliable decision-making in response to shark detections [136].

4.3. The Role of Collaboration, Crowdsourcing, and Social Media in Drone-Based Shark Research and Nearshore Monitoring

While drone use in shark science is rapidly expanding, collecting sufficient observations outside known aggregation sites remains challenging due to the high mobility and migratory behaviour of some shark species [3,146]. State-wide collaborations among scientists, governments, and organisations have facilitated the collection of data on sharks and other marine life across extensive regions [57,58,71]. These collaborative efforts provide valuable information for predicting species-specific shark distribution in nearshore areas, guiding risk assessments, and supporting the implementation of effective beach safety measures. Standardised monitoring programs are, however, relatively expensive to implement and maintain.

Increased drone use among the general population and the expansion of social media present new opportunities to incorporate footage collected by enthusiasts with data from established drone-based surveillance programs [14]. Crowdsourcing high-quality drone footage for scientific analysis enables research to be undertaken efficiently across large spatial scales, which may not be logistically or economically feasible otherwise [147,148]. The usefulness of opportunistic observational data depends on the specific objective, and post-flight analysis by researchers is recommended to ensure data quality.

The development of formal drone-based marine citizen science projects may also facilitate the collection of meaningful data for integration with long-term shark monitoring programs. These projects require experimental design (e.g., standardised sampling), clear guidance for participants on data collection, an online platform for data storage, and scientific supervision [148–150]. As drones record detailed georeferenced flight information along with high-quality imagery, the reliability and robustness of drone-based data can be superior to other types of data collected in citizen science projects. Ultimately, the success of these collaborations relies on strong scientific rigour, effective management, and active contributions from citizen scientists [147,149].

5. Civil Aviation and Drone Regulations

Drone-based shark surveillance programs require training, licensing, and permits before operations commence. Restrictions on drone operations are enforced by Civil Aviation Authorities (CAAs), although rules may also vary across administrative regions, such as countries, states, and local government areas [151]. Drone operations across most CAAs are typically limited to a maximum altitude of 400 ft above ground level and must remain within Visual Line of Sight (VLOS) to ensure the pilot can control and navigate the drone without additional visual aids [152–154]. As small multi-rotor consumer drones are generally capable of operating beyond 1 km from the ground control station, VLOS restrictions are often violated by remote pilots. Airspace restrictions are also implemented to ensure the safety of people and other aircraft, including no-fly zones near airports, helipads, and in populous areas.

In global shark-bite hotspots, height and distance restrictions often apply to drone-based monitoring, as drones flown at relatively low altitudes or close distances may disrupt the natural behaviour of certain marine animals (Table 1). Government-issued permits and authorisations are typically required to operate drones within marine parks and other marine protected areas. Similarly, scientific permits, licences, or both are needed to fly closer than the specified minimum distances to marine wildlife [155,156]. Consequently, drone-based shark surveillance programs require careful operational planning, particularly in nearshore areas heavily used by people or containing marine wildlife susceptible to drone disturbance.

Extended Visual Line of Sight (EVLOS) and Beyond Visual Line of Sight (BVLOS) flights are possible with additional training, licensing, personnel, and equipment, permitting drone-based shark surveillance over larger spatial areas. EVLOS operations require at least one observer to support the pilot during flight by maintaining direct sight of the drone throughout the mission and communicating information to the pilot to ensure safe operations [93,153]. BVLOS operations enable drones to be operated outside of the pilot's direct visual range; however, they are subject to strict regulatory requirements and additional risk assessments, which may vary depending on the region [152,153]. As regulations continue to evolve, understanding local laws prior to conducting any drone-based operations is essential.

Table 1. Examples of regional regulations for drone-based marine monitoring in public coastal waters or beaches in global unprovoked shark bite hotspots, including restrictions on wildlife monitoring and relevant governing bodies. Note: These restrictions are in addition to standard drone regulations enforced by regional aviation authorities, and additional permits (e.g., operating drones within marine parks and other marine protected areas) may be required prior to flight operations. If drone-specific laws are limited, general regulations protecting marine species are listed. * Information has been translated into English from non-English sources.

State/Region	Drone-Based Marine Monitoring Restrictions	Governing Body	Aviation Authority
USA			
Florida	No statewide drone-specific restrictions regarding use around marine fauna. Wildlife protections apply.	State of Florida Florida Fish and Wildlife Commission	
Hawaii	- Must not operate within 100 yards (91 m or 300 ft) of humpback whales.	State of Hawaii Department of Land and National Resources	Federal Aviation Administration (FAA)
California	- Must not fly lower than 100 ft over wildlife. - Must launch or land at least 100 yards (91 m) from wildlife.	State of California Department of Fish and Wildlife	- Max altitude: 400 ft - Remain in visual line of sight - Do not fly drone over people - Do not fly at night
South Carolina	No statewide drone-specific restrictions regarding use around marine fauna. Wildlife protections apply.	South Carolina Department of Natural Resources	- Must register drones >250 g
North Carolina	No statewide drone-specific restrictions regarding use around marine fauna. Wildlife protections apply.	North Carolina Department of Wildlife Resources Commission	

Please note additional U.S.-based entities with shared responsibility for the protection of marine mammals under the *Marine Mammal Protection Act of 1972*.

NOAA Fisheries — Responsible for the protection of whales, dolphins, porpoises, seals, and sea lions
U.S. Fish and Wildlife Service — Responsible for protection of walrus, manatees, sea otters, and polar bears

Key requirements include, but are not limited to:

- Prohibition of harming, disturbing, or harassing marine mammals, which includes causing disruption to behaviour.
- Avoid taking off, landing, hovering, or operating drones near marine mammals.
- Must not operate within 500 yards (457 m or 1500 ft) of North Atlantic right whales.

Table 1. Cont.

State/Region	Drone-Based Marine Monitoring Restrictions	Governing Body	Aviation Authority
Australia			
New South Wales	- Must not operate within 100 m of marine mammals.	NSW Government Environment and Heritage <i>Biodiversity Conservation Regulation 2017</i> under the <i>Biodiversity Conservation Act 2016</i>	Civil Aviation Safety Authority (CASA) - Max altitude: 400 ft - Remain in visual line of sight - Maintain 30 m distance from people - Do not fly at night or in low visibility - Must register drones used for business
Queensland		Queensland Government Environment, Land, and Water <i>Nature Conservation (Animals) Regulation 2020</i> under the <i>Nature Conservation Act 1992</i>	
Western Australia	- Must not operate within 60 m of marine mammals and whale sharks.	Government of Western Australia Department of Biodiversity, Conservation and Attractions <i>Biodiversity Conservation Regulations 2018</i> under the <i>Biodiversity Act 2016</i>	
South Australia	- Must not operate within 300 m of marine mammals.	Government of South Australia National Parks and Wildlife Service <i>National Parks and Wildlife (Protected Animals — Marine Mammals) Regulations 2025</i> under the <i>National Parks and Wildlife Act 1972</i>	
South Africa			
Countrywide	- Must not intentionally harass or pursue threatened or protected marine species, which includes most marine mammals and some sharks and rays. - Must maintain a distance of 300 m from any whale. No drone-specific restrictions regarding use around marine fauna. Wildlife protections apply.	Republic of South Africa Forestry, Fisheries, and the Environment <i>National Environmental Management: Biodiversity Act, 2004 (Act No. 10 of 2004)</i>	South African Civil Aviation Authority (SACAA) - Max altitude: 150 ft - Remain in visual line of sight - Maintain 50 m distance from people - Do not fly at night or in low visibility - Drones must be registered

Table 1. Cont.

State/Region	Drone-Based Marine Monitoring Restrictions	Governing Body	Aviation Authority
France			
Reunion Island	- Must not intentionally disturb, pursue, or harass marine mammals.* - Must maintain a distance of 100 m from marine mammals in marine protected areas.* No drone-specific restrictions regarding use around marine fauna. Wildlife protections apply.	The République Française Office français de la biodiversité <i>The French legal framework of cetacean protection: decree of October 20, 1970</i>	Direction générale de l'Aviation civile (DGAC) - Max altitude: 400 ft - Remain in visual line of sight - Do not fly over people - Do not fly at night - Drones must be registered
Brazil			
Pernambuco	- Must not intentionally harass or disturb any marine mammal.* No drone-specific restrictions regarding use around marine fauna. Wildlife protections apply.	República Federativa do Brasil Ministério do Meio Ambiente e Mudança do Clima <i>Brazilian Federal Law 7643/1987</i>	Agência Nacional de Aviação Civil (ANAC) - Max altitude: 400 ft - Remain in visual line of sight - Maintain 30 m distance from people - Must operate in clear conditions - Must register drones >250 g
The Bahamas			
Countrywide	- Do not harass or attempt to harass any marine mammal using an aircraft. No drone-specific restrictions regarding use around marine fauna. Wildlife protections apply.	The Government of the Bahamas Office of the Attorney General and Ministry of Legal Affairs <i>Marine Mammal Protection under the Marine Mammal Protection Act 2005</i>	Civil Aviation Authority Bahamas (CAAB) - Max altitude: 400 ft - Remain in visual line of sight - Maintain 50 m distance from people - Do not fly at night or in low visibility - Drones must be registered

6. Conclusions

Drones have emerged as a valuable, minimally invasive tool for real-time monitoring of shark presence in nearshore environments. Their effectiveness in enhancing beach safety relies on accurate risk assessment, rapid response times, and appropriate countermeasure implementation. Challenges remain for drone-based shark surveillance, including limited flight time, constraints due to poor weather or water conditions, and regulatory restrictions. Ongoing technological advancements (e.g., long-range capabilities, autonomous and remotely operated systems, and improvements in battery efficiency) are expanding the utility of drones for shark bite management programs. The integration of AI can further enhance real-time shark detection and species identification, thus strengthening decision-making for safety interventions. Multi-method approaches that combine drone surveying with SMART drumlines, tagged shark listening stations, and research can provide more comprehensive non-lethal risk mitigation. Additionally, the analysis of high-quality drone-collected data crowdsourced from researchers, enthusiasts, and social media can complement structured monitoring programs. These data sources may enable a deeper understanding of shark behaviour, spatial distribution, and nearshore movement patterns, which can inform management policies. As technologies advance and methodologies evolve, drone-based shark surveillance is expected to improve as a key tool for non-lethal shark bite mitigation, supporting adaptive and evidence-based beach management.

Author Contributions: Conceptualization, K.I.M., B.P.K. and P.A.B.; Methodology, K.I.M., B.P.K. and P.A.B.; Writing—Original Draft Preparation, K.I.M.; Writing—Review and Editing, K.I.M., B.P.K. and P.A.B.; Visualization, K.I.M.; Supervision, B.P.K. and P.A.B. All authors have read and agreed to the published version of the manuscript.

Funding: This project was made possible through the NSW Shark Management Program and Southern Cross University.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: We would like to thank the coastal managers and authorities, researchers, drone pilots, observers, volunteers, and all those involved whose contributions have made these shark research and management programs possible.

Conflicts of Interest: The authors declare no conflicts of interest.

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