Title

Taking the Bite out of the Bight: An Assessment of Non-Lethal Shark Bite Mitigation Strategies and Potential Applications in Southern California.

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An Assessment of Non-Lethal Shark Bite Mitigation Strategies and Potential Applications in Southern California

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Abstract

In recent decades, the incidence of shark encounters and bite incidents has been steadily increasing. This project seeks to address whether there are particular locations in California where the prevalence of shark bites has been higher or rising more rapidly, pinpointing the southern portion of the Southern California Bight (SCB) as a location where shark encounters and bites have been occurring with greater frequency in the two most recent decades. Notably, more incidents took place in this area from 2000-2019 than in the 'Red Triangle', a region in which approximately two-thirds of all California shark bites have historically occurred. In addressing the SCB, this project assesses available non-lethal shark bite mitigation tools, with the determination that none offer viable options for use in Southern California. Most of the current technological tools available come with high costs, low returns, and have not been extensively tested to determine their accuracy and effectiveness. This study recommends that continued effort be directed towards educating beach users to the risks inherent in ocean activities while providing practical suggestions for reducing the risk of shark bites.

Introduction/Background

Sharks and shark-related incidents did not always carry the same emotional undertones they do now. Prior to the 1900s, there was little consideration that sharks could pose a serious harm to humans. However, the early decades of the 20th century saw numerous shark bites and fatalities occurring in the United States and Australia. In July of 1916, a series of 5 shark bites (4 of which proved fatal) transpired within 12 days along the shores of New Jersey, making headlines throughout the country (Achen & Bartels, 2013). By the mid-1930s, the New South Wales (NSW) government in Australia had enacted a meshing program off their beaches in an attempt to increase bather safety (Francis, 2012). Notably, following the release of the movie "Jaws" in 1975, shark bite incidents began to draw significantly more media attention and sharks were cast in a more negative light (Neff, 2015). Perceptions of "rogue" sharks that had a taste for human flesh led to the notion that these particular individual sharks could be killed to protect bathers. And, as beach use continued to increase, more shark bites occurred. The implementation of lethal shark control methods by governments worldwide have persisted under the perception that such actions would reduce the risk of shark bites.

The methods used to cull sharks often involve the use of nets (unlike exclusion nets, which are used to keep sharks out of an area, these are similar to the gillnets used in fisheries, intended to entangle and kill animals) and drum lines (large, baited hooks tethered to buoys distributed offshore), which are intended to catch and kill potentially dangerous sharks (Meeuwig & Ferreira, 2014). The reality is that these devices ensnare, and often kill, far more bycatch species than the intended sharks. A government report on the 2017/2018 NSW shark meshing program noted that 92% of the animals ensnared in the nets were non-target species, and 70 of those animals (of which, 44 died) were threatened or protected species (Dalton & Peddemors, 2018). Similarly, the KwaZulu-Natal (KZN) region in South Africa has utilized shark nets since 1952 to reduce the risk of bite incidents. KZN began integrating drumlines in 2005 to reduce the high levels of bycatch involved with the shark nets, though drumlines still result in high mortality rates for non-target shark species caught (Dicken, Cliff, and Winker, 2016; Dudley, Haestier, Cox, and Murray, 1997). In addition to the bycatch involved, there is also little evidence that lethal methods reduce the frequency of shark bite incidents (Wetherbee, Lowe, and Crowe, 1994). Both the targeted killing of specific sharks and the broad-ranging culls of shark populations have diminished in public popularity, though they continue to be used in certain locations today, notably NSW and Queensland in Australia, KZN in South Africa, and Reunion island (Gibbs & Warren, 2015; Simmons & Mehmet, 2018). Meanwhile, other non-lethal methods focused on new and emerging technology have become available and have started to gain traction with the general public.

Seal and sea lion populations, which are a principal food source for adult white sharks, have strongly recovered in California after the Marine Mammal Protection Act passed in 1972 and provided federal protection (Laake et al., 2018). In 1994, white sharks were granted increased protections in California state waters resulting from stricter fishing regulations. Following these increases in prey availability and reductions in fishing pressure, the white shark population of California appears to have shown a strong recovery (Burgess et al., 2014). Coinciding with the increases in the white shark population and the number of people visiting the California coast, there has also been a steady increase in the number of shark bite incidents reported every decade since 1950 ("White Shark Information", 2019). During this period, Ferretti et al. (2015) found that the human population had more than tripled in coastal California communities, and that ocean activities had shown even more dramatic increases (a 125-fold increase in surfing and 204-fold increase in SCUBA diving). Coinciding with these and other factors, the researchers concluded that the relative risk of a shark bite for each individual California beach user has actually declined by over 91% over that time frame (Ferretti et al., 2015). However, social research has shown that successive shark bite incidents can increase intensity of media coverage and exaggerate public perceptions of risk (Sabatier & Huveneers, 2018). Thus, public fervor (and the corresponding political response) may be predicated on the absolute number of shark bite incidents, rather than their relative probability.

Considering that there could be an increase in the number of shark related incidents as beach use, prey availability, and shark populations all increase, and that increased numbers of shark bite incidents can result in heightened public perceptions of risk, it stands to reason that governments would develop proactive policy ideas for addressing coastal safety before such incidents occur. As stated by Neff (2015), "Following shark bites, there are often pressures placed on governments to act," and, given the considerations listed above, it is important to ensure that such government actions take into account the public and environmental concerns of lethal vs. non-lethal shark bite mitigation. As shark bite mitigation plans tend to be responsive rather than proactive, it can make it difficult to focus only on reasoned, scientifically backed management plans. The current literature contains some discussions of shark-safety policies, non-lethal technologies, and public and media perceptions, but has yet to pull this information together into a comprehensive data set and address the conditions of the California coastline and political atmosphere.

It is for this reason, that the goals of this project are to compile available information about newly developed coastal (non-lethal) shark monitoring technologies and shark bite mitigation tools and assess the feasibility of potential applications in California. In order to align with the changing public sentiment toward shark protection, to maintain conservation efforts for the oft misunderstood white shark, and to provide viable public safety options (should the need arise), this project aims to assess whether these potential methods are effective and if they should be utilized at California beaches.

Objectives

This project seeks to address three questions:

1) Are there specific regions within California where there is a higher prevalence of shark bite incidents?
2) What are the non-lethal methods currently available for reducing or preventing shark bite incidents, and how effective are they?
3) Do these methods pose viable options within California, particularly with regard to regions highlighted in addressing Question 1?

Description and Methods

In order to assess whether there are regions of higher shark bite prevalence in California, data were obtained from the Global Shark Attack File (GSAF) and analyzed using ESRI ArcGIS. Shark bite data have been limited to those events which were classified as 'unprovoked' and are confirmed shark-related incidents. For the purposes of this project "shark bite incident" or "shark attack" refers specifically to incidents in which a shark made contact with a person or the equipment they were using (a surfboard or dive fins, for example), and were organized as non-injury incidents (such as when a shark would bite a surfer's board or bump a diver), non-fatal injuries, and fatal injuries.

The data were sorted by decade to look at longer-term trends and were analyzed between 1950 and 2019. While the full dataset reached back to 1850, incidents further back in time were deemed less reliable in reporting and were excluded to ensure higher accuracy of the analysis. Within ESRI ArcGIS, kernel densities of shark bite incidents were generated for each decade to visualize locations of greater incident frequency, and each decade was formatted under the same classification scale to visualize trends in frequency across decades [Figure 1].

All recorded, unprovoked shark bites were also mapped together, to assess whether any regions in particular showed a high frequency of shark bites. The 'Red Triangle', a region encompassed by the Farallon Islands, Big Sur, and Bodega, has been cited as an area with particularly frequent shark bites, wherein 62% of all California shark bites have occurred (Curtis et al., 2012). By generating a polygon representative of the same geographic range as the Red Triangle, other locations in California were assessed for similar characteristics. The southern portion of the SCB displayed a similarly high frequency of shark bite incidents as the Red Triangle, with more bites occurring in the south SCB from 2000-2019 than in the Red Triangle during the same time period [Figure 2]. Based upon this information, the southern portion of the SCB is used as the region of interest for assessing applications of shark bite mitigation tools. While this study focused in Southern California specifically, the results are likely applicable to regions in the north as well. Considering that weather and oceanic conditions can be more severe in northern regions of California, it is unlikely that the methods posed herein would be more viable or effective under such circumstances.

In order to assess the different methods available for mitigation of shark bite incidents, current technological tools are broken down into subcategories of monitoring systems, which increase observational capabilities for locating sharks and potentially sounding alarms, and deterrent systems, which are intended to keep sharks from entering specific zones of human use. Deterrents are also assessed under different subcategories of those that are area-based (to deter sharks from entire regions) and for personal use (to keep sharks away from the individual user).

The description of each available tool (listed below) seeks to be comprehensive in reviewing the benefits and drawbacks of each. It incorporates (where available) some analysis of the associated costs for each system and aims to highlight additional external benefits that each system could afford. Data were collected through a review of publicly available literature, peer-reviewed studies, and interviews with targeted stakeholders (businesses, researchers, lifeguards, and policymakers). In order to compare financial differences, the approximate prices for each system are compiled in Tables 1-3 [See Figures and Tables]. Given that prices can vary depending on location, maintenance, installation, and other factors, the table incorporates approximate ranges for the different costs.

Results and Discussion

Monitoring systems:

Unlike deterrents and barriers, monitoring tools do not prevent the event of shark bites and encounters. Instead, they are intended to assist and improve the ability to monitor for potential hazards to provide for early warning systems. In theory, these systems can collect a variety of data which are beneficial for beach safety and increase our understanding of coastal regions. Monitoring systems are prone to two notable types of error: false negatives and false positives. False negatives are those situations in which sharks go unnoticed (due to weather conditions, technical accuracy, or otherwise), and could provide a false sense of security for beach users. False positives are those in which advisories or beach closures may occur when a non-shark object or animal is falsely identified as a shark. There is also a potential risk that using such systems to sound a warning system could induce panic and increase people's risk of injury.

Unmanned Aerial Vehicles (UAVs)

Aerial surveillance is a widely used method for monitoring sharks along coastal regions, primarily through the use of helicopters or spotter planes. The use of aircraft is cost-limited, with surveillance flights costing hundreds to thousands of dollars per hour (Leadbitter, 2017). The advent of affordable UAV technology, however, has opened up a new potential option for coastal shark surveillance. This technology has many applications and various operators from commercial to academic are utilizing it. For the purposes of shark surveillance, artificial intelligence (AI) software has been developed to allow for machine learning algorithms to locate and identify various species of sharks and other marine species in the water. Drones can also be modified to carry a small cargo, in the form of a flotation buoy or shark deterrent, which can be deployed in the case of a bite incident or other aquatic emergency. In January 2018, for example, the Little Ripper Lifesaver UAV was credited as the first drone used in a surf rescue after one was used in to locate two swimmers in distress and deploy a flotation device. The swimmers were able to hold onto the float and kick back to shore with no serious injuries (Beaini, 2018).

Recent research has shown that the ability for AI-augmented UAVs to correctly identify sharks in the water is significantly greater than that for human observers (Bryson & Williams, 2015; Gururatsakul, Gibbins, and Kearney, 2011). In addition to being able to identify species, the software also allows for quicker analysis of size, behavior, and proximity to people than could accurately be performed by human spotters from aircraft or from a lifeguard tower.

UAVs also present significant limitations that could hinder or prevent their use under certain circumstances. Adverse weather conditions (primarily those involving high winds above 25 miles per hour or rain) would make the use of UAVs impractical or improbable. While fewer people are likely to attend the beach during such conditions, there are presumably individuals who would still enter the water, particularly during periods of high surf. UAVs are limited by what remains a relatively short battery life: up to 30 minutes for off-the-shelf drones, and approximately an hour or longer for UAVs such as those being utilized by law enforcement and fire-rescue teams ("Impossible US-1", 2019). Thus, a system utilizing drones would likely require users to rotate spare batteries and/or additional UAVs to provide continuous monitoring. As technology continues to improve battery life, this limitation will be reduced, but will likely continue to remain a factor. These systems are also limited in their spatial presence and can only monitor for shark presence within their field of view; thus incidents could still occur at stretches of beach where visual surveillance is not occurring. Given that most drones are permitted to fly up to 400 feet in altitude, a UAV camera with focal length of 3.61mm and a 6.16mm x 4.62mm sensor (as in the DJI Phantom 3 Pro) would have a field of view that covers approximately 680 ft x 510 ft. More UAVs could be utilized to improve coverage but could create an increased possibility of nuisance to beach users and may potentially impact wildlife. UAVs are also limited by certain airspace regulations and restrictions, preventing or reducing their use in areas near airports and military bases without proper authorization, though permits are available for use in public safety operations (such as for lifeguards).

In California, multiple lifeguard agencies initially invested in drones to improve their aerial surveillance, though such use has since declined. In 2015, Seal Beach was the first agency in Southern California to begin using a drone for the purpose of shark surveillance. However, the lifeguard chief stated that such use has since been discontinued, as water turbidity and glare have made it difficult to spot sharks, the relative rarity of seeing sharks has made drone flights impractical for regular surveillance, and the lifeguards felt that it would give the public a false sense of security. Some locations, such as Newport beach, still occasionally deploy drones to monitor when shark sightings are reported, though the acting lifeguard chief has noted that helicopter monitoring "is more efficient" (Sclafani, 2018). While the incorporation of AI-augmented drones could help in this regard, cost still remains a significant limiting factor, with some lifeguard agencies stating that they would prefer money be spent on increased manpower.

Surveillance Balloons

Similar to the concept behind the use of UAVs for more affordable aerial surveillance, the use of durable weather balloons for shark surveillance has begun making its way to market. While drones and aircraft are limited in flight time by such factors as battery life and fuel, balloons reduce the impacts of such limitations. They provide the opportunity for a longer-duration aerial platform upon which to mount high resolution cameras. Machine learning software can be used in a similar capacity as with drones to improve identification accuracy. The ability of a balloon to maintain a constant altitude also improves the accuracy in measuring the dimensions of animals spotted (Bryson & Williams, 2015).

The main benefit of balloons also presents one of their most significant drawbacks: the inability to move. Sharks are highly mobile animals, capable of covering many miles every day. While balloons can maintain visual coverage of specific areas for the presence of sharks, they are unable to follow individuals to monitor their behavior. Similar to UAVs, they are also inhibited by severe weather conditions and high winds.

Sonar Buoys

Sonar-based systems, such as the Clever Buoy produced by Smart Marine Systems (SMS), provide the opportunity to maintain continuous monitoring of a select region of coastline. A stationary sonar platform is able to monitor for the presence of large and potentially hazardous wildlife and transmits that information in real time to human observers on shore. In essence, the system is able to create a 'virtual net' for monitoring a range of coastline and provide alerts. The machine learning algorithms in the software are continually being trained in the movement patterns of different marine species to identify target animals (SMS, 2017).

Due to the platform's stationary nature, it affords the advantage of monitoring continuously without the need to recharge batteries or refuel. The durability of the system also hypothetically allows for continued surveillance in rougher weather conditions and in surf areas. Additionally, due to the ability to incorporate additional oceanographic sensors and acoustic receivers, the system is capable of collecting an array of scientific data for further use.

Unlike the currently used tagging methods, sonar buoys also offer a noninvasive option for monitoring sharks (or other species). While the Clever Buoy system claims that it can be equipped with acoustic receivers to monitor for tagged animals, the sonar technology can also hypothetically monitor within its range for animals which have not been tagged (SMS, 2017). Another advantage offered by such a system is the ability to report in real time, as may not often be the case with monitoring of tagged animals.

Sonar detectors locate objects underwater due to the different sound refractions from objects of different densities. Given that the bodies of fish are primarily composed of water, the most refractive parts of their bodies are their bones and air-filled swim bladders (Steele, Thorpe, and Turekian, 2009). Sharks, however, are cartilaginous fishes without solid bones, and have large oily livers to maintain buoyancy, rather than air bladders. Thus, they don't contain body parts which tend to be highly recognizable to sonar monitoring, a complication which makes their identification by such a system far more difficult. A representative from Tritech, the company which manufactures the sonar hardware and software implemented in the Clever Buoy system, acknowledged that the accuracy of sonar in detecting sharks faces many limitations, particularly resulting from variability in weather or tidal conditions.

Each individual buoy costs approximately half a million dollars. This is approximately 2% of the annual budget for San Diego Lifeguards (approximately $23 million), and 15% of the combined salaries for all 42 Newport Beach lifeguards ("Fiscal Year 2019", 2018; Kiff & Matusiewicz, 2018). There is also an option to lease the buoys, which can cost roughly $50,000 to $70,000 USD per month per buoy, in addition to installation fees.

The Clever Buoy sonar system was trialed in Hawks Nest Beach off Port Stephens, NSW in 2016 and City Beach in Perth, Western Australia (WA) in 2017. Reports from both tests noted that false positives could have influenced the results, due to the inability to independently verify reports of shark detections (Gladstone, 2017; Shark Response Unit, 2017). Following the WA test, the report noted multiple outages in the Clever Buoy system throughout the trial period, and Surf Life Saving Western Australia was cited as stating that the system “requires further validation” and “was not prepared for rollout in an operational environment (Shark Response Unit, 2017).”

The system was also trialed in Newport Beach, California between October 2018 and January 2019, though the mayor of Newport Beach noted that the trial “did not produce conclusive results during the trial period.” While a representative from SMS stated that the system had detected 60 sharks during the Newport Beach trial, acting lifeguard chief Mike Halphide had noted that none of the detections were able to be confirmed (Fitzgerald, 2019). While the technology may provide better results with continued testing and improvement, current research has not yet shown whether such a system is actually effective in detecting sharks.

Others

One of the most prolific tools used presently for monitoring shark populations has been the use of tags to track shark movements and behaviors. There are numerous types of tags available for studying different characteristics. There are limitations to their use as a shark surveillance tool. Untagged sharks are essentially “unseen”, necessitating large scale investments in tags and human effort to tag as many sharks as possible for these purposes. While there are newer receiver buoys available now that are capable of transmitting in real time, tag data must be downloaded from older receiver buoys or when satellite transmissions occur. Prices are different depending upon the type of tag, though almost all cost thousands of dollars for each individual tag.

Smartphone apps have been another new tool for providing notifications and alerts to beach users, based upon sightings and surveillance. Such tools do not provide monitoring themselves but afford the opportunity to compile available sightings and surveillance data (through tags or otherwise) for informing beachgoers of high-risk conditions or beach closures. There is, at present, no research to show whether such tools have any effect in reducing shark incidents, but multiple apps have been developed for use in locations around the world, such as the Sharktivity app for use in Cape Cod and the SharkSmart apps in NSW and WA.

Environmental DNA (eDNA), has also been cited as a potential future tool for surveillance and monitoring of shark populations (Lafferty et al., 2018). By sampling ocean water, eDNA monitoring tools could hypothetically be used to alert beaches to the presence of nearby sharks, though such a use is still only a theoretical prospect, if possible.

While not a new technology, the incorporation of a human spotter program has also been used with success in South Africa as a non-lethal shark safety method. In most other locations, such a task generally falls upon lifeguards. Through the incorporation of dedicated shark spotters, this option could potentially be more effective considering lifeguards have numerous other tasks beyond monitoring for sharks. However, unless volunteer-based, such a program would require the money and manpower to employ multiple people. Considering that far more people die from drownings than shark bites, such investment would likely prove more practical in employing additional lifeguards rather than dedicated shark spotters.

Deterrent Systems:

These are broken down into 2 subsections: area-based deterrent systems designed to protect particular regions of coastline, and personal deterrent systems that can be used by individuals to reduce their own risk.

Area-Based

Barriers and Exclusion Nets

In an effort to exclude sharks from a beach region, without the negative effects of bycatch and high mortality that are common with shark nets, multiple companies have developed different forms of exclusion barriers for beach deployment. While each has its own unique features, they tend to share the same general characteristics. Often formed from nylon, the ropes and frames are intended to be durable enough to prevent the ingress of large predators but have holes to allow for the movement of water and passage of smaller fish. Unlike gillnets, the holes are intended to be small enough that animals do not become ensnared. There has also been evidence to show they may function similar to fish aggregating devices (FADs), which could be an added benefit for snorkelers and divers (though this also poses the reality that sharks could be attracted as well) ("Review of the Dunsborough Beach Enclosure Trial", 2014).

While such tools have been used with some success in places like Hong Kong and South Africa, their use can be strongly location dependent. Following a series of six fatal shark incidents in Hong Kong from 1991 to 1995, exclusion nets were deployed at 38 of the 41 government-run beaches with no shark bites having been reported since 1995 (though it is worth noting that no shark bites have occurred at non-netted beaches in Hong Kong either) (RMIT ABC Fact Check, 2013). Though there are often claims that such barriers are durable enough to withstand harsh conditions, there have been incidents in which strong wave action and rough weather have resulted in the destruction of barriers. In such instances, the barriers have become marine debris which can ensnare wildlife or impact coral reefs and sensitive marine habitats. While the full extent and economic impacts were not made public, such incidents have occurred at both Lighthouse Beach and Seven Mile Beach in Australia ("Ballina's Shark Problem", 2016; van Kempen, 2016).

Barriers and exclusion nets can often cost hundreds of thousands of dollars to deploy, with tens of thousands of dollars annually in maintenance costs. While these methods could be more effective in smaller, sheltered beach regions, they would likely cost millions of dollars annually to protect large stretches of coastline.

SharkSafe Barrier

The SharkSafe Barrier is a system designed to incorporate both visual and magnetic deterrent properties. Visually, the system is designed to look like a kelp forest. This notion was founded on the premise that white sharks tend to avoid entering kelp forests when hunting for pinnipeds and would thus be deterred from passing through a barrier that looks like a kelp forest (O'Connell et al., 2014; O'Connell et al., 2017). However, it is important to note that a recent observation demonstrated a white shark entering a kelp forest off South Africa, seemingly hunting for seals (Jewell et al., 2019). While this has only been the first observation of this behavior, it is important to note that further studies may be necessary to determine whether the visual stimuli of kelp forests actually pose a deterrent to sharks.

However, the SharkSafe Barrier also incorporates a secondary deterrent component, with magnets embedded within the imitation kelp. While studies have been mixed on the efficacy of magnets in deterring sharks, there have been multiple published reports demonstrating the apparent effectiveness of the SharkSafe design.

As with other barriers, there remains a risk that severe conditions could damage the barrier, generating marine debris. Further studies may also be needed to determine if the SharkSafe design has any unintended impacts on coastal ecosystems and other marine species. A company representative stated that the system would cost $35 per square meter, "calculated on 20 hectares of surfable water," (thus, approximately $7 million for 0.2 square kilometers).

Others

There have also been other systems in design and trial for deterring sharks from beaches. In order to address the shark concerns in the KwaZulu-Natal province of South Africa, the KwaZulu-Natal Sharks Board (KZNSB) has developed a system that involves suspended cables, extending from electrical conduits on the ocean floor, which can be arranged in a line parallel to the beach, akin to a simulated kelp forest. The cables emit an electrical field to deter sharks from passing the barrier, while theoretically posing no obstruction to other marine life. There remains little available information while it is still in trial, though it is likely that such a system will require substantial costs for installation and maintenance.

Shark Management Alert in Real Time (SMART) drumlines have also begun use in certain regions as an "environmentally-friendly" alternative to standard drumlines. SMART drumlines send alerts in real time when an animal is hooked, so that it can be attended to as soon as possible. If the animal hooked is a target shark then it can be tagged and relocated further offshore, while non-target species can be released without further effort. Though this method has been able to reduce mortality among target sharks and bycaught species, it has still resulted in some deaths and should not be considered a non-lethal tool. As with standard drumlines, SMART drumlines do not prevent shark bites from occurring, and come with high costs for regular maintenance.

Barrier systems, as a whole, appear largely impractical for use in California. The largest proportion of shark bites involve board users (surfers and body boarders) and given that barriers and exclusion nets are largely ineffective in surf zones, the high cost for exclusion systems appears unrealistic for use in Southern California.

Personal

The use of personal deterrent devices has also been assessed as an alternative to the use of larger-scale area-based measures. For regions in which other shark surveillance or bite mitigation measures are not feasible, personal deterrents could be incorporated into alternative plans. In 2017, for example, the government of WA began offering subsidies for individuals to purchase independently verified shark deterrent devices as part of its shark hazard mitigation plan ("Surf's up", 2019). This program has since subsidized the sale of approximately 3,400 deterrent devices.

Electronic

When it comes to personal deterrent devices, electrical deterrents currently present as the most viable tool. By running an electrical current from a battery through two electrodes, these devices seek to deter sharks by overwhelming their electrosensory organs, the Ampullae of Lorenzini. While different companies have developed their own methods and patents for the exact methodology, independent testing by Huveneers et al. (2018) has only been able to verify the Shark Shield technology employed in Ocean Guardian devices to have a significant effect on reducing shark interactions. That test showed the Shark Shield technology was able to reduce shark interactions with bait from 96% to 40%. The authors also noted that the effective deterrent range was highly influenced by the distance between the bait and the deterrent electrodes, observing that the Ocean Guardian Surf+ was likely more effective in deterring sharks than the Ocean Guardian Freedom 7, despite the fact that both devices employ the same Shark Shield Technology. The same study also tested the RPELA, another electrical deterrent device, and found that it had minimal effect on shark behavior (Huveneers et al., 2018).

Magnetic

Devices incorporating magnets are among the most commonly sold due to their low cost and ease of use. Based upon the idea that magnets can generate an electromagnetic field of their own and thus deter sharks, these devices don't require batteries or complex technology. The research regarding the deterrent effects of magnets on sharks has been mixed, with some evidence that they work and other evidence that they don't work (Godin, Wimmer, Wang, and Worm, 2013; Hart & Collin, 2014; O'Connell, Stroud, and He, 2014; Porsmoguer et al., 2015). In the independent test by Huveneers et al. (2018), the magnet based SharkBanz deterrent was not found to have a measurable deterrent effect on the sharks studied.

Semiochemical

Semiochemicals, which are sometimes also called necrimones, are pheromone-like chemicals which are emitted by some animals when they die to deter conspecifics from the area. Some sharks have appeared to show similar behavior, thus leading to the use of semiochemicals as a potential deterrent tool. Research has shown that semiochemicals may be effective in deterring sharks (O'Connell et al., 2014; Stroud et al., 2014), but their practical applications still appear limited. Currently, semiochemicals are available in single-use cans, so that they can be sprayed into the water to deter an oncoming shark. However, the likelihood of seeing a shark and deploying the chemical before being bitten are slim, considering that many shark bites occur without warning.

Visual

Another method that is currently being tested to reduce the incidence of shark bites involves the use of stripes and visual patterns on wetsuits and surfboards. Some are based upon a hypothesis that sharks may avoid venomous sea snakes based upon their black and white striped patterning, while others suggest that high contrast striping can help break up a person's outline so that they no longer resemble a prey animal. Neither premise has yet been scientifically verified, and there is currently little to no evidence to show that such a method will be effective in deterring sharks.

While personal deterrents could hypothetically provide an alternative for individuals seeking increased safety, most appear either impractical or ineffective. Even though the electrical Shark Shield device was shown to have some effect in reducing shark interactions, it was not shown to be 100% effective and could result in higher risk-taking from users. One study noted that: "Ocean users should be very critical of shark deterrent claims, as the use of untested devices may actually put lives at risk by giving users a false sense of security" (Egeberg et al., 2019).

Conclusion and Recommendations

Currently, there appear to be minimal viable options for increased shark surveillance and bite mitigation programs in Southern California. Surveillance tools remain susceptible to errors in accurate shark detection and may prove burdensome for lifeguards to operate in addition to other daily duties. Barriers are largely ineffective in surf zones, for which the beaches of Southern California are largely known and where the majority of shark-related incidents occur. Many personal deterrents on the market still require independent verification, and those which have been shown to have a deterrent effect still do not provide guaranteed protection, which could potentially give users a false sense of security and result in further risk-taking behavior. Considering the input from government representatives, lifeguards, and researchers, the high costs and low returns do not yet appear worth the investment in California.

This study recommends that further research be undertaken to determine the specific economic impact of shark-related incidents to coastal California communities. Shark bites may result in economic losses to local businesses when tourists leave the area due to beach closures and advisories. There have been few, if any, published studies assessing the economic impacts of shark bites and shark-related beach closures. An economic review would quantify the monetary loss into a specific dollar amount from shark-related incidents. Identifying these costs could help determine optimal budgets for investing in appropriate and effective shark bite mitigation methods.

While the current technological tools may not provide viable options now, it is possible that continued advances in technology will result in improvements and greater effectiveness from shark bite mitigation and surveillance tools. However, there is also the continued risk that ineffective alternatives are presented as viable options to beach communities seeking solutions. This study recommends that policy makers ensure shark surveillance and safety measures undergo rigorous and verifiable independent testing to ensure their effectiveness prior to implementation.

Lastly, this study recommends that coastal communities place an emphasis upon educating beachgoers to the risks inherent in ocean activities and the steps that can be taken to minimize said risks. In areas or times of higher shark activity, it may be pertinent to use signage or other methods to alert beach users to heightened risk. Through the use of educational and outreach methods, researchers can communicate effective methods for reducing risk of shark bites, similar to the method set to begin in the summer of 2019 by the California State University, Long Beach Shark Lab ("Shark Shacks", 2019). While shark bites have been gradually increasing, it is important to reassure the public that the risk to individual beach users has not, and current technological options do not pose viable options to prevent that risk.

Figures and Tables

Figure 1:

Decadal maps of shark bite trends throughout California, from 1950 to 2019. Populations of coastal counties are included as a rough proxy to estimate beach attendance.

Legend

Coastal County Populations

- 0 - 25,000
- 25,001 - 50,000
- 50,001 - 100,000
- 100,001 - 200,000
- 200,001 - 400,000
- 400,001 - 800,000
- 800,001 - 1,600,000
- 1,600,001 - 3,200,000
- 3,200,001 - 6,400,000
- 6,400,001 - 12,800,000

Density of Shark Incidents

- 0 - 1
- 1.000000001 - 2
- 2.000000001 - 3
- 3.000000001 - 4
- 4.000000001 - 5
- 5.000000001 - 6
- 6.000000001 - 7
- 7.000000001 - 8
- 8.000000001 - 9
- 9.000000001 - 10
- 10.00000001 - 11
- 11.00000001 - 12
- 12.00000001 - 13
- 13.00000001 - 14

Shark Incidents

! Non-Fatal

! Fatal

Figure 2:

The spatial dimensions of the "Red Triangle" are utilized to determine another potential emerging "hotspot" region in Southern California. Contained within a polygon of the same dimensions, the new region of interest in the southern SCB encompasses 54 total shark bite incidents, 34 of which have occurred since the year 2000. The "Red Triangle" region encompasses 84 total shark bite incidents, 29 of which have taken place since 2000.

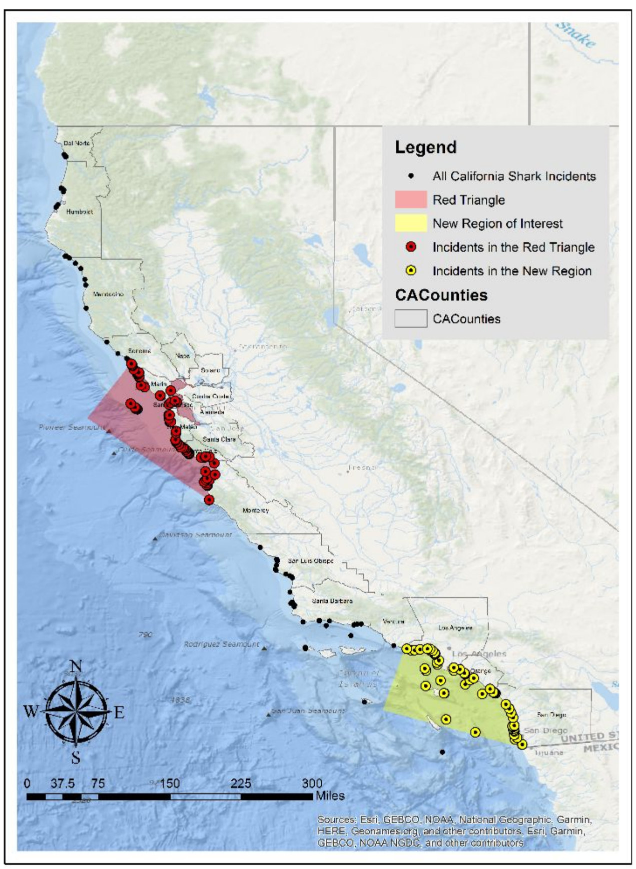

Table 1: Approximate costs for surveillance tools

Tool	Estimated Costs (in USD)
Drone	$250 - $250,000
Clever Buoy	$350,000 - 500,000 per buoy (Purchase)
	$10,000 - $20,000 per buoy per month (Lease)
Altametry Balloon	$3,000 - $20,000 per balloon
Tags	$2,000 - $9,000 per tag
Receiver Buoys	$50,000 - $70,000 per year
Helicopter/Spotter Plane	$200 - $4,000 per hour

Table 2: Approximate costs for barriers and area-based deterrents

Tool	Estimated Costs (in USD)
SharkSafe	$35 per square meter
SMART Drumlines	$6,000 per day
Eco Shark Barrier	$100,000 - $1 million*
Global Marine Enclosures	$100,000 - $1 million*
KZNSB Shark Cable System	Unknown**

* Prices for these methods are largely unknown. Ranges are speculative based upon prices made publicly available for prior installations.
**Product is still under trial and has no current price established.

Table 3: Approximate costs for personal deterrents

Tool	Type	Estimated Costs (in USD)
Ocean Guardian Shark Shield	Electrical	$499 - $599
RPELA	Electrical	$345
SharkBanz	Magnetic	$84
Radiator Wetsuits	Visual	$345
Radiator Surfboard Sticker	Visual	$70
SharkTec Spray	Semiochemical	$90
Chillax Surf Wax	Olfactory	$25

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