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SHORT COMMUNICATION

Testing the exclusion capabilities and durability of the Sharksafe Barrier to determine its viability as an eco-friendly alternative to current shark culling methodologies

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Abstract

1. Following a shark attack, local governments often rapidly respond by implementing indiscriminate shark culls. These culls have been demonstrated to have substantial localized and adverse effects on a variety of marine organisms, and therefore there is an increasing need for an eco-friendly alternative that maximizes both beachgoer and marine organismal safety.
2. In response to such culls, the novel magnetic barrier technology, the Sharksafe Barrier was developed and rigorously tested on a variety of sharks implicated in shark attacks (e.g. bull sharks – *Carcharhinus leucas* and white sharks – *Carcharodon carcharias*). Although these studies exhibited promise in shark swim pattern manipulation and *C. leucas* exclusion, research was lacking in assessing if the technology could serve as an alternative to shark nets, or more specifically, if it could exclude motivated *C. carcharias* from bait.
3. Using a 13 m × 13 m square exclusion zone, this study aimed to test the *C. carcharias* exclusion capabilities of the Sharksafe Barrier while additionally assessing the long-term structural integrity of the system.
4. After 34 trials and approximately 255 hours of total video collected over two years, data illustrate that all interacting *C. carcharias* were successfully excluded from the baited Sharksafe Barrier region, whereas teleosts and other small elasmobranch species were not. In addition, the long-term deployment potential of this barrier system held promise owing to its ability to withstand harsh environmental conditions.
5. Therefore, with the successful exclusion of a second large shark species, *C. carcharias*, from a baited region, continued long-term research and implementation of this system at other locations should be considered to assess its viability and overall success as a bather and shark protection system.

KEYWORDS

beach, behaviour, coastal, engineering, fish, protected species

1 | INTRODUCTION

After a shark attack, there is often an immediate governmental response in an attempt to prevent future incidents (Government of Western Australia, 2014; Neff, 2012; NSW Department of Primary Industries, 2017). Occasionally, these responses lead to the implementation of indiscriminant shark culls, through the use of drum lines and/or shark nets, that have been demonstrated to have substantial localized and adverse effects on a variety of large marine animals, including elasmobranchs (Dudley, 1997; Dudley & Cliff, 1993; Government of Western Australia, 2014; Neff, 2012). Such activities often correlate negatively with conservation objectives since the loss of top-order predators may compromise marine ecosystem functioning (Burkholder, Heithaus, Fourqurean, Wirsing & Dill, 2013; Ferretti, Worm, Britten, Heithaus & Lotze, 2010; Ruppert, Travers, Smith, Fortin & Meekan, 2013). Owing to potential negative implications of losing these top-order marine predators from an ecosystem (Ferretti et al., 2010), efforts to implement ecologically responsible techniques to minimize shark encounters are currently being trialled and/or implemented. These include exclusion nets (McPhee, 2012; Nel & Peschak, 2006), shark spotters (Kock et al., 2012), and electrical devices (Huveneers et al., 2012; Smith, 1973). Unfortunately eco-friendly technologies are often associated with deployment limitations, including biological (e.g. aquatic plant and other marine debris entering exclusion nets; Nel & Peschak, 2006), environmental (e.g. wave action, water visibility, or glare; Von Blerk, 2015), or geographic (e.g. requiring an elevated spotting platform to extend spotting capabilities; McPhee & Blount, 2015) features, which make deployment at regions currently associated with shark nets and culls difficult. In an attempt to address this, and specifically with the increasing need to implement an eco-friendly alternative that can withstand a high-energy coastline, the current study intertwined two unique concepts. The first stems from observations demonstrating that large white sharks (*Carcharhinus carcharias*) rarely enter a high density kelp forest (i.e. one stalk per metre; O'Connell, Andreotti, Rutzen, Meÿer & Matthee, Submitted). The second is based on the scientific evidence that magnets can manipulate the swimming behaviour of *C. carcharias* (O'Connell, Andreotti, Rutzen, Meÿer & He, 2012). The combination of the above concepts resulted in a study to examine the effects of the novel conservation engineering technology, the Sharksafe Barrier, on *C. carcharias* behaviour (O'Connell, Andreotti et al., 2014). With continuous chumming through 8 m magnetic and non-magnetic sections, the Sharksafe Barrier demonstrated the ability to significantly manipulate the swimming patterns of 63 different *C. carcharias* (O'Connell, Andreotti et al., 2014). However, although the barrier exhibited promise, it was uncertain if the technology could be a suitable and eco-friendly alternative to shark nets since the *C. carcharias* exclusion capabilities of the technology are unknown. Therefore, with the use of baited remote underwater video systems (BRUVS) – a technology that has successfully demonstrated the ability to attract *C. carcharias* in Australian waters (Harasti, Lee, Laird, Bradford & Bruce, 2016) and to both attract *C. carcharias* and elicit continuous bite responses at a location directly adjacent to the present study site (O'Connell et al., Submitted). This study had three key objectives: (1) to determine if the Sharksafe Barrier can exclude motivated *C. carcharias* from bait; (2) to determine if the barrier exhibits exclusion properties on other elasmobranchs species and/or teleosts; and (3) to assess the long-term structural integrity of the barrier. First, similar to O'Connell et al. (2012) and O′Connell, Andreotti et al. (2014), it was hypothesized that both the control (i.e. regions containing artificial kelp) and magnetic (i.e. regions containing both artificial kelp and magnets) regions will manipulate the swimming patterns and exclude all interacting *C. carcharias* from the bait. Secondly, as seen in previous magnetic repellent studies (O'Connell & He, 2014; Stoner & Kaimmer, 2008), it is hypothesized that since many other marine organisms lack the ampullary organ, the Sharksafe Barrier technology will deter only elasmobranchs and will have no observed effect on teleosts swimming behaviour. Lastly, due to the structural engineering of each barrier unit and novel anchoring system, it was hypothesized that the entire barrier would remain intact throughout the 10-month observation period.

2 | METHODS

Trials were conducted from May–August 2015–2016. Initially, a 169 m^2 Sharksafe exclusion zone was deployed and over the course of 59 at-sea days, the exclusion capabilities of the system was tested on interacting *C. carcharias* and other marine organisms within the Dyer Island Nature Reserve (Kleinbaai, Gansbaai, South Africa; 34°41′S; 19°25′E; Figure 1). The barrier base was composed of two alternating rows of 0.75 m (diameter) × 0.16 m (height) concrete anchors to create a 13 m × 13 m square formation. To facilitate barrier element attachment and reduce chafing, each anchor was equipped with a loop constructed of a 0.019 m diameter polyethylene rope covered with a PVC-reinforced rubber hosing sheath. Once in place, the entire barrier base was inter-connected using polyethelene rope to prevent barrier base repositioning due to heavy sea conditions and/or strong currents. Once secured, divers attached each barrier element to create two equisized (26 m total length) experimental sections: control (i.e. two rows of barrier elements) and magnetic (i.e. outer row contains magnet-integrated barrier elements and inner row contains non-magnetic barrier elements); with each section representing one half of the experimental square (Figure 2). Each barrier element consisted of 0.09 m (diameter) by 9 m (length) black high density polyethylene (HDPE) piping, that was used to mimic the visual appearance of sea bamboo (*Ecklonia maxima*), the kelp species that predominates the marine ecosystems around the Dyer Island Nature Reserve. Each barrier element was internally fitted with a predetermined quantity of buoyancy bottles to ensure appropriate buoyancy (i.e. each barrier element remained perpendicular to the seafloor and extended from the seafloor to the sea surface). Furthermore, each barrier element was cut into two segments (i.e. upper segment = 8 m, lower segment = 1 m) and interconnected with a high strength polyethylene rope containing a PVC-reinforced rubber hosing sheath to create a displacement joint. These joints aided in current and wave energy displacement to maximize the structural integrity of the barrier and to ensure the barrier elements remained upright throughout deployment. For the magnetic treatment barrier section, the outer rows consisted of magnetic piping. The magnetic pipes were of identical construction to the control pipes; however, custom-sized barium-ferrite ($BaFe_{12}O_{19}$) permanent magnets were placed at 1 m intervals within the pipe to create a vertical and continuous magnetic field that extended from just above the barrier base to the sea surface (Figure 2). In addition, owing to the ~1 m barrier element spacing, the magnetic fields (i.e. ~30–50 cm) between adjacent pipes overlapped creating a continuous magnetic field region on the horizontal scale. Unlike previous experiments where multiple replicates of each section were deployed (O'Connell, Andreotti et al., 2014) and a completely randomized experimental design was implemented (Hulbert, 1984) or the placement of the experimental barrier units was changed during experimentation (O'Connell, Hyun, Rillahan & He, 2014), researchers were limited by permit regulations and therefore, utilized the same experimental setup throughout the experimental period.

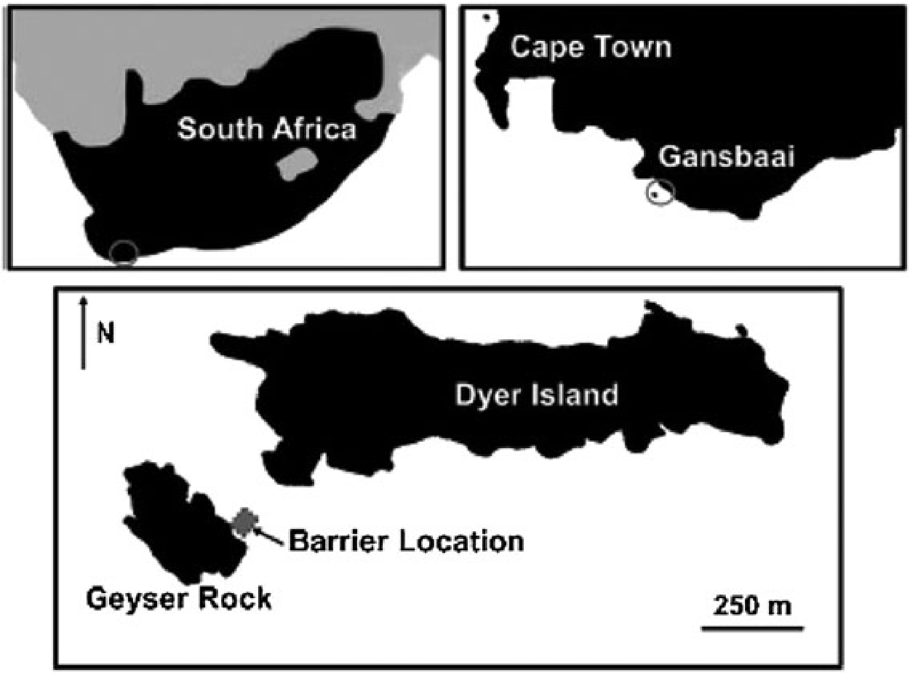

FIGURE 1 Map illustrating research location within the Dyer Island nature Reserve

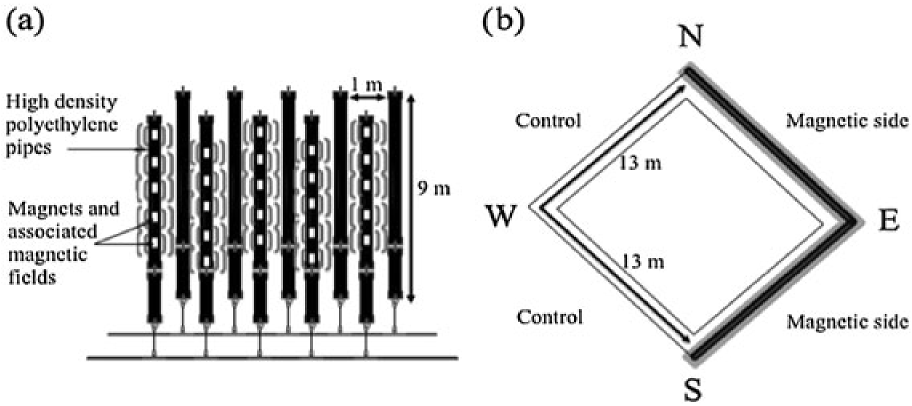

FIGURE 2 Schematics of the barrier elements that were used for both exclusion experimentation and structural integrity testing. **(a)** schematic illustrating a unit of five barrier components, distributed on two lines; the distribution of the magnets is indicated with the white rectangles on the external line of pipes. The grey and concentric field lines represent the associated magnetic fields. **(b)** schematic illustrating the distribution of the magnetic and control sides in the exclusion experiment. The semi-transparent grey region on the outer row of the magnetic side represents the range of the effective magnetic field

2.1 | Barrier exclusion efficacy experiment

To commence experimentation, a 60.96 cm × 45.72 cm baited remote underwater video system (BRUVS) was placed in the centre of the experimental square. At one end of the BRUVS, a bait canister was filled with 5 kg of natural fish chum (i.e. minced tuna and sardines) whereas on the opposite side an HD 1080p Go Pro Hero 3 camera was securely attached to permit post hoc video observations to assess if any sharks or other fish penetrated the barrier and attempted to feed on the bait. Additionally, two, HD 1080p Go Pro 3 cameras were strategically deployed along the outer regions of the barrier and activated to aid in observing behavioural interactions around the barrier perimeter. Once successfully deployed, the 8 m research vessel was placed directly upstream from the barrier where researchers collected secondary behavioural data (should *C. carcharias* interactions have occurred outside the recording capabilities of the deployed Go Pros) and to obtain Go Pro footage to permit individual shark identification for shark quantity assessment. More specifically, where possible individual sharks were identified using a previously developed dorsal fin photo-identification technique (Anderson, Chapple, Jorgensen, Klimley & Block, 2011; Anderson & Goldman, 1996; Andreotti et al., 2014; Chapple et al., 2011). If the dorsal fin could not be clearly identified from the obtained footage, short-term identification characteristics were used, such as: shark size, shark sex, presence/absence of a tag, shark colour, scars or fin damage, and pigmentation variation on the lower caudal fin (Domeier & Nasby-Lucas, 2007). However, owing to the long-term nature of this study and the non-permanence of some of the short-term identification characteristics, sharks observed in subsequent years that could not be positively identified using dorsal fin photo-identification or having a well-defined characteristic (e.g. missing a substantial portion of the caudal region) were categorized as new animals. For other elasmobranchs and teleosts encountered during experimentation, researchers were unable to identify unique individuals and therefore, the maximum quantity of each species observed within the trial was used to create an estimate of sample size. For each 2 h 30 min camera deployment (i.e. each trial), researchers recorded the following: species, abundance, region of interaction, and behaviours. Two key behaviours were recorded, visits and entrances. A visit was recorded when a shark swam within one body length of the barrier, whereas an entrance was recorded if a shark was observed to swim through the barrier elements. To address our hypotheses, data were first subjected to a Mann–Whitney U test to determine if data could be aggregated between years. Following this procedure, all data were separated by species and an entrance frequency was created (e.g. number of trials where entrances occurred/number of trials where species was sighted) for each treatment region and then subjected to a Mann–Whitney U test to test for significant differences.

3 | RESULTS

In total, 34 trials were conducted and 85 hours of video footage were collected from each camera deployment location (i.e. magnetic outer side; control outer side; and the baited inner region) between May and August 2015–2016. Upon initial inspection, research year was found to have no significant influence on the entrance frequency for any of the most abundantly observed species: *C. carcharias* ($Z = 0.047$, $P = 0.96$), other elasmobranchs ($Z = 0.452$, $P = 0.652$), hottentot (*Pachymetopon blochii*; $Z = 0.452$, $P = 0.653$), groovy mullet (*Liza dumerili*; $Z = 0.365$, $P = 0.719$), and maasbanker (*Trachurus trachurus*; $Z = 0.029$; $P = 0.976$). This justified data aggregation over the two-year period to increase sample size.

For the first study year (June–August 2015), four to six different *C. carcharias* were identified using short-term identification characteristics and post hoc video analysis. For the second study year (June–August 2016), 13 to 16 different *C. carcharias* were identified, with none of these being re-sighted individuals from the previous year. Therefore, the overall inter-annual total number of unique *C. carcharias* was between 17 and 22. A sighting range was utilized since five sharks could not be identified owing to swimming distance or swimming in a manner in which the identifying characteristics (e.g. pigmentation patterns, dorsal fin notch patterns, sex, size) were masked. In addition to *C. carcharias*, the roughly estimated sample sizes of the other species were: *P. blochii* ($n = 100$); *L. dumerili* ($n = 200$); *T. trachurus* ($n = 300$); dark shyshark (*Haploblepharus pictus*; $n = 1$); puffadder shyshark (*Haploblepharus edwardsii*; $n = 1$) and leopard catshark (*Poroderma pantherinum*; $n = 1$).

Video analysis paired with surface observations revealed that *C. carcharias* were present during 32.4% of all trials. During these trials, no significant difference in entrance frequency was detected as zero entrances occurred through both the control and magnetic regions ($Z = 0.044$, $P = 0.968$; Figure 3). In contrast, the barrier did not exhibit any observable exclusion capabilities on any of the other frequently encountered species. For 'other elasmobranchs' (*Haploblepharus pictus*, *H. edwardsii*, and *P. pantherinm*), which were sighted during 32.4% of the trials, there was no significant difference in entrance frequency for either experimental section ($Z = 0.295$, $P = 0.772$; Figure 3). For teleost species, which included *P. blochii* (sighted during 100% of trials), *L. dumerili* (sighted during 61.8% of trials), and *T. trachurus* (sighted during 35.3% of trials), there was no significant difference in entrance frequency between experimental sections ($Z = 0.010$, $P = 0.992$; $Z = -0.277$, $P = 0.779$; $Z = 0.029$, $P = 0.779$; respectively; Figure 3).

3.1 | Barrier structural integrity

To assess the structural integrity of the barrier, researchers deployed 20 barrier elements at the research site in August 2015 (Figure 4a and 4c). These barrier elements and environmental conditions

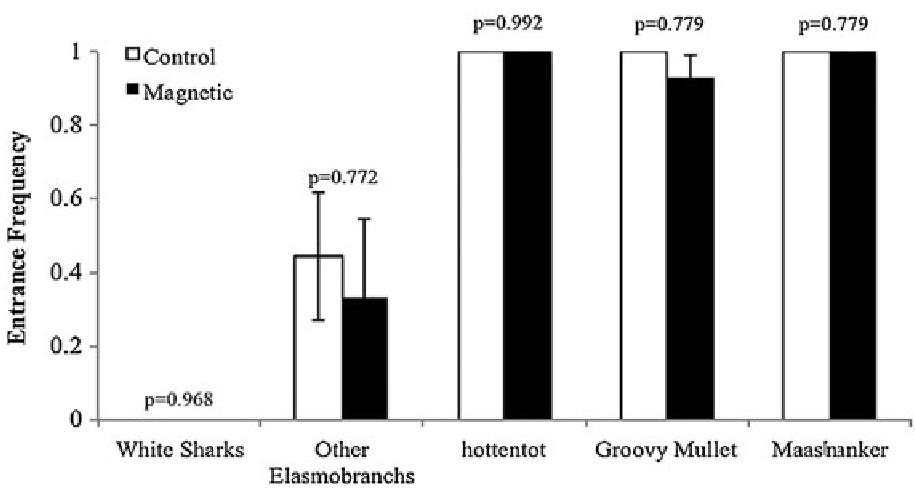

FIGURE 3 The entrance frequencies (number of trials where entrances occurred/number of trials where animal was sighted) ± standard error of the most frequently viewed species, white shark (*Carcharodon carcharias*); 'other elasmobranchs' – Dark shyshark (*Haploblepharus pictus*), puffadder shyshark (*Haploblepharus edwardsii*), and leopard catshark (*Poroderma pantherinum*); hottentot (*Pachymetopon blochii*); groovy mullet (*Liza dumerili*); and maasbanker (*Trachurus trachurus*); during the Sharksafe Barrier exclusion experiment

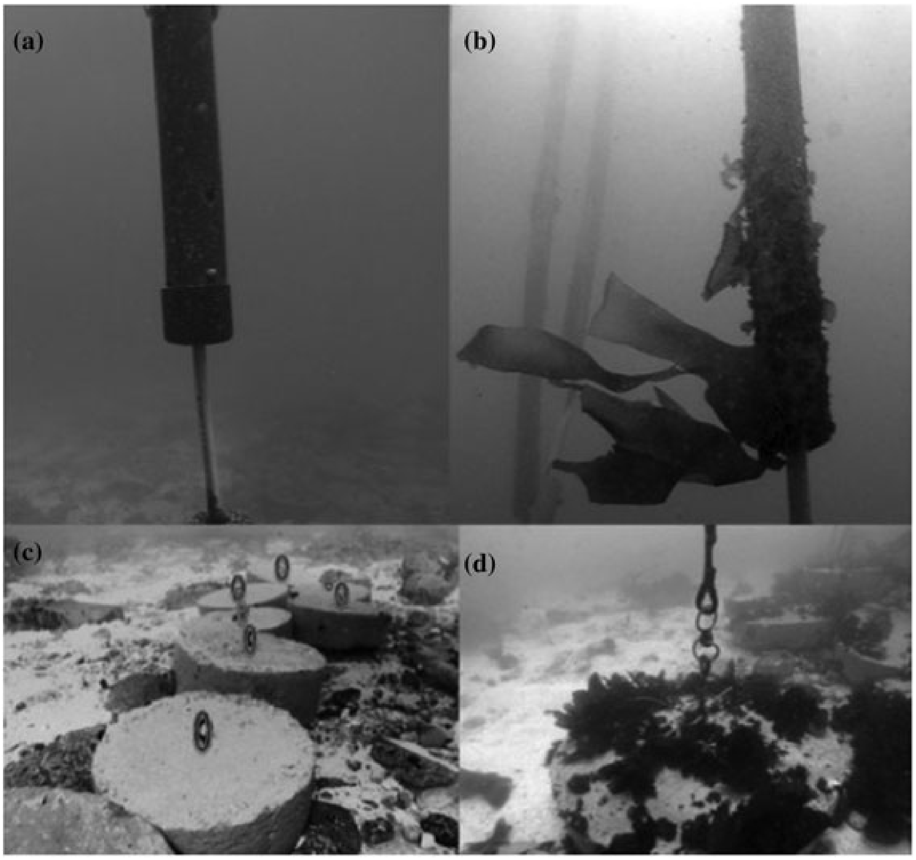

FIGURE 4 Photographs showing barrier elements and base at day 1 (a,c) and day 300 (b,d) of deployment during the barrier structural integrity experiment

(e.g. current speed and swell height) were routinely observed by trained scuba divers until experimental implementation in May 2016.

Rapid algal growth (i.e. biofouling) occurred on both the base and the barrier elements; however, owing to the continued perpendicular positioning of the barrier elements (e.g. extending from the sea floor to the sea surface) researchers determined that this biofouling was not sufficient to inhibit Sharksafe Barrier efficacy. In addition, 17 of the 20 barrier elements remained intact after the 300-day deployment period, suggesting that this system can withstand the ocean conditions of Gansbaai across different seasons. The three barrier elements that detached were due to accidental excess pipe buoyancy, which was adjusted and standardized in subsequent deployments.

4 | DISCUSSION

Based on this 2-year study, it appears that the Sharksafe Barrier can exclude *C. carcharias* from a baited region, which is suggestive that this technology may be an eco-friendly alternative to shark culling devices for beach protection. The results further illustrate that both the control and magnetic regions of the barrier had a similar observable effect on *C. carcharias* swim patterns, questioning the overall importance of magnetic inclusion for *C. carcharias* exclusion. However, continued experimentation in high turbidity or nighttime conditions where visibility is substantially limited may prove important since shark sensory allocation may be context-specific (O'Connell et al., 2013), making magnets an effective barrier component when the visual stimuli of the barrier are masked by environmental conditions. Beyond its exclusion capabilities, the results illustrate that the Sharksafe Barrier exhibits the ability to tolerate a high energy coastline. Although three barrier elements detached during the 300-day trial period, the problem was identified and rectified. Clearly, continued research pertaining to the barrier's structural integrity is required, especially in environments that contain continuous breaking waves (e.g. a surf zone), as observed in current shark net locations (e.g. Durban, Kwazulu-Natal, South Africa).

Furthermore, the present findings illustrate that barrier exclusion efficacy was species-specific, where large *C. carcharias* were excluded and the swimming patterns of smaller elasmobranch species and teleosts showed no observable signs of manipulation. Although the results associated with teleosts can be supported by previous magnetic deterrent studies that suggest that the apparent lack of an ampullary system (O'Connell & He, 2014; Rigg, Peverell, Hearndon & Seymour, 2009; Stoner & Kaimmer, 2008) may result in elasmobranch-specific deterrent capabilities, it is uncertain as to why the other elasmobranch species were not deterred. One potential explanation may be related to organismal body size, as previous studies demonstrate that neonate and juvenile teleost and elasmobranch species can utilize and manoeuvre through complex benthic habitats (e.g. mangrove roots), whereas larger predators are excluded (Guttridge et al., 2012; Hammerschlag, Morgan & Serafy, 2010). Therefore, it is possible that body size, more specifically, body width, may be a key contributor to overall barrier exclusion efficacy as narrow marine organisms can simply manoeuvre through the barrier elements. In addition, another potential explanation may be the lack of magnetic stimuli along the barrier base and in the two, non-magnetized, control sides. This small gap in magnetism may be sufficiently large enough to facilitate small elasmobranch entry. In contrast to these findings and suggestive that this system is not *C. carcharias*-specific, O'Connell, Hyun et al. (2014) conducted a similar Sharksafe Barrier exclusion study on the bull shark (*Carcharhinus leucas*), another potentially dangerous species. Over 18 days, a minimum of 23 different *C. leucas* interacted with the Sharksafe Barrier and no sharks entered through the barrier elements to feed on the bait. Thus, the exclusion capabilities observed in the present study and those in O'Connell, Hyun et al. (2014) illustrate that the system is not *C. carcharias*-specific and, additional research on species that pose a potential threat to beachgoers (e.g. tiger sharks – *Galeocerdo cuvier*) is required to determine if this technology can be a viable alternative to general shark culling methods.

With the possibility of local extirpation of top-order marine predators and the consequential adverse impacts that culling events could have (Dudley & Cliff, 1993; Ferretti et al., 2010; van Der Elst, 1979), there exists an increasing need to implement eco-friendly approaches to prevent future environmental degradation. However, although ecologically responsible shark hazard mitigation techniques are of upmost importance, technologies often fall short in relation to two critical components that are integral to successful deployment and technological longevity. More specifically, recent efforts have been unsuccessful because of technological insufficiencies stemming from structural designs that are incapable of withstanding harsh coastal conditions (e.g. Aquarius barrier; NSW Department of Primary Industries, 2017). Unlike these technologies, the repetitive and rigorous field-testing of the Sharksafe Barrier's structural integrity illustrates that it can withstand a variety of conditions; however, in order to be considered a successful alternative, it is imperative that deployment and structural integrity analyses are conducted in regions with breaking waves. In addition to structural integrity, cost has a substantial impact on technological implementation. Although shark hazard mitigation is a pressing issue, funding is often limited and therefore, if a technology is successful yet economically impractical, the odds of implementation through governmental-funded initiatives are minimal. Although not an element of the present study, marine engineers have re-designed the Sharksafe Barrier from its earlier 2011 form making it an economically feasible option. Therefore, with the successful exclusion of a second large shark species (*C. carcharias*) from a baited region, the demonstration of barrier deployment longevity through the present structural integrity analysis, and its economic feasibility, the possibility of governmental adoption and future deployments that extend along a shoreline as an eco-friendly alternative to lethal methods is a foreseeable possibility.

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