Received: 18 January 2024 | Accepted: 30 March 2025

DOI: 10.1002/pan3.70054

BRITISH ECOLOGICAL SOCIETY People and Nature

RESEARCH ARTICLE

Novel risk assessment framework to compare shark-bite mitigation strategies

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Handling Editor: Alex Erwin

Abstract

1. Human–wildlife conflicts (HWCs) are increasing globally and are some of the most pervasive problems for the conservation of terrestrial and marine species. Stakeholders often hold different values and concerns surrounding HWCs, and understanding these values and their relative importance among stakeholders allows for more effective decision-making.
2. We developed a multi-objective decision analysis framework to compare and assist in determining preferred mitigation measures to reduce HWCs. We illustrate how this framework can be used to identify appropriate mitigation measures to reduce the risk of shark bites, which have been increasing worldwide and have led to ongoing controversy and debate between governments and other stakeholders. We combined expert assessment of shark-bite mitigation measures against socio-economic and environmental criteria, while accounting for subjective ranking of the importance of these performance criteria across stakeholders.
3. Our flexible framework was tested to compare 15 mitigation measures for the Gold Coast region of Queensland, Australia, using 12 performance criteria.
4. Results reiterated the societal shift towards non-lethal measures and highlighted which mitigation measures or performance criteria lacked information, helping to identify knowledge gaps and research needs.

5. The flexibility of our framework makes it applicable to a broad range of contexts and HWCs and allows the incorporation of location-specific requirements and views that may vary between stakeholders.

KEYWORDS
control programmes, decision-making framework, human–wildlife conflict, multi-objective decision-making, shark bite, shark control, shark mitigation

1 | INTRODUCTION

Human–wildlife conflict (HWC) describes situations when humans and wildlife have the potential to negatively impact one another either economically, physically or psychologically (Lute et al., 2016). As most places inhabited by humans overlap with wildlife habitat, HWC is increasingly common across both terrestrial and marine domains (Adams et al., 2020; Blackwell et al., 2016; Crossley et al., 2014; Harich et al., 2013; Jani et al., 2019; Lucrezi & Gennari, 2021) and can lead to a lack of public support for policies geared towards conservation projects (Colefax et al., 2020; Killion et al., 2020; Lute et al., 2016). Strategies and tools, such as physical separation and financial compensation, are often established to mitigate, manage or offset a conflict situation (Ravenelle & Nyhus, 2017). However, when communities are more severely physically or financially impacted, for example loss of human life or consistent loss of assets, retaliatory killing or lethal control to eradicate problematic individuals or reduce populations can occur (Nunny, 2020; Ravenelle & Nyhus, 2017), placing pressure on species which may already be facing external threats, such as habitat fragmentation, exploitation or climate change (Barua et al., 2013; Ravenelle & Nyhus, 2017).

Interactions between humans and sharks are complex and have arisen from the broad range and increasing activities that humans undertake in the marine environment, including extractive use of marine resources and recreation (Simpfendorfer et al., 2021). Out of these varied types of interactions, shark bites on people are arguably the most reported in social and traditional media (Muter et al., 2012; Le Busque et al., 2019), which can lead to public misconceptions of risk (e.g. events that are easier to recall are perceived to be more common, i.e. availability bias; Crossley et al., 2014), despite the probability of a shark bite being extremely low (McPhee et al., 2021; Midway et al., 2019; Riley et al., 2022). While mitigation measures to reduce shark-bite risk and bites have been used worldwide and for nearly a century (i.e. the first large-scale programme was deployed off New South Wales (Australia) in the 1930s), the increasing number of shark bites impacting communities and regions combined with the rise of environmentally conscious attitudes and behaviour of the general public has led to ongoing controversy and debate between governments and stakeholders (Adams et al., 2020; Couper & Walters, 2020; Martin et al., 2022; Meeuwig et al., 2015; Meeuwig & Ferreira, 2014). For example, several shark bites in quick succession (e.g. in Reunion Islands, Brazil or Australia) have prompted calls from some parts of the community for government-led shark control programmes (Chapman & McPhee, 2016; Gibbs & Warren, 2015; Hazin & Afonso, 2013), which subsequently led to public outcry from other sectors of the community because of the lethal methods being used.

Historically, governments have often relied on lethal methods to reduce local shark populations using nets, drumlines, longlines, and/or targeted fishing (Chapman & McPhee, 2016; Gray & Gray, 2017; Meeuwig & Ferreira, 2014; Stokes et al., 2020). Lethal shark-bite mitigation programmes currently in operation include nets in New South Wales (Australia), nets and drumlines in Queensland (Australia), nets and drumlines in KwaZulu-Natal (South Africa), and drumlines in Réunion (France). These programmes have, however, come under public scrutiny because of the challenges determining their level of effectiveness due to the inherent low number of shark bites and therefore their ability to substantially reduce the risk of shark bites (McPhee et al., 2021). Lethal methods are also criticised for their unselective nature, leading to the capture of non-target species, including threatened species (Adams et al., 2020; Chapman & McPhee, 2016; Cliff & Dudley, 2011; Gibbs & Warren, 2015; Gibbs et al., 2019; Sumpton et al., 2011). As a result, the community is increasingly advocating for governments to develop and implement non-lethal shark-bite mitigation measures (Gibbs & Warren, 2015; Gibbs et al., 2019; Martin et al., 2022). This has led the New South Wales and Queensland governments to evolve their existing shark mitigation programmes to reduce their impacts and to develop, evaluate, and integrate several non-lethal mitigation measures to further reduce risk. For example, the New South Wales Government introduced a 5-year programme in 2015 to explore new technological advances and trial non-lethal measures, including manned and unmanned aerial surveillance, tagging operations, SMART (Shark-Management-Alert-in-Real-Time) drumlines, alternative barrier materials and education strategies (Adams et al., 2020; Martin et al., 2022; McPhee et al., 2021). The Western Australian Government also ran a SMART drumline trial which further confirmed the reduced mortality rate of both target and non-target species due to short response times following capture (Taylor et al., 2022). Similarly, the Queensland Government introduced SMART drumlines (which they referred to as Catch Alert Drumlines), drone surveillance trials at selected beaches along with a focus on understanding shark behaviour in relation to human activities (Barnett et al., 2022) and shark smart community awareness and education campaigns (Barnett et al., 2022; Martin et al., 2022; Smith et al., 2021).

Beyond these area-based mitigation measures, personal deterrents that are either worn and/or attached to equipment, such as surfboards, can also be used to reduce the likelihood of shark bites (Gauthier et al., 2020; Huveneers et al., 2018; Riley et al., 2022;

Thiele et al., 2020). Acknowledging the effectiveness of some personal deterrents and with a view to encouraging water users to share some of the responsibility for shark mitigation, the Western Australian Government provides a rebate for some independently tested personal deterrents. Although non-lethal options are widely accepted and supported by the community (Adams et al., 2020; Martin et al., 2022; Rosciszewski-Dodgson & Cirella, 2021), they can be expensive and are limited in some ocean and weather conditions (Adams et al., 2020; Colefax et al., 2020; Provost et al., 2020; Taylor et al., 2022). The risk of shark bites can also be reduced by managing human behaviours, for example reducing behaviours that can attract sharks (e.g. fishing, splashing, waste disposal and other sensory cues) or increasing behaviours that minimise shark encounters (e.g. avoiding swimming at higher-risk locations or times; Killion et al., 2020). Effective behavioural interventions require a thorough understanding of both human behaviour and shark-human interactions. For example, understanding how sharks respond to human activities may help to predict how or when a species will interact with humans, which can be used to inform strategies to reduce the risk of shark bites (Blackwell et al., 2016).

Stakeholders often hold different values and concerns surrounding a conflict situation. Understanding these values and their relative importance among stakeholders allows for more effective decision-making (Killion et al., 2020; Lute et al., 2016). A structured decision-making framework can help navigate the diversity of values and priorities among stakeholders and the trade-offs between multiple management strategies (Baruch-Mordo et al., 2013). With many shark-bite mitigation devices and strategies now available and with more expected to emerge, deciding on the optimal management strategy can be challenging for stakeholders. In addition, conflict between stakeholder groups (e.g. government agencies, surf lifesaving clubs, tourism operators and the general public) is likely as different values emerge and trade-offs become inevitable (Adem Esmail & Geneletti, 2018), leading to human-human conflict related to managing wildlife interactions. A multi-objective decision analysis framework is an effective method to support decision-makers to compare several management options (Adem Esmail & Geneletti, 2018; Davies et al., 2013). Multi-objective decision-making frameworks provide an approach to navigate complex problems and help identify strategies for conflict resolution. Similar frameworks have been used to assess protected area boundaries (Voskamp et al., 2023), wildlife disease management (McEachran et al., 2024), wildlife ethics assessments (Smith et al., 2023) and harvest management strategies (Robinson et al., 2016).

Such frameworks can help process and compare management strategies put forward to decision-makers and ensure transparent and comprehensive assessments prior to implementing conflict management strategies (Hemming et al., 2018). Conflict management often involves a range of possible resolution options that will affect stakeholders in varying ways. A process is therefore required to assess all aspects of a problem, for example: financial costs, mental impacts, loss of life, habitat disturbance, tourism implications, and the indirect and long-term impacts that may occur following the implementation of a management strategy. Frameworks that help navigate the complexities of HWC can facilitate a comprehensive assessment of conflict management strategies and help decision-makers evaluate management strategies proposed by regulators or the public (Hemming et al., 2018).

In our study, we develop and use a multi-objective decision analysis framework to assist in highlighting shark-bite risk mitigation by using expert assessment against socio-economic and environmental criteria (i.e. *objectives*) while considering stakeholder priorities. Not all criteria used in this study will be relevant to all conflict situations, and there may be additional factors that need to be considered in other localities and circumstances. However, our framework is flexible and structured, such that decision-makers using it can modify the criteria and management options being compared, allowing for appropriate adaptations to address location- and conflict-specific situations. Here, we use the Gold Coast region of Queensland, Australia, to illustrate how this framework can be developed and applied to identify and compare the many shark-bite mitigation measures available and proposed by stakeholders.

2 | METHODS

Our framework incorporates an objective quantitative assessment of possible shark-bite mitigation approaches, while accounting for subjective opinions of what stakeholders find most important regarding these approaches. The multicriteria decision analysis (Geneletti & Ferretti, 2015; Hemming et al., 2018; Linkov & Moberg, 2011; Saarikoski et al., 2016) and expert opinion were formulated for shark-bite mitigation. We developed and implemented the framework in five phases: (1) the identification of the *objectives*, *mitigation measures* and *performance criteria*; (2) assessment of *mitigation measures* using *performance criteria*; (3) gathering stakeholder preferences; (4) calculation of overall scores and ranking; and (5) sensitivity analysis (Figure 1). The experts used to determine the framework's criteria, *mitigation measures* and ranking system were selected based on their expertise in shark behaviour and human-shark conflict and included representatives from all Australian states with frequent shark-bite incidents. All experts have either published peer-reviewed publications in relation to shark-bite mitigation measures, are regularly consulted by government agencies about shark-bite mitigation measures, are members of committees focused on shark-bite *mitigation measures* or work for government agencies in a role related to shark-bite mitigation. The expert panel included eight scientists and five government staff involved in managing shark mitigation programmes from the states of Queensland, New South Wales, South Australia and Western Australia (Table S1).

2.1 | Identification of *objectives*, *mitigation measures* and *performance criteria*

We conducted an online workshop with the expert panel to discuss and identify by consensus important factors when considering shark-bite

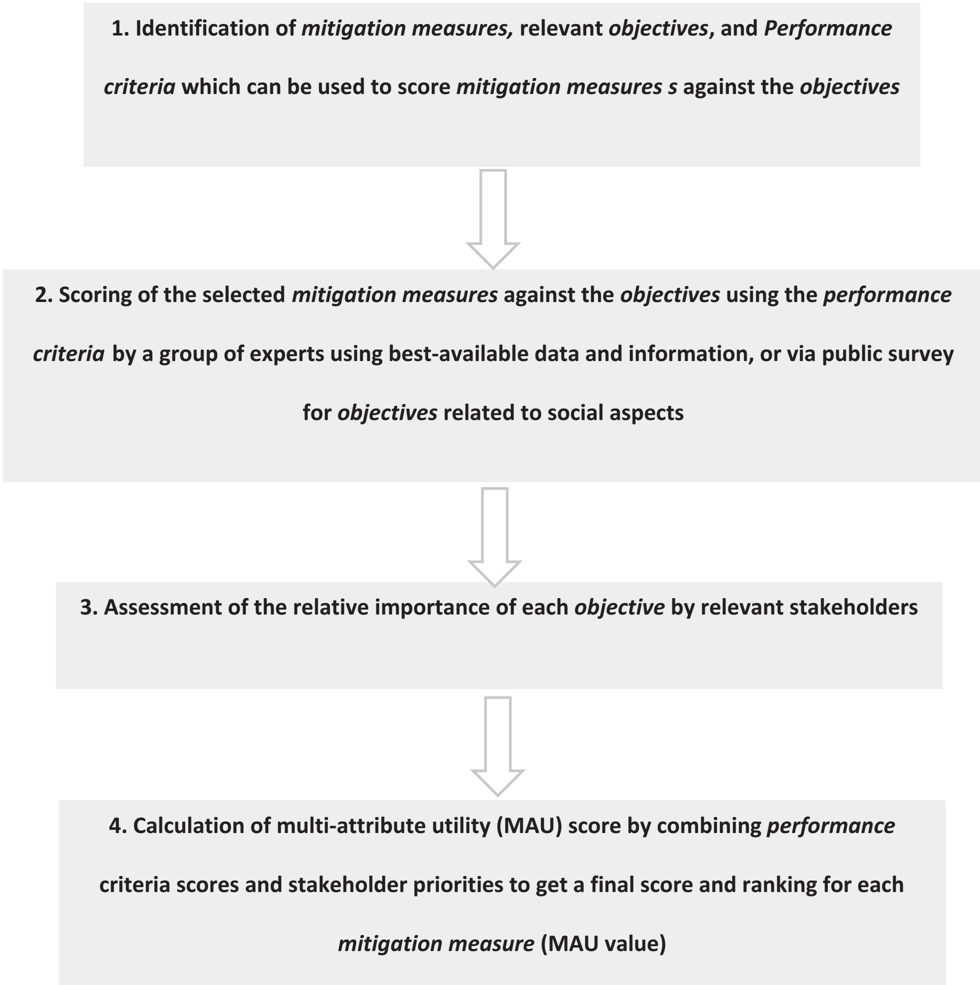

FIGURE 1 Schematic representation of the development and implementation of the multicriteria decision analysis framework incorporating subjective stakeholder preferences, which was used to assess and compare the suitability of shark-bite *mitigation measures*.

mitigation measures (*objectives*), the possible mitigation measures which could be assessed (*mitigation measure*), and a *performance measure* for each *objective*. Following the workshop, a list of *objectives*, *mitigation measures* and *performance criteria* was sent to the expert panel for comments and feedback, with a final list that incorporated all comments and feedback sent to the expert panel for approval. Each member of the expert panel was then tasked to assess one *mitigation measure* (*different for each expert*) using the agreed *performance criteria* to identify any issues or challenges. Minor adjustments to the *performance criteria* were made following this process.

2.2 | Assessment of *mitigation measures* using the *performance criteria*

Experts were then asked to individually score the performance of each *mitigation measure* against the *objectives* for the Gold Coast region (see Study region below). Each individual was asked to provide scores based on their expertise and standard resources (e.g. peer-reviewed publications and reports).

The foundations of the framework focused on a multi-objective decision analysis process that adopted from the IDEA protocol ('Investigate', 'Discuss', 'Estimate', 'Aggregate') (Hanea et al., 2016; Hemming et al., 2018). The IDEA protocol is designed to provide a rigorous approach to expert opinion by accounting for bias and uncertainty. Although the use of expert judgement is useful, biases, such as overconfidence, anchoring, availability and groupthink, may occur (Burgman et al., 2011; Hanea et al., 2016; Vidal et al., 2011). Structuring an elicitation protocol reduces biases and improves the quality of expert judgement by enhancing the transparency and accuracy of the results (Burgman et al., 2011). The Delphi procedure outlines a systematic way of presenting questions through a three-to-five step process (Hemming et al., 2018). In our framework, we adopted a three-step process where each expert was asked to provide their best estimate, lower limit and upper limit (Vidal et al., 2011) in response to the performance of a shark-bite *mitigation measure*. The lower and upper limit refer to the performance of a *mitigation measure* based on a worst- and best-case scenario. Experts were also given an opportunity to provide justification for their chosen performance scores for all assessed measures available.

Two of the *objectives* related to minimising impact on social values could not be scored by the expert panel: (1) support community well-being (i.e. sense of safety felt when *mitigation measure* is present) and (2) maximise community support. To address these two *objectives*, we conducted an online public survey and distributed it throughout the study region and surrounding areas. We designed the online survey using FreeSurveysOnline and distributed it via social media (i.e. Twitter, Facebook and Instagram), Gold Coast Sea World staff newsletter, e-mail, word of mouth and participation flyers posted along an 8-km stretch of coastline along public access to the beach and surrounding park areas. To assess community well-being, survey participants ($n=395$) were asked to provide their level of willingness to be in the ocean with each *mitigation measure* by selecting either 'not willing', 'not really willing', 'undecided', 'somewhat willing' and 'completely willing'. Participants were also asked how willing they would be to enter the ocean if no *mitigation measures* were in place, which was used as the baseline to compare the responses for willingness against a range of mitigation strategies and technology. To assess community support, participants were asked to provide their level of support by selecting either 'do not support', 'don't really support', 'undecided', 'somewhat support' and 'completely support'. We presented the results of the surveys as a comparison using situations when no *mitigation measures* are present as the baseline. For example, if 50% of the respondents were 'somewhat willing' to go in the water when no *mitigation measures* are in place and that 70% of respondents were 'somewhat willing' when drones are in place, it would represent a 20% increase in respondents being 'somewhat willing'. Conversely, if 50% of the respondents 'don't really support' no *mitigation measures* being in place and that 20% of respondents 'don't really support' beach meshing, this would represent a 30% decrease in respondents 'not really supporting' beach meshing. At the beginning of the survey, standard demographic questions were asked. Survey responses were filtered by postcode, age, education level and gender. Survey responses were also separated between participants working in recreational businesses, local ocean-based businesses, local non-ocean-based businesses, local cafes and restaurants, tourism businesses and their involvement in surf lifesaving and/or non-government organisations (NGOs).

2.3 | Gathering stakeholder preferences for shark-bite mitigation

Once the performance of the *mitigation measures* was scored by experts, the framework accounted for the trade-offs between *Objectives* by weighting performance scores using a ranking provided by stakeholders (Parnell & Trainor, 2009). This step was important to understand which *mitigation measure* performed well for what mattered the most. To determine the weighted importance of an *objective*, stakeholders were asked the following hypothetical situation. If all *objectives* for a *mitigation measure* were to perform at their worst level, which *objective* would the participant prioritise to 'swing' from the worst to the best level? The *objective* chosen first is considered the most important and receives 100 points. The participant then determines the next *objective* they would choose and assigns points comparative to the first *objective*. If *objectives* hold equal weighted importance, they are assigned equal points. Relative pairwise judgement was used to determine the degree of importance between two *objectives* in the ranked order. For example, assigning an *objective* with 100 points and the second *objective* with 50 points indicates the first *objective* is 2× more important than the second choice. Once all *objectives* were given a score, the swing weights were calculated by dividing the score (points given) by the sum of all the scores. All weighted scores sum up to 1.0. Each organisation within a stakeholder group was asked to provide a swing weight representing the organisation as a whole. We then calculated the average, standard deviation and a 95% confidence interval (CI) of weighted scores across all organisations within a stakeholder group. The following stakeholder groups were asked to rank each *objective* from most to least important: NGOs, scientists, surf lifesaving clubs (SLSC), the Queensland Government (due to the test case study being the Gold Coast region) and the general public from the study region. The NGOs we asked to rank *objectives* included the following marine conservation-focused NGOs: Sea Shepherd, the Australian Marine Conservation Society, the Humane Society International and ENVOY Productions. Each organisation was contacted via email asking to rank *mitigation measure* using a spreadsheet provided to them.

2.4 | Calculation of overall scores and ranking of shark-bite *mitigation measures*

To determine the final assessment for shark-bite mitigation, we assessed the overall performance of each *mitigation measure* by combining *objective* performance from the expert scores (Step 2) with the subjective preferences of the stakeholders (Step 3). We aggregated *objective* performance scores with the swing weights, producing a multi-attribute utility (MAU) score. First, performance scores were normalised (*Vn*) to ensure all values were on a common scale. As the direction of the performance scales may vary among the *objectives*, the equation was modified to adjust for *objectives* which have the desired outcome to be minimised (Equation 1; e.g. lowering costs of a strategy), or to be maximised (Equation 2; e.g. improving the protection of non-target species).

$$Vn = \frac{V_{ij} - \min(V_i)}{(V_i) - (V_i)} \tag{1}$$

$$Vn = \frac{V_{ij} - \max(V_i)}{(V_i) - (V_i)} \tag{2}$$

where V_i is the value for the highest/lowest assigned score for the *i* th *objective* and *Vij* is the value *j* for *objective i*.

Once the scores were normalised, the *objective* performance scores were aggregated with the swing weights, producing a multi-attribute utility (MAU) score (Equation 3)

$$\text{MAU} = U_j = \sum_{i=1}^{n} W_i V_{ij} \quad (3)$$

where U_j is the overall score of the *mitigation measure j*, W_i is the weight of the *objective i*, and V_{ij} is the performance score of *mitigation measure j* for *objective i*. The MAU score provided a value between 0 and 1, with a score closer to 1 considered a better performing *mitigation measure*. For each stakeholder group, the average MAU, standard deviation and 95% CI were calculated.

2.5 | Sensitivity analysis

When gathering the performance scores, the expert panel was asked to provide their best estimate along with their predictions under a worst-case and best-case scenario. This helped identify uncertainty when assessing *mitigation measures*. We calculated the average scores between all experts for both worst- and best-case scenarios and the difference between worst- and best-case. A *mitigation measure* or *objective* presenting a higher difference indicates a higher degree of uncertainty and a possible gap in our knowledge.

2.6 | Case study region

We applied the framework to the Gold Coast region (−28.03471°, 153.43234°; Queensland, Australia), including ocean beaches and the region's network of waterways, for example canals and broadwaters often used for swimming and other in-water activities. The Gold Coast is located in Southeast Queensland, with a permanent population of ~722,000 residents. The Gold Coast is a popular location for national and international visitors with both hinterland and coastal natural attractions. It covers 26 nautical miles of coastline, encompassing 23 ocean beaches with 35 drumlines and 11 nets deployed for shark-bite mitigation (Figure 2). These beaches have typically high water clarity and are exposed to swell and surf conditions. The Gold Coast network of waterways is the largest constructed canal network in the southern hemisphere and is composed of lakes and canals linked to the natural Nerang River. The river is connected at several locations to the 200-km network of tidal canals that vary in width and depth (15–100 m and 0.5–15 m, respectively), and are used throughout the year for recreational activities, including boating, water-skiing, fishing and swimming

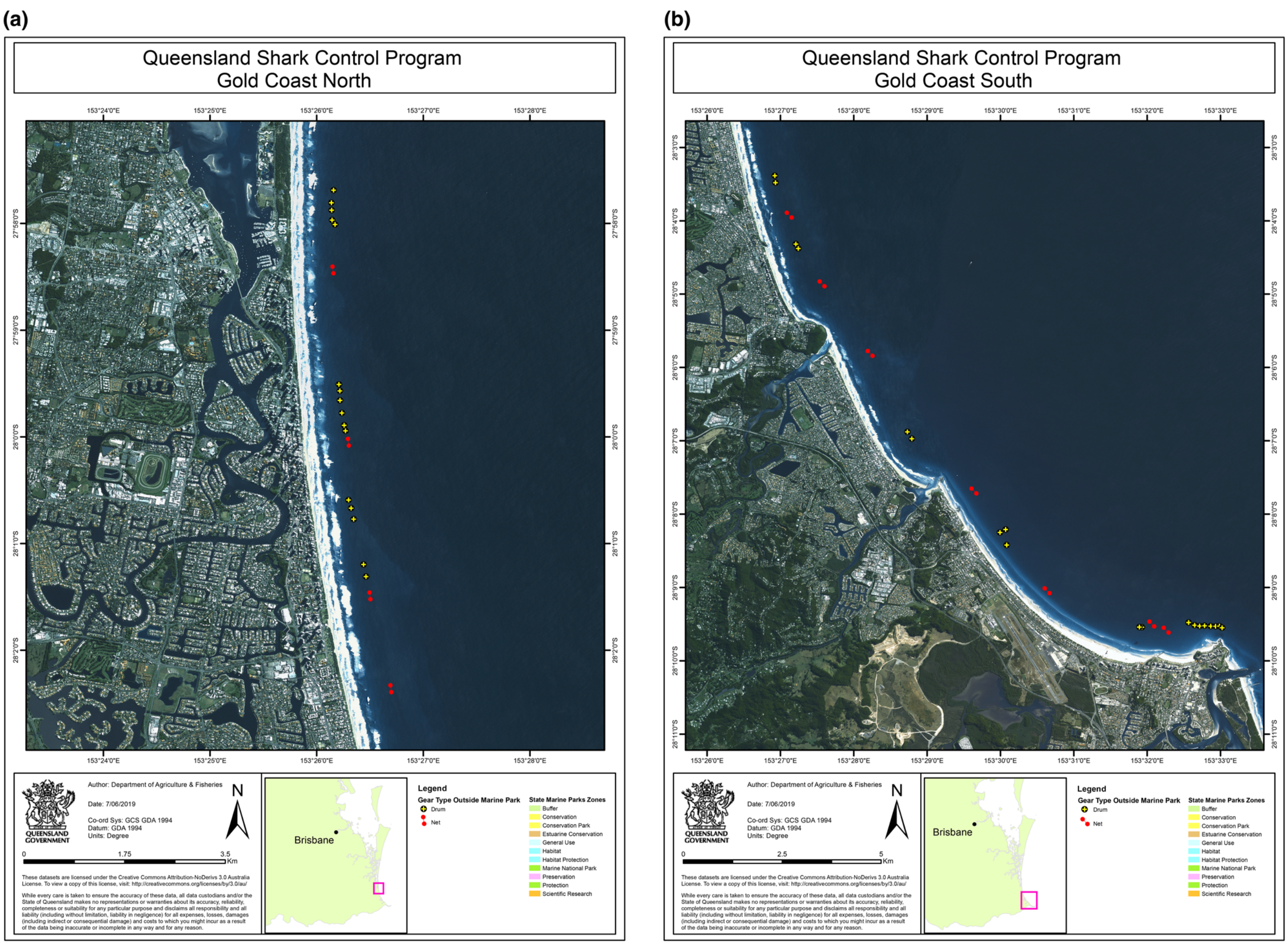

FIGURE 2 Shark control equipment distribution for the part (a) northern part of the Gold Coast (from Main Beach to Kurrawa) and part (b) southern part from Miami to Rainbow Bay. Yellow dots represent baited drumlines, and red dots represent mesh nets. Distance between closest red dots indicates the length of one net. Reproduced with permission from the Department of Agriculture and Fisheries.

(Werry et al., 2012). A high density of residential high rises line both ocean beaches and the waterway network.

2.7 | Ethics consideration

All participants contributing to the public survey were asked to indicate their written consent to completing the survey and were notified that no personal information was required and would not be stored, and that all answers would be collected anonymously. The participants were made aware of the intent to publish the findings collated from the survey, and that they were free to withdraw at any time. The study adheres to the guidelines of the National Statement on Ethical Conduct of Human Research. This research was conducted under the Ethics ID number HE002175.

3 | RESULTS

3.1 | Identification of *objectives*, *mitigation measures* and *performance criteria*

Fourteen *mitigation measures* were identified by the expert panel, in addition to not using any *mitigation measure*, i.e. 'Nothing' (Table 1). These included measures previously or currently used by the Queensland Shark Control Program at the Gold Coast (e.g. beach mesh nets), recently trialled in Queensland (e.g. drones), trialled in other jurisdictions (e.g. sonar technology), or new technologies which might be used in the future (e.g. blimps). The range of *mitigation measures* encompass both lethal and non-lethal methods. Lethal measures are likely to lead to the death of an animal through capture or post-release mortality, for example via the use of nets and drumlines. Non-lethal measures do not lead to the death of both target and non-target species. Non-lethal *mitigation measures* were further categorised into (1) barriers; (2) detection and alert systems; (3) personal deterrents; (4) education; and (5) no strategy. Barriers provide separation between humans and sharks and include visual barriers and electric barriers that aim to reduce the likelihood of sharks entering an area, or physical barriers that close off an area and stop sharks accessing that area. Detection and alert systems are *mitigation measures* that enable the early detection of sharks, warning the public that sharks are in proximity, and can sometimes lead to beach evacuation. Examples of alert systems include helicopters, drones, blimps, human observation from high vantage points and acoustic receivers. Personal deterrents are devices individuals can wear or use to deter sharks and include devices that use electric fields, magnets or semi-chemicals. Education can also be used as a tool to reduce shark-bite risk and refers to providing beachgoers with information to elicit behavioural changes, for example avoid swimming in areas where bait fish are present. SMART drumlines are designed to be non-lethal but can still lead to mortalities, albeit to a much lesser extent than standard drumlines (Gallagher et al., 2019; Tate et al., 2019).

Table 2 represents the framework criteria which each *mitigation measure* was assessed against and the ranking system which was used to do so. Where there was a monetary value (i.e. cost) a ranking of high to low was most appropriate, whereas when a scale was required to measure the impact on an *objective* (i.e. human safety, the environments and tourism) a scale indicating an increase to decrease was used.

3.2 | Social impact and public sentiment

A total of 395 survey participants responded to the questions related to their willingness to be in the ocean and support for *mitigation measures*. Respondents' age was homogenous across age categories, with 20–25% of the respondents being 18–29, 30–39, 40–49 and 50–59 years old. About 60% of respondents had a tertiary education and >95% had a secondary education or higher. Sex was slightly female-biased (55.6%) and ~13% of the respondents owned a local recreational or hospitality business.

Respondent's willingness to be in the ocean ('Completely willing') increased by up to 35% when *mitigation measures* are introduced (Figure 3). Lethal drumlines and SMART drumlines were the only two *mitigation measures* for which respondents' feelings of being 'completely willing' to be in the ocean did not increase and were also the only *mitigation measures* for which the number of 'not at all willing' responses increased (by 3%–10%). Physical barriers were the *mitigation measures* for which the 'completely willing' answer increased the most. The increase in 'completely willing' and decrease in 'not really willing' was relatively similar across all other *mitigation measures*. Notably, electric barriers and personal deterrents had the greatest increase in 'undecided'.

Lethal measures were the least supported *mitigation measure* with the level of 'do not support' increasing by up to 62% compared with having no *mitigation measures* in place (Figure 4). These lethal measures also had the highest reduction in 'completely support' and 'somewhat support' by (~50% combined). Respondents also did not support SMART drumlines, with the number of participants 'not supporting' increasing by 20% and the number of 'completely support' decreasing by 30%. Visual and physical barriers had a 6%–10% increase in support ('somewhat support' and 'completely support'), while electric barriers had a 10% decrease in 'complete support' and a 13% increase in 'undecided'. All detection and alert systems along with personal deterrents and changes in human behaviours had an increase in support ('somewhat support' and 'completely support') and decrease in 'no support' and 'don't really support'. The largest increase in 'completely support' was for drones (31%) and behavioural intervention (42%). Respondents' willingness to be in the ocean with a *mitigation measure* in place and support for each *mitigation measure* (i.e. not the comparison against no measure in place) is provided in Figures S1 and S2, respectively.

TABLE 1 Shark-bite *mitigation measures* selected for assessment.

Category	Mitigation measure	Definition
Capture methods	Beach nets	Shark nets adjacent to popular swimming beaches. This includes the use of nets either all year round or on a seasonal basis
	Lethal drumlines	Baited drumlines
	SMART (Shark-Management-Alert-in-Real-Time) drumlines	Baited drumlines with an automated system that alerts authorities when a shark is hooked, enabling prompt responses to assist in reducing mortality of the animal caught. SMART drumlines are also used to capture sharks for acoustic tagging and subsequent detection
Barriers	Visual/kelp-like barrier (e.g. SharkSafe Barrier)	Barrier using kelp-like structures and magnets, providing a magnetic deterrent and visual barrier
	Physical barrier (e.g. structured fixed enclosures, Eco Shark Barrier and Aquarius Barrier)	Swimming enclosures that prevent the entry of large animals
	Electric barrier (e.g. Ocean Guardian and Natal Sharks Board)	Barrier using an electric field to deter sharks from entering an area
Detection and alert systems	Sonar technology (e.g. Clever Buoy)	Underwater system used to automatically detect sharks and identify potentially dangerous species, and relay information to onshore authorities (e.g. surf lifesavers)
	Fixed-winged and helicopter surveillance	Crewed aerial observation systems used to detect sharks and identify whether it is likely to be a potentially dangerous species, and relay information to onshore authorities (e.g. surf lifesavers) for temporary beach evacuation, if required
	Drones	Remotely piloted aerial surveillance via video feed to detect nearby sharks enabling temporary water for water evacuations, if required
	Blimps	Near-continuous elevated surveillance (weather dependent) aiming to detect nearby sharks enabling temporary water evacuations if required
	Real-time acoustic receivers (e.g. VR4 receivers and tagging operations)	Acoustic receivers used as a near real-time detection system to alert onshore authorities of the presence of an acoustically tagged shark
	Human observations from high vantage points (e.g. Spotters or shark towers)	Surveillance by observers in high rises, cliff tops or dedicated shark towers to detect nearby sharks enabling temporary water evacuations if required.
Personal deterrents	Personal deterrents	Device worn by individual surfers, divers and bathers to deter sharks
Human behavioural change	Behavioural Intervention, for example avoid swimming near bait balls	Improving education around shark behaviour and behaviours that individuals can adopt that are likely to reduce shark-bite risk
No strategy	Nothing	No risk mitigation methods implemented.

3.3 | Stakeholder rankings of framework *objectives*

Experts, NGOs, SLS groups and the public ranked the *objectives* in terms of which was most important to them (Table S2a–d; Table 3). Overall, human safety was the most important *objective* for managers, scientists and NGOs, with managers having the highest swing weight for this *objective* (0.17). The *objectives* related to minimising impact on biodiversity had the next highest swing weights for scientists, NGOs and the public (0.10–0.13). Scientists and NGOs had similar swing weights, while the public and SLSC also had similar swing weights but put more importance on minimising impacts on non-target threatened and iconic species and surrounding habitat (~0.12) than on improving human safety (0.08–0.09). Responses from the managers differed the most by ranking the minimisation of the impact on biodiversity the lowest (0.02–0.05).

3.4 | Comparison of the multi-attribute utility scores for *mitigation measures* in the Gold Coast region

The swing weights were combined with the performance scores (Table S3a) to provide a final multi-attribute utility (MAU) score, where the higher the MAU score, the higher the rank. Physical barriers had the highest MAU score ranging 0.26–0.37 across all groups, followed by drones (0.27–0.32), personal deterrents (0.26–0.32), behavioural interventions (0.25–0.29), and detection and alert systems (0.20–0.32). Lethal *mitigation measures*, that is drumlines and nets, were ranked lowest (0.13–0.23), aside from doing nothing which was ranked even lower (0.06–0.12). The sonar system had the lowest MAU score (0.20–0.21) of all detection and alert systems, while visual barriers had the lowest MAU scores (0.19–0.20) for all barrier *measures*. There were no major differences in the ranking of *mitigation measures* across

TABLE 2 Framework criteria against which each *mitigation measure* was assessed and the ranking system that was used to do so.

			Performance criteria		
Primary objective	Secondary objective	Objective definition	Scale	Definition	Percentage (where applicable)
Improve human safety	Improve human safety	Reducing the likelihood of a shark incident occurring. Maximised reduction of shark-bite risk for ocean users (e.g. swimmer, diver, snorkeler, surfer)	1. Negligible	Very low reduction of shark-bite risk	<5%
			2. Low	Low reduction of shark-bite risk	5%–20%
			3. Moderate	Moderate reduction of shark-bite risk	21%–50%
			4. High	High reduction of shark-bite risk	51%–85%
			5. Very High	Very high reduction of shark-bite risk	85%+
Minimise social impact	Support community well-being	Supporting community willingness to partake in ocean-based activities and enhance a sense of safety. How communities enjoy the water when a particular alternative is implemented. (information obtained through public survey)	1. Not at all willing	Will not partake in ocean-based activities due to shark-bite risk	
			2. Not really willing	Hesitant about partaking in ocean-based activities due to shark-bite risk, but could be persuaded	
			3. Undecided	Need more information to know how to feel about it	
			4. Somewhat willing	Willing to partake in ocean-based activities but is still concerned about shark-bite risk	
			5. Have no concerns	Willing to partake in ocean-based activities, without concerns of shark-bite risk	
	Maximise social acceptance of the established mitigation method	Community acceptance of and willingness to support the mitigation alternative (information obtained through public survey)	1. Do not support	Does not support the alternative in any capacity	
			2. Don't really support	Does not support the mitigation measure unless some changes could be made. This alternative is not the most desirable and other options should be considered first	
			3. Undecided	Unsure of level of support	
			4. Somewhat support	Support the mitigation measure but may need some changes or receive more information. This measure is not the best option but is promising.	
			5. Completely support	Complete support for the alternative and see it as the best, or one of the best, options	
Minimise economic impact	Minimise management costs	The costs of implementing an alternative. This includes costs of salaries (e.g. contractors), equipment, maintenance, repairs and management costs	1. No cost 2. Low cost 3. Medium cost 4. High cost 5. Very high cost	Specific $ value is not provided but response for each alternative should be in relation to each other	
	Support local businesses related to marine activities (e.g. surf shops and dive shops)	How well a particular alternative supports local marine-based businesses and reduce negative impacts. This involves the total change in revenue and/or the rate of customer influx. Choice of measurement is dependent on the location and information available	1. Significant Decrease	Significant decline in revenue and/or customers, leading to financial hardship	>30% decline
			2. Decrease	Decrease in revenue and/or customers	>10% < 30% decline
			3. Stable	Limited changes in revenue and/or customers, with no impact on the business	≤10% increase or ≤10% decrease
			4. Increase	Increase in revenue and/or customers	>10% < 30% increase
			5. Significant Increase	Significant increase in revenue and/or customers	>30% increase
	Support local businesses not related to marine activities (e.g. cafes, restaurants and hotels)	How well a particular alternative supports local non-marine businesses and reduce negative impacts. This involves the total change in revenue and/or the rate of customer influx. Choice of measurement is dependent on the location and information available	1. Significant Decrease	Significant decline in revenue and/or customers, leading to financial hardship	>30% decline
			2. Decrease	Decrease in revenue and/or customers	>10% < 30% decline
			3. Stable	Limited changes in revenue and/or customers, with no impact on the business	≤10% increase or ≤10% decrease
			4. Increase	Increase in revenue and/or customers	>10% < 30% increase
			5. Significant Increase	Significant increase in revenue and/or customers	>30% increase

(Continues)

TABLE 2 (Continued)

Primary objective	Secondary objective	Objective definition	Performance criteria: Scale	Performance criteria: Definition	Performance criteria: Percentage (where applicable)
	Support tourism (regional, inter-state and international tourists)	How an alternative supports the influx of domestic and international tourist to the local area (e.g. visitation rates and number of tourists)	1. Significant Decrease	Significant decline in visiting tourists	>30% decline
			2. Decrease	Decrease in visiting tourists	>10% < 30% decline
			3. Stable	Limited changes in visiting tourists	≦10% increase or ≦10% decrease
			4. Increase	Increase in visiting tourists	>10% < 30% increase
			5. Significant Increase	Significant increase in visiting tourists	>30% increase
Minimise environmental impact	Minimise impact on non-protected target sharks (i.e. large [>2 m] tiger, bull and whaler sharks)	Minimise injuries and death, including post-release stress and mortality, of target and non-protected shark species.	1. No Impact	No impact to the population	
			2. Low/Minor	Minor, short-term impact where population size recovers quickly. No long-term impact on the population	
			3. Moderate	Moderate, short-term impact or minor, long-term impact on population size. No long-term impact on the population	
			4. High	Significant short-term and/or moderate long-term impact on population size. Minor to medium decrease in population size, but unlikely to lead or contribute to the species being listed as threatened or affect the species functional role	
			5. Severe	Severe long-term impact on population size. High likelihood of substantial reduction in population size, leading to, or contributing, to the species being listed as threatened or affecting the species functional role	
	Minimise impact on protected target sharks (i.e. large [>2 m] white shark)	Minimise injuries and death, including post-release stress and mortality, of target threatened/ protected sharks	1. No Impact	No impact to the population	
			2. Low/Minor	Minor, short-term impact where population size recovers quickly. No long-term impact on the population	
			3. Moderate	Moderate, short-term impact or minor, long-term impact on population size. No long-term impact on the population	
			4. High	Significant short-term and/or moderate long-term impact on population size. Minor to medium decrease in population size, but unlikely to lead or contribute to the species being listed as threatened or affect the species functional role	
			5. Severe	Severe long-term impact on population size. High likelihood of substantial reduction in population size, leading to, or contributing, to the species being listed as threatened or affecting the species functional role	

TABLE 2 (Continued)

Primary objective	Secondary objective	Objective definition	Performance criteria		
			Scale	Definition	Percentage (where applicable)
	Minimise impact on non-target species populations (other sharks, rays and fishes). Species not listed as threatened or protected (under EPBC/States)	Minimise injuries and death, including post-release stress and mortality, of non-target sharks	1. No Impact	No impact to the population	
			2. Low/Minor	Minor, short-term impact where population size recovers quickly. No long-term impact on the population	
			3. Moderate	Moderate, short-term impact or minor, long-term impact on population size. No long-term impact on the population	
			4. High	Significant short-term and/or moderate long-term impact on population size. Minor to medium decrease in population size, but unlikely to lead or contribute to the species being listed as threatened or affect the species functional role	
			5. Severe	Severe long-term impact on population size. High likelihood of substantial reduction in population size, leading to, or contributing, to the species being listed as threatened or affecting the species functional role	
	Minimise impact on non-target and iconic species (including threatened and protected species under EPBC/States)	Minimise injuries and death, including post-release stress and mortality, of iconic species. This includes endangered, threatened and protected species, and species which hold symbolic value and/or have widespread popular appeal and public support	1. No Impact	No impact to the population	
			2. Low/Minor	Minor, short-term impact where population size recovers quickly. No long-term impact on the population	
			3. Moderate	Moderate, short-term impact or minor, long-term impact on population size. No long-term impact on the population	
			4. High	Significant short-term and/or moderate long-term impact on population size. Minor to medium decrease in population size, but unlikely to lead or contribute to the species being listed as threatened or affect the species functional role	
			5. Severe	Severe long-term impact on population size. High likelihood of substantial reduction in population size, leading to, or contributing, to the species being listed as threatened or affecting the species functional role	
	Minimise impacts on the ecosystem and surrounding habitat	Minimise disruption to the ecosystem and surrounding habitat (e.g. damage to the seafloor and benthic communities and decreased water clarity). Choice of measurement is dependent on the location	1. No Impact	No detrimental impact	
			2. Low	Minor, short-term impact that is acceptable with quick recovery	
			3. Moderate	Moderate, short-term impact or minor, long-term impact that is somewhat acceptable with a moderate chance of full recovery	
			4. High	Significant short-term and/or minor long-term impact that Is not desirable with a longer recovery time. Impacts can be mitigated with regulated strategies	
			5. Severe	Large widespread and/or significant long-term impact that is not acceptable. Impact is too harmful to regulate or mitigate sufficiently. Cons outweigh any potential benefits of a mitigation strategy	

Note: Where there was a monetary value (i.e. cost) a ranking of high to low was most appropriate, whereas when a scale was required to measure the impact on an *objective* (i.e. human safety, the environments and tourism) a scale indicating an increase to decrease was used.

scientists, NGOs, SLSC and the public. There were, however, significant differences in weighted scores provided by the managers (Table 4), with managers' MAU score for lethal *mitigation measures* being higher than those from other stakeholders (0.20–0.23 vs. 0.13–0.15).

3.5 | Sensitivity analysis

Overall, the *mitigation measure* with the highest level of uncertainty, that is the difference between best and worst-case scenarios, was

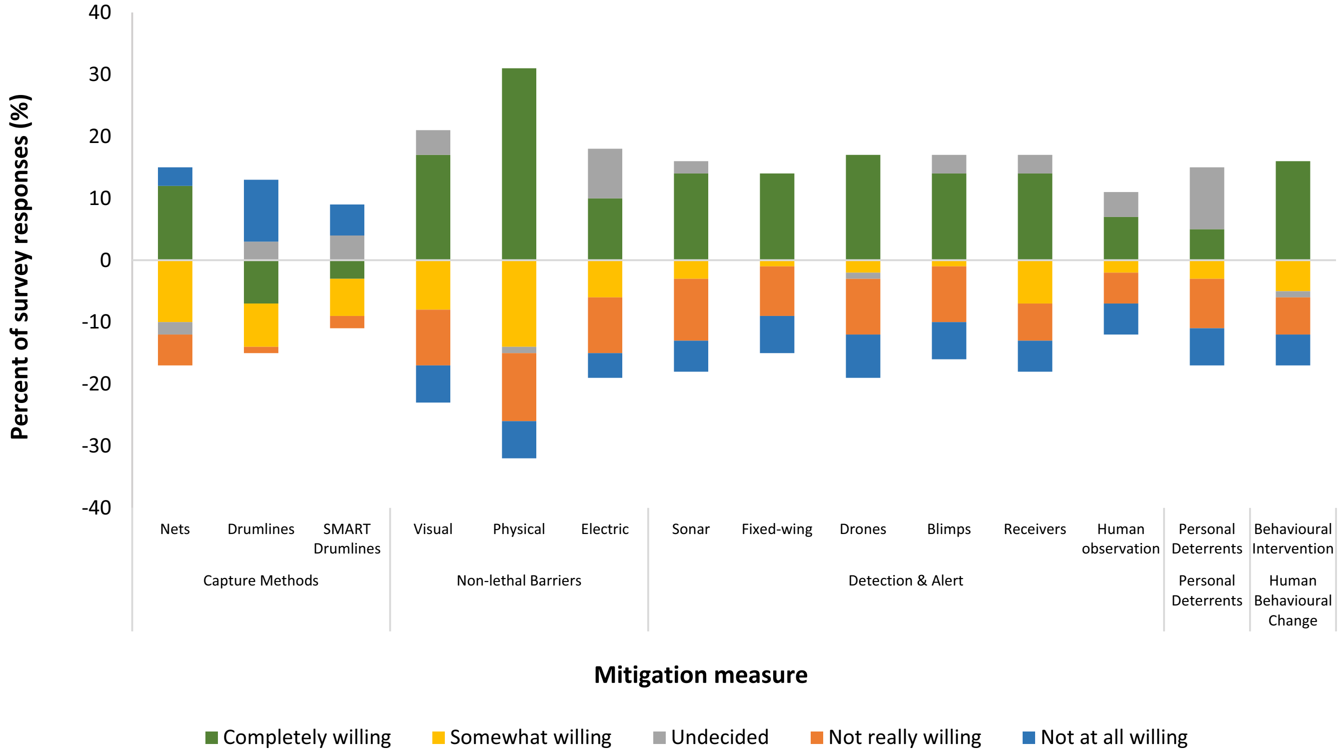

FIGURE 3 Change in the willingness to be in the ocean with a *mitigation measure* in place compared with situations when no *mitigation measures* are in place, which was used as the baseline. For each *mitigation measure*, percentages were estimated by subtracting the percentage of respondents in each Likert category from the corresponding percentage for situations when no *mitigation measures* are in place. Positive percentages indicate an increased number of respondents in that category; negative percentages indicate a decreased number of respondents.

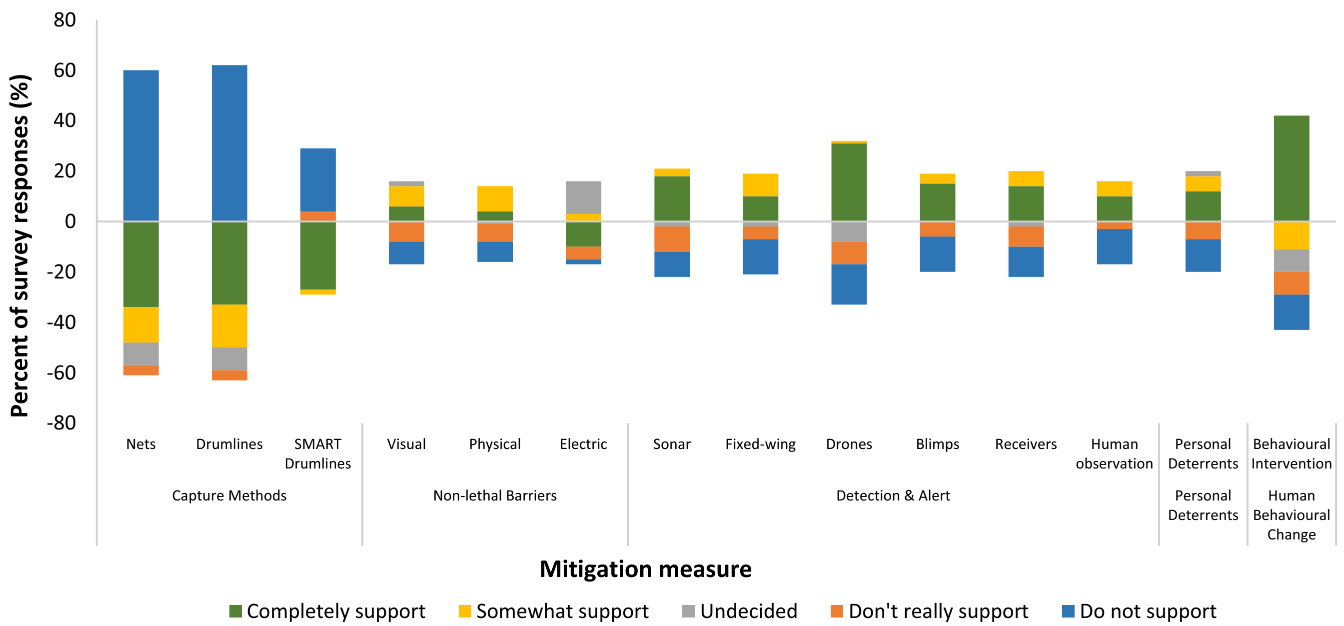

FIGURE 4 Change in respondents' support for *mitigation measure*, in place compared with respondents' support for not having any *mitigation measures* in place, which was used as the baseline. For each *mitigation measure*, percentages were estimated by subtracting the percentage of respondents in each Likert category from the corresponding percentage for situations when no *mitigation measures* are in place. Positive percentages indicate an increased number of respondents in that category; negative percentages indicate a decreased number of respondents.

TABLE 3 Swing weights for each *objective* and stakeholder.

Objectives		Stakeholder				
Primary	Secondary	Scientists	NGOs	SLSC	Public	Managers
Improve human safety	Improve human safety	0.13	0.12	0.1	0.08	0.17
Minimise impact on the economy	Minimise management costs	0.06	0.03	0.05	0.04	0.08
	Support local ocean-based businesses	0.05	0.05	0.07	0.06	0.12
	Support local non-ocean-based businesses	0.03	0.04	0.06	0.05	0.12
	Support tourism	0.06	0.06	0.08	0.06	0.12
Minimise impact on social values	Support community well-being	0.07	0.08	0.08	0.07	0.12
	Maximise community support for mitigation method	0.08	0.07	0.08	0.07	0.08
Minimise impact on biodiversity	Minimise impact on target non-protected sharks	0.1	0.12	0.08	0.1	0.02
	Minimise impact on target protected sharks	0.13	0.12	0.08	0.1	0.02
	Minimise impact on non-target species populations not listed as threatened or protected	0.11	0.12	0.09	0.12	0.05
	Minimise impact on non-target threatened and iconic species	0.12	0.12	0.12	0.12	0.05
	Minimise impacts to surrounding habitat	0.06	0.07	0.11	0.12	0.05

Note: Blue represents a higher swing weight score and yellow indicates the lowest score given for the stakeholder group. A higher score indicates higher importance placed on the given *objective* by the stakeholder group with green indicating the least importance level given.

TABLE 4 Multi-attribute utility (MAU) scores representing the suitability for each *mitigation measures*.

		Stakeholders				
Mitigation measures		Scientists	NGOs	SLSC	Public	Managers
No activity	Nothing	0.12	0.12	0.11	0.12	0.06
Capture methods	Nets	0.15	0.15	0.15	0.13	0.23
	Drumlines	0.14	0.14	0.14	0.13	0.20
	SMART drumlines	0.18	0.19	0.18	0.17	0.21
Non-lethal barriers	Visual barrier	0.20	0.20	0.19	0.19	0.20
	Physical barrier	0.31	0.31	0.28	0.26	0.37
	Electrical barrier	0.22	0.22	0.20	0.20	0.23
Detection and alert	Sonar	0.20	0.21	0.20	0.20	0.20
	Aerial surveillance	0.23	0.24	0.24	0.23	0.25
	Drones	0.28	0.29	0.28	0.27	0.32
	Blimps	0.27	0.27	0.26	0.25	0.29
	Tagging	0.22	0.22	0.21	0.20	0.23
	Human observation	0.23	0.23	0.22	0.22	0.23
Personal deterrents	Personal deterrents	0.30	0.29	0.28	0.26	0.32
Human behavioural change	Behavioural interventions	0.27	0.27	0.26	0.25	0.29

Note: Scores represent the aggregate of the performance scores listed in Table 3 and stakeholder swing weights in Table 4. Darker blue indicates a higher MAU score and therefore higher ranking. Yellow represents the lower MAU and suitability.

SMART drumlines, non-lethal barriers and sonar (Table 5). Detection and alert systems and behavioural intervention were the *mitigation measures* with the least amount of uncertainty. While the level of uncertainty related to personal deterrents was typically low, their ability to improve human safety was highly uncertain. This *objective* was also the most uncertain *objective* across most *mitigation measures*.

TABLE 5 Temperature-coloured (from light yellow to dark blue) representing the difference between the predicted scores of best-case and worst-case scenarios.

	No activity	Capture methods			Non-lethal barriers			Detection and alert						Personal deterrents	Human behavioural change
Objectives	Nothing	Mesh nets	Drumlines	SMART drumlines	Visual barrier	Physical barrier	Electrical barrier	Sonar	Aerial surveillance	Drones	Blimps	Tagging	Human observation	Personal deterrents	Behavioural intervention
Improve human safety	0.2	1.9	1.9	1.7	1.4	0.8	2	1.1	1.7	2	2	1.9	1.5	2.6	1.3
Minimise management costs	0	1.1	1	0.9	0.8	0.8	0.1	0.6	1	1	0.9	1	0.9	0.9	1.3
Support local ocean activity-based businesses	0.9	1.4	1.6	1.4	1.4	1.6	1.4	1.3	1.4	1.6	1.3	1	1.3	1	1.1
Support local non-ocean activity-based businesses	0.6	1.3	1.6	1.2	1.1	1.4	1	1.1	1.3	1.2	1.1	0.9	0.9	0.6	0.9
Support tourism	0.8	1.4	1.3	1.3	1.4	1.3	1.1	1.1	1.4	1.4	1.1	0.9	1.3	0.7	1
Minimise impact on non-protected target sharks	0	2	2	1.2	0.9	0.6	0.9	0.5	0	0.2	0	0.4	0	0.7	0.2
Minimise impact on protected target sharks	0	2	2.1	1.1	0.9	0.6	0.9	0.5	0	0.2	0	0.7	0	0.7	0.2
Minimise impact on non-target species populations	0	1.8	1.6	1.2	1	0.7	0.9	0.6	0	0.2	0	0.1	0	0.7	0.2
Minimise impact on non-target and iconic species	0	1.8	1.6	1.2	0.9	0.6	0.8	0.6	0	0.2	0	0.3	0	0.4	0.2
Minimise impacts to surrounding habitat	0	1.1	0.9	0.8	1.8	1.9	1.8	0.9	0.2	0.2	0.4	0.8	0	0.3	0.2

Note: Scores indicate the level of uncertainty surrounding the performance of a *mitigation measure* against an *objective*. Light yellow indicates little uncertainty, and dark blue indicates high uncertainty.

In contrast, the least uncertain *objectives* were the *objectives* related to minimising environmental impacts, aside from lethal measures and non-lethal barriers for which the uncertainty related to minimising environmental impacts remained high. The score variation across experts showed similar trends to the difference between best and worst-case scenarios (Figures S3–S5).

4 | DISCUSSION

We developed a new framework to assess and rank shark-bite mitigation against a newly defined set of *performance criteria* that incorporates the social, economic and environmental aspects often mentioned when considering shark-bite mitigation programmes. Our framework used an expert panel combining scientists and managers from government agencies involved in shark-bite mitigation to identify and use 12 performance standards (*objectives*) to compare 15 mitigation devices and/or strategies (*mitigation measures*), while accounting for subjective ranking of the importance across stakeholders. Likewise, with other multi-decision assessments of HWC, this study considered *objectives* across social, economic and ecological aspects; however, the number of *objectives* and *mitigation measures* exceeds those compared with similar studies assessing around 6–8 criteria used to produce a performance score (Davies et al., 2013; Voskamp et al., 2023). We provide a flexible assessment framework that can identify which *mitigation measure*(*s*) are best suited to a location and tested our framework for the Gold Coast region in Australia. Our framework provides a quantitative method to compare between the increasingly diverse *mitigation measures* currently being used and developed, and incorporates location-specific requirements and subjective views, which may vary between locations or stakeholders.

A key feature of our framework is its flexibility in terms of *mitigation measures* included in the assessment and of the *performance criteria* used to assess the *mitigation measures*. Measures can be added or removed depending on the location where the framework is used, as the suitability of some *mitigation measures* will vary between locations. For example, while human observations from vantage points have been successfully used in Cape Town for over 10 years (Engelbrecht et al., 2017), their use is limited to locations with high vantage points in proximity to beaches. Similarly, many barriers are less likely to be usable at ocean beaches due to the large swell and surf. Multi-objective analysis usually only accounts for the performance of *mitigation measures* against secondary *objectives* within a broader category, possibly causing disparity in the weighting of scores for the primary *objectives* that hold more secondary *objectives* (Davies et al., 2013; Robinson et al., 2016; Smith et al., 2023; Voskamp et al., 2023). To help avoid this issue, our framework accounts for the potential disproportionate number of secondary *objectives* within each primary objective by calculating MAU scores based on the average MAU for each primary *objective* (i.e. grand mean of MAU scores). This prevents the number of secondary *objectives* from affecting the importance of primary *objectives*. Yet, differences in performance scores among secondary *objectives* are still available and can be used to investigate details of the assessment (Table S3a). For example, within the *objective* to minimise impacts to biodiversity (primary *objective*), mesh nets might have minimal impact on surrounding habitats while negatively impacting target and non-target species. Our framework also accounts for different swing weights across the secondary *objectives*, which can hold varying degrees of importance among stakeholders.

Our framework can be used to assess a range of HWC issues using different management options and criteria to score these options, while incorporating preferences from relevant stakeholders of the HWC being considered. For example, the framework could be used to compare *mitigation measures* to reduce shark depredation, that is where fishers lose their catch to sharks (Mitchell et al., 2022; Smith et al., 2022). In this situation, our framework could be modified by including recreational and commercial fishers or groups as stakeholders, while an important criterion to consider might be the applicability of the measure or device across sectors and fishing gear. Our framework is a quantitative and flexible method that can be used to identify and compare management options for a range of complex environmental issues, including bycatch mitigation approaches in fisheries management (Gilman et al., 2021; Squires et al., 2021), water resource management (Mysiak et al., 2005) or climate change mitigation strategy selection (Cohen et al., 2019; Daniell et al., 2011; Roelich & Giesekam, 2018).

Our framework expands on standard multi-objective decision-making tools used in previous environmental management studies (e.g. Davies et al., 2013; Martin et al., 2009; Robinson et al., 2016) by estimating the variations in the best-estimate scores across the expert panel and differences in scores between best-case and worst-case scenarios. The combination of these two types of variations helps improve the value of decision-making outcomes by estimating variability and uncertainty in the effectiveness of a management solution (Nicholson & Possingham, 2007). While it is expected that variations in best-estimates across experts and differences between best-case and worst-case scenarios are correlated, there might still be instances when there is little variation in the best-case score across experts, but where the differences between best-case and worst-case scenarios remain large, for example when little information is available, but experts are in agreement. Both estimates of variations are useful means to highlight which *mitigation measures* or *performance criteria* lack information and identify knowledge gaps and research needs.

Our comparison of shark-bite *mitigation measures* is one of the first to use a multi-objective decision-making tool to compare solutions to manage marine-based HWC and accounts for the uncertainty in evaluating the different and ever-growing mitigation strategies available. Our study also highlights the intricate trade-offs that arise from the different and sometimes competing values of diverse stakeholders and the importance of accounting for them when considering management options (Edelenbos & Klijn, 2006; Scolobig & Lilliestam, 2016; van Vilet et al., 2020). Tools like our framework will become increasingly valued and sought after as HWC become more prevalent with humans increasingly encroaching and interacting with nature (Schell et al., 2021). In addition, the management of these conflicts will become more complex from the range of factors that need to be considered (Marshall et al., 2007; Messmer, 2000; Ravenelle & Nyhus, 2017) and growing public expectation of governmental response and management (Berry & Rondinelli, 1998).

4.1 | Comparison of shark-bite *mitigation measures* for the Gold Coast region

In our case study of the Gold Coast region, physical barriers, drones or blimps, personal deterrents and behavioural interventions were the highest ranked across all stakeholders, while lethal measures were the lowest ranked measures (aside from not having any *mitigation measures* in place), aligning with the social shift in public preference and growing support for non-lethal measures (Martin et al., 2022; Pepin-Neff & Wynter, 2018; Simmons et al., 2021; Simmons & Mehmet, 2018). While this preference is shared across stakeholders, it also highlights the complexity of selecting *mitigation measures*. Indeed, the framework identified disparate *mitigation measures* as the top four measures, that is a barrier, detection system, deterrent and behavioural intervention. This is likely to be linked to the Gold Coast encompassing different types of water bodies, for example enclosed bays, surf beaches, turbid canals and water users, e swimmers, divers, surfers. Multiple *mitigation measures* can also be used concurrently such that there does not need to be one measure surpassing all others. For example, the New South Wales Shark Management Program uses a variety of measures to reduce the risk of shark bites, including SMART drumlines, drones, mesh nets and tagging.

Physical barriers were ranked highest across all *mitigation measures* because of their ability to reduce shark bites by stopping sharks from entering a specific area (e.g. popular a swimming area), and therefore score highly for 'improving human safety' which was also the most important *objectives* for most stakeholders. However, the installation and maintenance of physical barriers is not practical at many Gold Coast beaches due to the large swell and surf and are better suited to non-surf beaches and canal systems. Other types of barriers, such as visual or electrical, have lower MAU scores due to their reduced ability to ensure human safety compared with physical barriers. For example, previous studies assessing the efficacy of visual barriers have shown varied ability to fully exclude sharks with some sharks frequently going through the barrier (e.g. SharkSafe Barrier; O'Connell et al., 2017, 2019, 2021).

Overall, the framework identifies a lack of support for lethal measures from most stakeholders. Managers scored lethal measures higher compared with other stakeholders (due to the managers' lower score for the *objective* of minimising impact to biodiversity), suggesting that the support for lethal measures is greater from managers than other stakeholders. Yet, non-lethal measures ranked more highly than the lethal measures currently being used across all stakeholders. These results further highlight the societal shift documented in public sentiment surveys showing the increasing preference for non-lethal measures (Martin et al., 2022; Simmons et al., 2021; Simmons & Mehmet, 2018). However, our findings also highlight a discrepancy between managers and all other stakeholders, that is scientists, NGOs, SLSC and the public, as scores for lethal measures from other stakeholders were much lower than those from managers. This might be linked to government policies or cultural changes in how lethal measures are perceived. Regardless of the scores for lethal measures, they also had some of the highest levels of uncertainty, highlighting the challenges of scoring these measures.

SMART drumlines were ranked as the lowest scored non-lethal *mitigation measure*, mostly because of their low score in the social component of the assessment. The relatively low score was probably driven by the limited understanding of the new technology, and the possible belief that SMART drumline baits attract sharks and should not be located near swimmers, and/or because of concerns about the potential impacts of capture and handling (Martin et al., 2022). However, recent studies show that bull sharks are infrequently caught by SMART drumlines and therefore unlikely to be attracted to them (Tate et al., 2019) and that SMART drumlines do not affect the alongshore movement of white sharks (Colefax et al., 2020; Guyomard et al., 2020). Studies have also shown that sharks are released in good health and with minimal stress (Gallagher et al., 2019; Tate et al., 2019), and that they temporarily move offshore following release (Butcher et al., 2023; Grainger et al., 2022). However, response time will be location-dependent, and it might not be feasible to ensure a 30-min response time in some locations, potentially affecting the likelihood of survival, especially for sensitive species, such as hammerhead sharks (*Sphyrna* spp.; Dapp et al., 2016). As SMART drumlines remain a capture method, they scored lower for impacts on protected species and non-target species compared with other non-lethal measures. The low rank of SMART drumlines in our study highlights that while they are popular in some other regions, the Gold Coast region might not be favourable towards SMART drumlines. If SMART drumlines were intended to be used off the Gold Coast, education about the likelihood of attracting sharks and their post-release condition could increase public understanding and acceptance prior to introducing this technology.

Devices using electric fields, that is, electric barriers and personal deterrents, also did not rank highly in the social component as many respondents were 'unsure' about how willing they would be to go in the water with these type of *mitigation measures* in place. While the ability of electric fields to deter sharks has been shown across several studies and species (Clarke et al., 2024; Gauthier et al., 2019; Huveneers et al., 2013; Huveneers et al., 2018; Kempster et al., 2016; Riley et al., 2022; Thiele et al., 2020), a remaining public concern is that electric fields might be attracting sharks to an area prior to deterring them at close range, leading to these devices increasing shark-bite risk rather than reducing it (Martin et al., 2022). There might therefore be a need to improved education about the efficacy of electric deterrents and to address the misconceptions regarding these devices.

Drones are increasingly identified as appropriate shark-bite *mitigation measures* (McPhee et al., 2021; Stokes et al., 2020), receiving a lot of public support (Martin et al., 2022). In contrast, aerial fixed-wing surveillance scored lower and received less public support. Both aim to reduce shark-bite risk by detecting sharks from the air and have similar constraints (i.e. poor detection on days with poor weather conditions, observer fatigue, detection biases; Butcher et al., 2019, 2021; Colefax, 2020). The disparity in ranking might therefore be because of the 'shiny object syndrome', with drones and blimps being relatively new, or because they can also spend much more time over individual beaches than manned aircraft, especially if multiple batteries are being used, and are therefore more efficient and are significantly cheaper than rotary or fixed-wing aircraft (Butcher et al., 2021; Colefax, 2020).

Sonar technology has the lowest MAU scores of the detection and alert category across stakeholders. This is likely due to the limited capacity of this technology to detect sharks consistently and accurately. This technology is also not currently able to cover large areas or the surf zone characteristic of the Gold Coast (Chapuis et al., 2019; McPhee et al., 2021; Parsons et al., 2014). If sonar technology is able to overcome the technological limitations over longer distances, it could be a viable option for the future as it remains a non-lethal mitigation that is highly supported by the general public (Martin et al., 2022).

Tagging has relatively low MAU scores, similar to sonar technology and electrical barriers. This is likely because of the relatively lower performance scores for impacts on human safety compared with other *mitigation measures* like aerial surveillance and physical barriers, due to the need for an extensive tagging programme to ensure that a sufficiently large proportion of sharks are tagged for this *mitigation measure* to be successful. It also requires an extensive network of acoustic receivers (Bradford et al., 2011), an effective way of communicating those tagged-shark detections to the community. The information provided to the community also needs to drive behavioural change, which might not necessarily occur. For instance, tagging and community alerts can lead to information fatigue where beachgoers begin to opt out from receiving the information or draw upon other cues to choose how they will use the beach (van Putten et al., 2022).

The high score of behavioural interventions highlights an increasing acceptance that adjustments to human behaviour can reduce risk of shark bites (Barnett et al., 2022; van Putten et al., 2022). This sentiment has previously been observed where education and increased personal responsibility were considered more important in reducing the likelihood of shark-bite incidents than shark control programmes, highlighting that managing people is preferred to trying to manage the animals (Barnett et al., 2022; van Putten et al., 2022). However, scoring behavioural interventions was particularly difficult because the likely success of behavioural interventions is dependent on elements which were not captured by the framework we used. Specifically, the success of behavioural change interventions should consider the potential impact of the behavioural change sought and the likelihood of changing behaviour through the intervention (Berger-Tal & Saltz, 2016). There are also many possible behavioural interventions (e.g. policies, 'no go' zones, educational programmes and communication) and our framework focused on those likely to reduce the chance of being bitten (e.g. do not go in the water in proximity to bait balls or spearfishers, do not swim at dawn and dusk). Other means to use behavioural interventions include reducing probability of encountering sharks, for example avoid areas and/or times where sharks occur more frequently (Hoel & Chin, 2020; Smith et al., 2021). A separate framework exploring the various behavioural interventions available and different *performance criteria* might be more suitable and required to assess behavioural interventions.

Education is an essential component of any shark-bite mitigation programme. Effective education and communication programmes can help ensure the public understands actual (rather than perceived) shark-bite risk, the principles and limitations of each *mitigation measure*, and their ability to reduce risk. Education about *mitigation measures* will help ensure that public sentiments regarding these measures are based on accurate information rather than misleading opinions. For example, if the public wrongly overestimate the ability of a *mitigation measure* to reduce risk, this measure might score highly in the 'support community wellbeing' and 'maximize community support' *objectives* and rank highly overall because of a misconception. While public opinion is often considered when making management decisions, the benefit of our framework will be greatest if public sentiment is based on accurate information rather than misconception. This is particularly important as public opinion that may not be accurate and/or is missing key information can influence policy decisions (Cullen-Knox et al., 2017). For example, the Australian government imposed a moratorium on the operations of a large factory trawler against science-based advice from the government's own independent fisheries management agency in response to an intense social media campaign led by international conservation groups, Green politicians and recreational fishers (Tracey et al., 2013). In the case of shark-bite *mitigation measures*, public opinion can be influenced through marketing campaigns by companies selling mitigation products and can overestimate efficacy in a situation or environment where a measure is unlikely to reduce risk. In our study, the survey respondents placed more importance on the impacts on non-target species and surrounding habitat, while placing less importance on human safety compared with other stakeholders. While these views may be representative of the general public, the results could be biased towards the views of respondents with links to conservations groups. Education around shark awareness is also crucial to ensure that people know how to reduce their personal risk through behavioural changes (e.g. avoiding swimming/surfing at times of higher probability of a shark-human interaction, when to consider using a personal deterrent, or being able to respond to a shark bite with suitable first aid/trauma kit).

The score variation between experts and differences between best-case and worse-case scenarios shows that 'improve human safety' had the highest uncertainty across *mitigation measures*, highlighting the challenges of empirically estimating the efficacy of a measure. Minimising impact on the economy also had high uncertainty as a group (aside for minimising management costs) because of the lack of quantitative studies estimating the economic impacts of shark bites on local businesses and tourism. High uncertainty can also represent true variability. The uncertainty of the 'improve human safety' *objective* for personal deterrents was highest across all *mitigation measures* and *objectives* because of the documented variability in efficacy of shark deterrents, with some devices reducing the probability of being bitten by 60% while others having negligible effects (Gauthier et al., 2019; Huveneers et al., 2018).

5 | CONCLUSION

With the increase in the number of shark bites over the last decade, the concern for human safety, combined with the rise of environmentally conscious attitudes and behaviour of the public, has led to ongoing controversy and debate among stakeholders (Meeuwig et al., 2015; Meeuwig & Ferreira, 2014). Our multi-objective framework helps to identify and compare shark-bite *mitigation measures* by considering a range of criteria (i.e. efficacy, and the social, economic and environmental aspects), while accounting for subjective ranking of the importance of these *performance criteria* across stakeholders. It is a flexible framework that can be used across a broad range of locations and situations (e.g. high turbidity, calm, enclosed bay; clear, dynamic, exposed surf beach) and could enable authorities to assess and compare candidate *mitigation measures* for their areas. It also acknowledges that more than one measure might be suitable, and that a combination of measures, recognising a collective responsibility between government and individuals, for example area protection, behavioural changes and education, would likely be most efficient in reducing risk. The flexibility of our framework also means that the measures included in the assessment can be modified depending on stakeholder requirements to include new *mitigation measures* as they are being developed or reduce the number of *mitigation measures* included to focus on specific situations or water users. The *mitigation measures* and *objectives* can also be substituted to address other HWC, for example with bears (Gore, 2004) or baboons (van Doorn & O'Riain, 2020), making the framework applicable to a broad range of contexts and HWC. Yet, this framework only forms part of the solution to the complex management of HWC, and other innovative, multidisciplinary methods and approaches that incorporate multiple perspectives will continue to be required.

AUTHOR CONTRIBUTIONS

Michelle Henriksen and Charlie Huveneers conceived the ideas, collected the data, analysed the data and led the writing of the manuscript. Adam Barnett, Paul Butcher, Andrew Chin, Katherine Frisch, Marcel Green, Jason How, Daryl McPhee, Michael Mikitis, Tracey Scott-Holland, Colin Simpfendorfer and Stephen Taylor assisted with the design methodology and contributed critically to the drafts, and gave final approval for publication.

FUNDING INFORMATION

This research did not recieve any specific funding.

CONFLICT OF INTEREST STATEMENT

All authors of this paper declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy restrictions.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Table S1. Expert panel contributing to the identification and scoring of *mitigation measures* against *objectives* using *performance criteria*.

Table S2. The rank of importance (1-12), being 1 the most important and 12 the least important, and the weighted score (out of 100) provided by the experts (a) Expert panel, (b) NGOs, (c) SLSC and the public (c), and the Government (d).

Table S3. Temperature-coloured (from light yellow to dark blue) table representing standard error of scores across experts for (a) best estimate, (b) worse case, and (c) best case scenarios.

Figure S1. Overall percentage of respondent's willingness to be in the ocean with a *mitigation measure* established.

Figure S2. Overall percentage of the respondent's support for a particular *mitigation measure*.

Figure S3. Mean expert response for a *mitigation measures' performance* against the *objective* criteria under a best estimate scenario using a scale for (a) maximizing the *objective* (higher performance score if preferred); and (b) minimising the *objective* (lower performance score is preferred).

Figure S4. Mean expert response for a *mitigation measures'* performance against the *objective* criteria under a worst-case scenario using a scale for (a) maximizing the *objective* (higher performance score if preferred); and (b) minimising the *objective* (lower performance score is preferred).

Figure S5. Mean expert response for a *mitigation measures'* performance against the *objective* under a best-case scenario using a scale for (a) maximizing the *objective* (higher performance score if preferred); and (b) minimising the *objective* (lower performance score is preferred).

How to cite this article: Henriksen, M., Barnett, A., Butcher, P., Chin, A., Frisch, K., Green, M., How, J., McPhee, D., Mikitis, M., Scott-Holland, T., Simpfendorfer, C., Taylor, S., & Huveneers, C. (2025). Novel risk assessment framework to compare shark-bite mitigation strategies. *People and Nature*, *7*, 1559–1580. https://doi.org/10.1002/pan3.70054