The evolving relationship between humans and sharks

A review and discussion of current shark hazard management strategies to foster co-existence

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Introduction

As the human footprint on the planet grows ever larger, wildlife in both terrestrial and aquatic realms is facing unprecedented challenges, sometimes existential in scale (Ripple et al. 2014; Juan-Jordá et al. 2022; Sherman et al. 2023). These challenges can take a variety of forms. Habitat loss, brought about, for example, by land clearing for agricultural needs (Green et al. 2005), river regulation for power generation (McClure et al. 2008), or through the impacts of human-induced climate change (Hoegh-Guldberg et al. 2017), can strongly affect wildlife, eroding species' resilience and genetic diversity (Laurance et al. 2002; Aguilar et al. 2008; McClure et al. 2008) and constraining foraging, breeding, and dispersal opportunities (Fahrig 2003). Overharvesting of wild marine resources is another serious challenge. This can disrupt demographic processes, force population declines and raise extinction risk (Dulvy et al. 2003; Field et al. 2009; Juan-Jordá et al. 2022), as can the removal of wildlife perceived by humans to pose a threat to the environment or to humans themselves. At the heart of all these challenges lies some 'interaction' between humans and wildlife. When such interactions are deemed adverse to either party, they are often referred to as 'human–wildlife conflicts' (HWCs) (Conover 2002). This definition implies that wildlife is able to consciously engage in conflicts (Peterson et al. 2010). Indeed, recent calls have been made to redefine HWCs more broadly, consisting of two elements: (i) biodiversity 'impacts' that deal with direct interactions between humans and wildlife; and (ii) biodiversity 'conflicts' that centre on human interactions – that is, between those seeking to conserve species, and those with other goals (Young et al. 2010; Redpath et al. 2013).

With the rate and diversity of biodiversity impacts and conflicts predicted to increase globally (Young et al. 2010; Kansky and Knight 2014), solutions are needed that promote coexistence between humans and wildlife while fostering engagement and the willingness for compromise among the human actors involved (Carter and Linnell 2016; Gallagher 2016). Though much of the work on HWCs and their solutions to date has focused on terrestrial systems (e.g. Redpath et al. 2013; Chapron et al. 2014, Kansky and Knight 2014; Carter and Linnell 2016) a marine example involving interactions between humans and sharks poses an intriguing and ongoing challenge for balancing conservation and human safety outcomes, tapping into both the 'impact' and 'conflict' elements of HWCs (Neff 2012; Sabatier and Huveneers 2018; Simpfendorfer et al. 2021).

Human–shark interactions are always multidimensional and often emotional affairs comprising different ecological, social and economic elements. Sharks are unique among marine wildlife in that they can predate upon humans, compete with humans for marine resources and are predated upon by humans in fisheries (Simpfendorfer et al. 2021; Sherman et al. 2023). Given this multifaceted role that sharks play, their iconic nature, in conjunction with the globally threatened conservation status of many shark and ray species (Dulvy et al. 2021; Pacoureau et al. 2021; Sherman et al. 2023), the complexity, conflict and controversy that often surround decisions on how best to manage human–shark interactions and their consequences are hardly surprising.

We focus on this issue further here, motivated by a recent spate of human–shark interactions in New Caledonia, and the actions taken by local authorities to reduce the risk of further negative interactions. We first provide some background into the various roles that sharks play as ecosystem sentinels and cultural totems. Next, we dig deeper into the world of human–shark interactions and chart the evolution of thinking around methods to minimise negative outcomes. We then provide an evidence-based overview of current strategies available for mitigating the risk of negative human–shark impacts in nearshore environments, and conclude with a call for further research into solutions centred around understanding and coexistence between humans and sharks.

Sharks as ecosystem sentinels and cultural icons

Sharks and rays (Class: Chondrichthyes, Subclass: Elasmobranchii) are an ancient, remarkably diverse group of slow-growing predatory fishes that reside in all aquatic environments, from rivers and estuaries, to coastal, pelagic and demersal marine habitats. While the trophic roles of the over 1200 extant shark and ray species are often varied, system-dependent and challenging to assess (Heupel et al. 2014; Roff et al. 2016), their importance as key predators in aquatic ecosystems is universally accepted. Sharks can impart strong top-down effects on ecosystems via direct predation or by inducing behavioural changes in prey taxa (i.e. risk effects – Creel and Christiansen 2008; Heithaus et al. 2008) (e.g. Frid et al. 2007; Heithaus et al. 2007), and

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Hawaiian Proverbs and Sayings That Mention Sharks

ʻŌlelo Noʻeau: Hawaiian Proverbs and Poetical Sayings
by Mary Kawena Pukui
(Honolulu: Bishop Museum Press, 1983)

ʻAi a manō, ʻaʻohe nānā i kumu pali
When the shark (manō) eats, he never troubles to look toward the foot of the cliff. (Said of a person who eats voraciously with no thought of who provided the food, shows no appreciation for what has been done for him, nor has a care for the morrow.)

E ao o pau poʻo, pau hiʻu ia manō
Be careful lest you go head and tail into the shark [manō]. (A warning to be on one's guard. Nanaue, of Waipiʻo, Hawaiʻi, had two forms—that of a man and that of a shark. As people passed his farm to go to the beach, he would utter his warning. After they had passed, he would run to the river, change into a shark, and swim under the water to the sea where he would catch and eat those he had warned. No one knew that it was Nanaue who was eating the people until someone pulled off the shoulder covering he always wore and discovered a shark's mouth between his shoulder blades. After he was put to death the people were safe again.)

He manō holo ʻāina ke aliʻi
The chief is a shark [manō] that travels on land. (The chief, like a shark, is not to be tampered with.)

He niuhi ʻai holopapa o ka moku
The niuhi shark that devours all on the island. (A powerful warrior. The *niuhi* shark was dreaded because of its ferociousness. It was believed that a chief or warrior who captured this vicious denizen of the deep would acquire something of its nature.)

Hoʻahewa na niuhi ia Kaʻahupāhau
The man-eating sharks [niuhi] blamed Kaʻahupāhau. (Evildoers blame the person who safeguards the rights of others. Kaʻahupāhau was the guardian shark goddess of Puʻuloa [Pearl Harbor] who drove out or destroyed all the man-eating sharks.)

Figure 1. Panel of Hawaiian shark-related proverbs (drawn from Pukui 1983)

have the capacity to shape aquatic community structure and function across broad spatial and temporal scales (Ferretti et al. 2010; Roff et al. 2016). There is now compelling evidence that the loss of sharks from ecosystems can have dramatic impacts on food web dynamics, releasing mesoconsumers and affecting the abundance and/or distribution of primary consumers and producers (Myers et al. 2007; Ruppert et al. 2013; Rasher et al. 2017). Wide-ranging sharks also act as important nutrient transfer agents and provide energetic linkages among habitats, as was neatly demonstrated recently for grey reef (*Carcharhinus amblyrhynchos*) and black tip reef (*C. melanopterus*) sharks on Palmyra Atoll (McCauley et al. 2012; Williams et al. 2018). Such results highlight that the impacts of even localised declines in shark populations are capable of extending far beyond the local ecosystem (Simpfendorfer et al. 2021).

In attempting to quantify sharks' roles and place within aquatic ecosystems – ecosystems also used, inhabited and increasingly affected by humans – comparing the cultural status of sharks in different societies may help us to contextualise the longstanding and ongoing debate around how best to manage human–shark interactions (Muter et al. 2013; Neff 2012; McCagh et al. 2015; Hammerton and Ford 2018). In many Pacific Island countries and territories, sharks are revered as deities and guardian spirits, seen as a manifestation of ancestors, a guide to travellers, as a source of food and the subject of countless tales and proverbs (Pukui 1983; Magnuson 1987; Taylor 1993; Hutching 2012; Ames 2013; Kane 2014) (see Fig. 1).

Through this framing, Pacific Island peoples' traditional attitudes towards sharks arguably appear to revolve more around reverence and respect rather than fear (Pukui 1983; Magnuson 1987; Hammerton and Ford 2018). Viewing sharks through this cultural lens can, in many cases, align with conservation objectives, for example, when the hunting and consuming of threatened species or particular specimens is taboo (Ames 2013; Kane 2014). Yet, certain customs might also hamper current conservation goals, for instance, where sharks and shark products have value as food, traditional medicine, art or jewellery (Vannuccini 1999), or contribute to past losses of specimens harvested for characteristic weapons like the *te unun* (shark's tooth spear) (Fig. 2) and the *tetoanea* (shark's tooth sword club) of the Gilbert Islands, Kiribati (Murdoch 1923; Drew et al. 2013).

In contrast to many Pacific Island and indigenous cultures, fear has been a dominant force in traditional western thinking around sharks (Philpott 2002; see Neff and Hueter 2013 for a brief yet comprehensive history). The media and film industry are widely credited with perpetuating the negative perception of these animals, playing on our 'terror of the unknown' (Magnuson 1987; Neff and Yang 2013) and

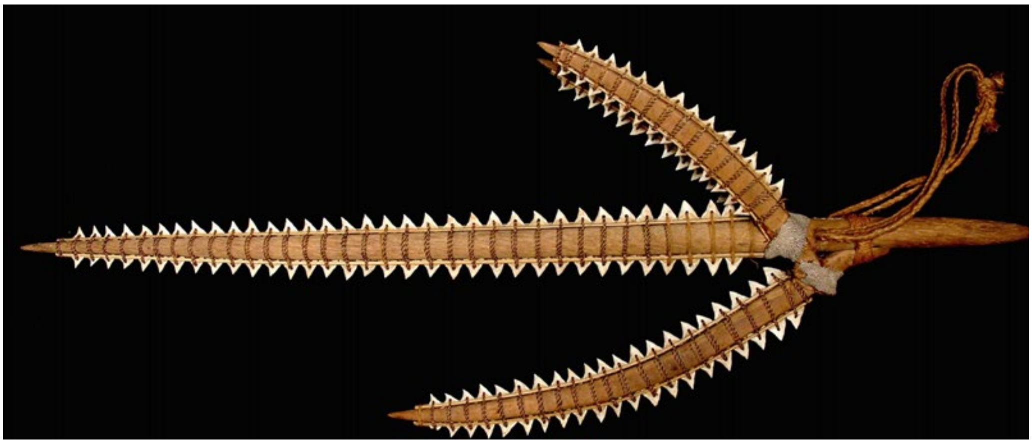

Figure 2. A *te unun*, traditional weapon from the Gilbert Islands, Kiribati (courtesy: National Geographic).

often intensifying public hostility towards sharks through coverage emphasising the risks they pose to humans (Muter et al. 2012). This portrayal has often been associated with suboptimal outcomes from the shark's perspective. The case of the Western Australian (WA) response to a spate of seven fatal shark bites between 2010 and 2013 provides a useful example of how legitimate concerns for human safety and a powerful media influence on public discourse can still override ecological or sociological data and lead to policy decisions with lethal endpoints (e.g. Gibbs and Warren 2015; McCagh et al. 2015; Neff 2015; Gallagher 2016). However, this example also highlights that public sentiment towards sharks and approaches to shark hazard management in Australia (and other Global North nations) is gradually shifting away from traditional themes around fear and the need to control nature towards understanding and celebrating it (Simpfendorfer et al. 2011; Whatmough et al. 2011; Neff and Yang 2013; Dorling 2014). This was evidenced by strong public and scientific opposition to the WA Government's implementation of a baited drum line programme targeting white (*Carcharodon carcharias*), tiger (*Galeocerdo cuvier*) and bull (*Carcharhinus leucas*) sharks following these seven fatalities (see Cressey 2013; McCagh et al. 2015). In 2013, over 100 of the world's leading shark experts wrote an open letter to the WA Government against the drum line proposal[1] that questioned the effectiveness of such programmes in terms of increasing human safety, cited scientific recommendations against its implementation in WA waters (McPhee 2012), and promoted the use of alternative, non-lethal strategies coupled with enhanced public education and awareness as better ways forward. Despite the letter's publication, together with an online petition opposing the programme that collected 34,000 signatures, the programme went ahead, capturing 172 sharks in total, including 50 tiger sharks, which were destroyed, and no white sharks, the primary target of the cull (McCagh et al. 2015; Gallagher 2016). In mid-2014, the WA Government submitted a proposal to the state's Environmental Protection Authority (EPA) to extend the programme for three years (EPA 2014a). During the seven-day period for public comment on the proposal, the EPA received over 20,000 public submissions, most of which opposed the proposal and requested that the EPA undertake a formal assessment (EPA 2014b). Finally, in September 2014, the EPA recommended against the proposal, ending the programme and citing the 'high degree of scientific uncertainty about impacts on the viability of the south-western white shark population' (EPA 2014b).

While just one example covering the initiation, implementation and outcomes of a shark hazard management strategy (see Dudley and Cliff 1993; Wetherbee et al. 1994; Neff 2012; Lemahieu et al. 2017; Gibbs et al. 2020 and Table 1 for others), this Australian case study does illustrate the changing perception of sharks in the western public eye. Criticisms of lethal approaches to managing human–shark impacts are growing in concert with (1) appreciation of the global conservation challenges sharks face, (2) new scientific discoveries in shark biology, behaviour and their roles in maintaining ecosystem health, and raised public awareness of these discoveries, (3) concerns around the environmental consequences of approaches with lethal endpoints and their effectiveness for improving human safety, and (4) the proliferation of effective non-lethal alternatives (see McPhee et al. 2021 and Table 1 for examples). However, as highlighted recently by Simpfendorfer et al. (2021), the concept of the shark remains a divisive force, both among and within societies, and biodiversity conflicts around what these creatures represent, how we value them, and how best to manage human–shark interactions are unlikely to cease in the near-term.

Human–shark interactions – the how, the threats, the opportunities, the solutions

Humans and sharks can interact in at least five different ways: (1) through fishing and fishing-related industries, (2) through science, film and other media, art, customs, folklore or imagination, (3) through underwater, land- or vessel-based encounters with no direct contact, (4) through direct biodiversity impacts from shark bites on humans, and (5) through shark hazard management programmes. Interactions arising via 1, 4 and 5 can pose direct threats of physical harm to one or both parties, though humans stand to gain socio-economically (i.e. through 1), politically and health-wise (i.e. through 5) in some cases. Interactions arising via 2 and 3 might cause psychological distress to people (and sharks too perhaps), embed a negative image of sharks and evoke the 'Jaws Effect' as a political instrument in policy-making (Neff 2015). Yet, such interactions can also bring financial benefits through ecotourism (e.g. Huveneers et al. 2017) and foster human understanding and interest in shark behaviour and current conservation concerns (Apps et al. 2018) that may translate to better physical outcomes for sharks in the long run (Topelko and Dearden 2005). We now delve a little deeper into the threats and opportunities arising from human–shark interactions before presenting some possible solutions in the next sections.

A large number of shark and ray species are currently at high risk of extinction (Dulvy et al. 2021; Pacoureau et al. 2021; Juan-Jordá et al. 2022; Sherman et al. 2023). Indeed, recent analyses based on global biodiversity indicators including the International Union for Conservation of Nature (IUCN) Red List Index, which charts changes in the relative extinction risk of taxa, have shown that three quarters of oceanic species (Pacoureau et al. 2021) and 59% of coral reef–associated species (Sherman et al. 2023) are threatened with extinction. Overfishing is widely accepted as the number one cause (Dulvy et al. 2021). Since 1970, the

[1] https://www.southernfriedscience.com/more-than-100-shark-scientists-including-me-oppose-the-cull-in-western-australia/

global abundance of oceanic sharks and rays has decreased by 71%, with the 18-fold increase in relative fishing pressure observed over the same period being identified as the key driver of the decline (Pacoureau et al. 2021). Populations of coral reef–associated species have also undergone marked declines over the past 70 years approximately, primarily as a result of fishing, but also compounded by the effects of climate change and habitat loss (Dulvy et al. 2021; Sherman et al. 2023). Shark and ray species are mostly 'K-selected', exhibiting low lifetime reproductive potential and reaching maturity late (Conrath and Musick 2012). Hence, many species are both highly susceptible to overfishing (Dulvy et al. 2008, 2021; Feretti et al. 2010; Gallagher et al. 2012) and recover slowly from it (Smith et al. 1998).

Despite these well publicised declines, sharks and rays continue to be heavily harvested across the world's oceans (Clarke et al. 2013; Davidson et al. 2016; Peatman et al. 2023). In the western and central Pacific Ocean (WCPO) annual elasmobranch (sharks, rays and skates) catch from the tuna fishery estimates have been trending up since 2015, with the most recent estimate (for 2019) approaching 100,000 individuals per year (Peatman et al. 2023). This is a small (yet still significant) quantity of animals compared with global landings, which peaked at between 63 and 273 million individuals per year in the early 2000s, with more recent estimates of around 780,000 tonnes caught per annum (Davidson et al. 2016). It is important to note also that these figures are likely to be underestimates of the true catch, given that shark catches are often underreported in fishery statistics (Clarke et al. 2013) and fisheries observer records (Forget et al. 2021; Peatman et al. 2023).

Shark catches contribute to a lucrative global trade in shark products, including meat, fins, gill plates, skin and liver oil (Dent and Clarke 2015; McClenachan et al. 2016; Wu 2016; HSI 2021) which in turn supports livelihoods, economies and food security in many countries (Dent and Clarke 2015). Of all shark-derived products, fins provide the greatest economic value at all levels of the supply chain (Simpfendorfer and Dulvy 2017; Human Society International (HSI) 2021; Hasan et al. 2023). With continuing high demand across the Global South and North (HSI 2021; but see Eriksson and Clarke 2015), coupled with poor traceability and industry regulation, fishing for, and trade in, shark fins is seen to represent one of the key global threats to shark populations (Hasan et al. 2023). These issues again highlight the tension between socio-economic needs of some groups of humans and the conservation objectives of others, with sharks sitting squarely in the middle. That said, a focus on improving industry transparency, product traceability and a better integration of science-based management, by leveraging the power of international treaties such as the Convention on Migratory Species and the Convention on International Trade in Endangered Species (CITES), may be one path towards more sustainable shark fisheries and the ethical use of products they provide (Vincent et al. 2014; Simpfendorfer and Dulvy 2017; Hasan et al. 2023).

Ecotourism based around shark observation offers an alternative way for humans and sharks to interact. Since the early 1990s, shark tourism, commonly involving diving, snorkelling or other forms of visual engagement with sharks, has grown in popularity internationally and is now highly profitable (Anderson and Ahmed 1993; Dicken and Hosking 2009; Cisneros-Montemayor et al. 2013; Huveneers et al. 2017; Gonzáles-Mantilla et al. 2021). In a global survey of the distribution and economic value of shark-based ecotourism operations up to 2010, Gallagher and Hammerschlag (2011) identified 376 established operations in 83 locations across 29 different countries. Soon after, Cisneros-Montemayor et al. (2013) evaluated the global economic benefits associated with shark 'watching', which they defined as "... any form of observing sharks in their natural habitat without intention to harm them". They estimated that around 590,000 divers partake each year internationally, contributing greater than USD 314 million per annum and supporting 10,000 jobs. These figures were predicted to more than double by the early 2030s (Cisneros-Montemayor et al. 2013), a prediction supported recently by Healy et al. (2020) who documented shark tourism operations occurring across at least 42 countries as of November 2017. Shark tourism also represents an important tourist sector for small island nations (e.g. Anderson and Ahmed 1993; Anderson et al. 2011; Gonzáles-Mantilla et al. 2021), including PICTs, with several studies confirming its socio-economic value to Fiji (Brunnschweiler 2010; Vianna et al. 2011), French Polynesia (Clua et al. 2011), and Palau (Vianna et al. 2012), among others. Palau designated the world's first shark sanctuary in 2009, and a 2010 socio-economic survey of divers, dive operators, guides and fishers indicated that shark-diving was the third largest contributor to the Palauan gross tax revenue, contributing USD 18 million per year to the economy and 8% of annual gross domestic product (Vianna et al. 2012). It was estimated that if the approximately 100 sharks regularly visited by tourist operators at that time were captured by fishers, their economic value would represent a fraction of what these animals were worth as a tourist drawcard (Vianna et al. 2012).

Aside from the economic benefits, there is also evidence that shark tourism can impart important community and conservation benefits, providing value to humans and to sharks through strengthening our connection with nature and raising our awareness of sharks' important roles within it (Apps et al. 2018). Even so, the industry can pose risks to target species, environments and humans if human–shark interactions are poorly handled or in the absence of appropriate management controls (see Clua 2018; Healy et al. 2020 for examples).

It is clear that humans and sharks can interact in diverse ways, but few interactions present a more challenging social and environmental conundrum than when a shark bites a human (Gibbs et al. 2020). Each year across the world, a small number of interactions between humans and sharks result in human injury or death. These interactions are commonly referred to as 'shark attacks' or 'shark bites'. The most recent data from the Florida Museum of Natural History's International Shark Attack File (ISAF)[2] highlights the strong year-to-year, decadal and regional variability in both the numbers of unprovoked shark attacks recorded globally (Fig. 3) and the rate of attacks (Midway et al. 2019). Though some caution is warranted in interpreting this data due to changes in reporting rates through time, a general decrease in annual numbers of shark-bite incidents since 2015 is evident. Moreover, the fatality rate from these incidents continues its longer-term decline (Fig. 3; ISAF 2023).

These declines in part reflect advances in beach safety, medical treatment and public awareness (ISAF 2023). Interestingly, in some regions where the incidence of attacks has risen through time (e.g. white shark attacks in California), the attack risk for individual ocean users has declined, a pattern exposed after accounting for human population growth and trends in ocean use (Ferretti et al. 2014). Attack risk is often linked with human population size, though other factors like the level of coastal development, local- and broad-scale environmental conditions, and changes in behaviour and spatial distribution of humans and sharks are emerging as important (West 2011; McPhee 2014; Chapman and McPhee 2016).

While the mechanisms influencing shark attack risk are still under study, we do know that shark attacks pose a low chance but high consequence risk for humans, one that can impart substantial physical and psychological damage to individuals and potentially affect the economies of beach communities (McPhee 2012). Rather unsurprisingly then, how best to manage and mitigate this risk remains a complex, emotionally charged, hotly debated topic. Neff (2012) neatly captures the complexity:

> "There are no simple government solutions when sharks bite people. These rare and sometimes fatal incidents are fraught with uncertainties regarding what happened, why it occurred, and how best to respond. Shark bites represent an unresolved puzzle for coastal managers, scientists, policymakers, and conservationists, who attempt to balance the protection of endangered predatory marine animals with the harm the public can experience from human–marine life conflicts. This dilemma is complicated by the low probability and dreadful consequences of these events, the high degree of public emotion they elicit, and policy responses that can deplete endangered species' populations. Yet, shark bite incidents are reported annually in nations across the globe, usually without policy changes. It is when human behaviours or perceptions change, not shark behaviour, that problems are observed and government action is requested."

Logic dictates that on a global scale, developing solutions to support human and shark coexistence is necessary for conservation of sharks and minimisation of risks to humans (Gallagher 2016; Simmons and Mehmet 2018; Gibbs et al. 2020). This need is particularly pressing, given the increase in anthropogenic activities in coastal areas and current threats faced by shark populations. A substantial body of research now exists into methods aimed at minimising the chance of negative human–shark encounters, with substantial progress made in recent times due to the interplay of technological advances and improved scientific and public understanding of shark behaviour (e.g. McPhee 2012; DeNezzo 2019; Gibbs et al. 2020; McPhee et al. 2021, 2022). Therefore, in defining the most appropriate action to take to mitigate the

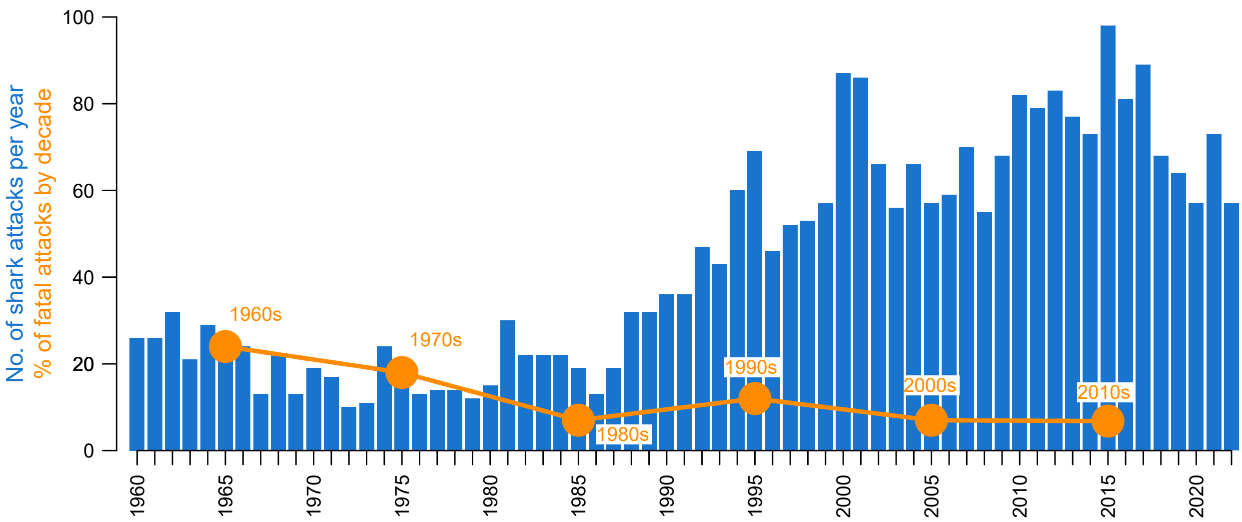

Figure 3. Number of unprovoked shark attacks per year worldwide between 1960 and 2022 (blue bars) and the percentage of attacks that were fatal by decade (orange circles) (Data sourced from the ISAF https://www.floridamuseum.ufl.edu/shark-attacks/trends/frequency-rates/world/) [accessed 12 December 2023]

[2] https://www.floridamuseum.ufl.edu/shark-attacks/

risk of attack by a particular species and/or in a particular locality, it might be prudent to look at examples from elsewhere to gain the most objective, evidence-based views on the appropriate strategy or strategies to employ.

To this end, in Table 1 we list the current shark hazard management strategies available for mitigating risk of negative human–shark impacts in nearshore environments. By providing information on the key benefits and drawbacks of each strategy, linked to relevant scientific literature, the table aims to provide a reference to managers and policy-makers faced with decisions around how to balance social, economic, environmental and political values to achieve optimal outcomes for sharks and humans. Strategies are classified under 'lethal' and 'non-lethal' subheadings, reflecting the endpoint from the shark's perspective.

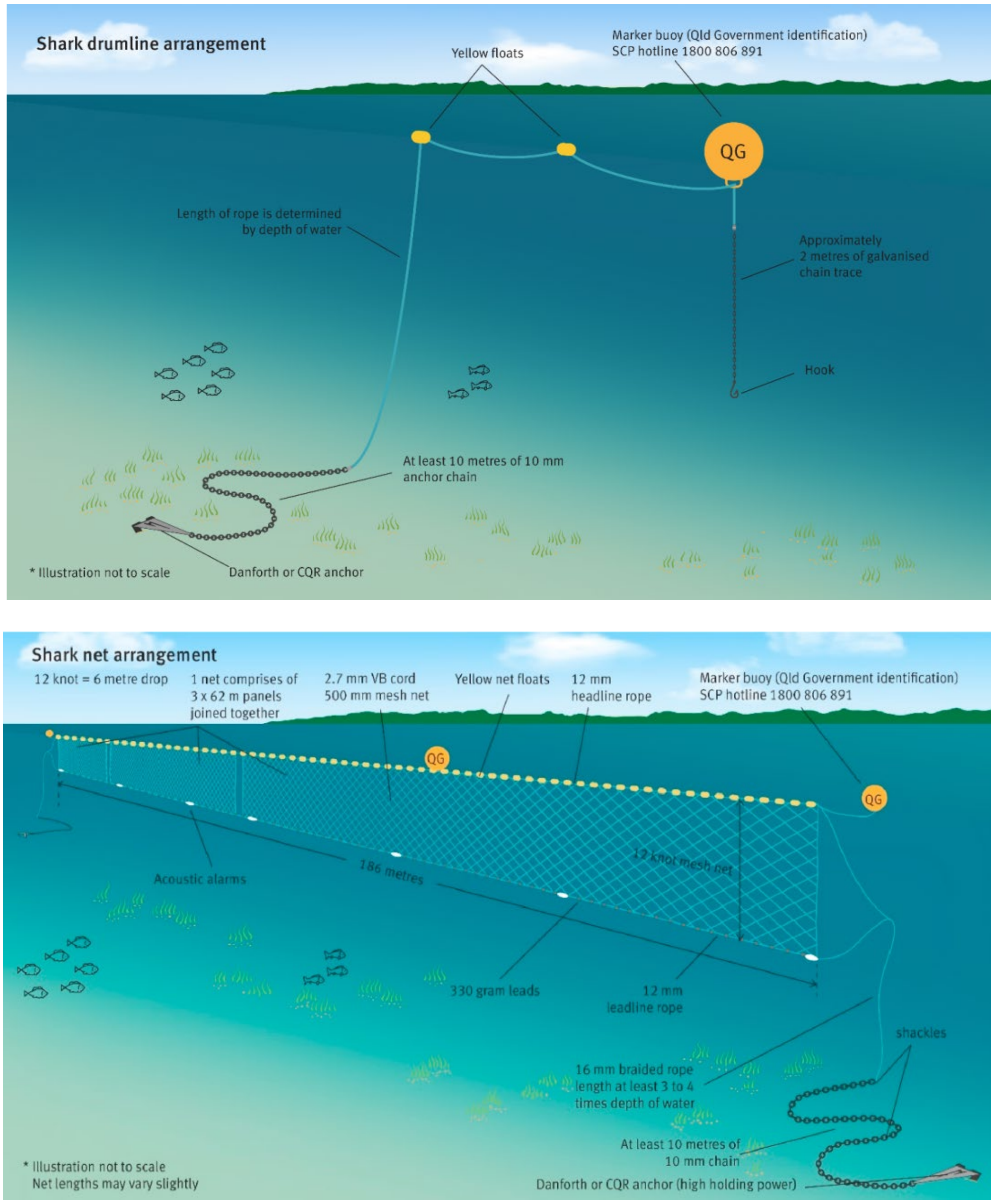

Figure 4. Lethal shark hazard management strategies - shark nets and shark drumline (redrawn from McPhee et al. 2021)

Table 1. Available strategies for mitigating risk of negative human–shark impacts in nearshore environments

Management strategy	Positive consequences	Negative consequences	Notes	References
Lethal strategies				
Shark culling • Several methods: gillnets (a.k.a "shark nets"), baited drum lines, longlines. • Active and passive gears. • Lethal control methods.	• Decreased perceived level of risk to public. • Public feel that action is being taken to reduce shark bite/attack risk. • If implemented in collaboration with scientists, could provide opportunities for collection of biological samples from captured animals to better understand shark biology, ecology and genetics.	• Lethal end point for sharks. • Contributes to global trends of elasmobranch (sharks, rays and skates) population decline. • Extremely challenging to objectively quantify success or failure of culling efforts. • Unpredictable effects of removal of top predators on ecosystem dynamics and functioning. • Potentially high non-target, by-catch species entanglement and/or mortality (depending on gear type used for culling). • The two main targeted species in New Caledonia, the tiger shark (*Galeocerdo cuvier*) and bull shark (*Carcharhinus leucas*), are classified as 'Near Threatened' internationally on the IUCN Red List. • Growing public concerns about the environmental impacts of culling exercises. • Uncertainty around their effectiveness for improving human safety. • Poor public approval – inconsistency with contemporary societal values in the face of effective non-lethal technologies becoming available. • Approach ignores the potential for long-range movement of these species and immigration back into previously fished areas. • Set up and operational costs: high: approx. AUD 1,000,000 per year for large programmes.	• Lack of scientific evidence for culling activities measurably decreasing attack rates from tiger or bull sharks (see case studies in Hawaii, South Africa, and Queensland and New South Wales, in Australia). • No correlation found between the abundance of sharks in the local area and the risk of a shark attack (see results from the 2014 tiger shark drum line programme in Western Australia).	Wetherbee et al. 1994 Treves et al. 2006 Gibbs et al. 2020 Feretti et al. 2010 Burkholder et al. 2013 Ruppert et al. 2013 Ripple et al. 2014 McPhee 2012 McPhee et al. 2021 (Fig. 4) Administrative Appeals Tribunal of Australia, 2019*

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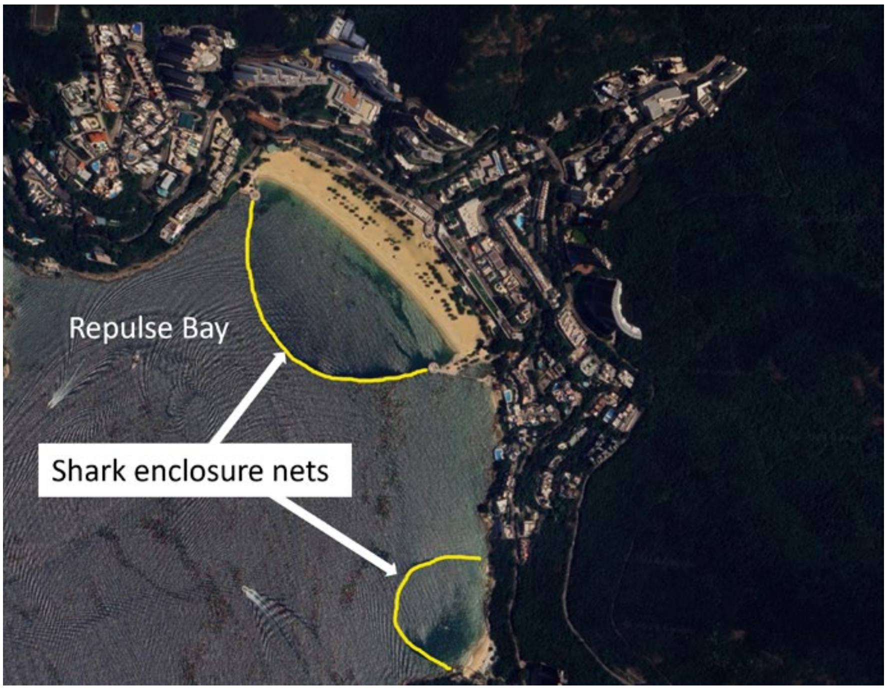
Management strategy	Positive consequences	Negative consequences	Notes	References
Shark nets • Not a physical barrier. • Rather, aimed at reducing shark populations. • Passive gear. • Lethal control method.	• Decreased perceived level of risk to public. • Public feel that action is being taken to reduce attack risk.	• High mortality of sharks and high potential risks to threatened, vulnerable and endangered non-target species (including other sharks, rays, turtles, dugong, dolphins). • Potential negative consequences for tourism (bad publicity and impact on iconic species populations). • Low support from public due to conservation ethics. • Effectiveness unproven: attacks still occurring in areas where nets have been long established. • Need effective data collection and monitoring systems in place. • Potential environmental cost: large. • Set up and operational costs: high. • Nets need to be checked regularly.	• Need to be differentiated from physical shark barriers	Curtis et al. 2012 Marsh et al. 2001 McPhee et al. 2021 (Fig. 4) Green et al. 2009 Brazier et al. 2012 Atkins et al. 2013; 2016 Daly et al. 2021 Worm et al. 2013 Gibbs et al. 2020 DeNezzo et al. 2019
Non-lethal strategies				
Shark barriers • Physical barrier from sharks. • Often enclosures for swimmers. • Non-lethal control method. e.g. Fish Hoek exclusion net (South Africa) (Davison and Kock 2014) (Fig. 5) e.g. Global Marine Enclosures - Aquarius Gen 2 Barrier** (Fig. 5)	• Proven very effective at excluding sharks in swimming areas, though from limited trials. • Non-lethal method for sharks. • Very limited by-catch, especially if temporary. • Public safety perceived, and increased public support for government action. • Good publicity for the government/tourism, as non-lethal option. • Not dependent on water clarity. • Set up cost: medium. • Operational cost: low. • Some light barriers are easily removed for cleaning or during lower beach use or storm season	• For swimmers only (small enclosure close to beach): not appropriate to surfers, kite-surfers, etc. • Further trials needed to test efficacy. • Not designed to cover large areas (max ~500m). • Need to be deployed in calm waters only. • Damaged by storms or strong waves if permanent. • Biofouling decreases longevity. • If temporary: high operational needs • Potential conflict with other human use of the area. • If permanent, need to be inspected by divers regularly. • Uncertain community attitude. • Set up cost: medium.	• More rigid than a shark net, from bottom to surface and large mesh to let other marine life swim through. • Flexible deployment strategy: can be permanent or temporary (the latter reducing potential damage from storms, waves, biofouling)	McPhee 2012 (Fig. 5) McPhee et al. 2021 Kock et al. 2012 Davison and Kock 2014 Simmons and Mehmet 2018 Green et al. 2009 DeNezzo et al. 2019 Hydrobiology 2014

Management strategy	Positive consequences	Negative consequences	Notes	References
SMART (Shark Management Alert in Real Time) or Catch-Alert drum lines				
• Non-lethal control method. • Drum lines with the addition of an alert system to ensure the relevant parties are notified when something is hooked.	• Non-lethal. • Works in all sea states and water clarity conditions. • Allows tagging and relocation of targeted sharks and release of bycatch at the capture location.	• Catches non-target species. • Need to be reactive, with a team ready to free and relocate sharks. • Set up cost: moderate. • Operational cost: high. • High human resource needed.		McPhee et al. 2021 McPhee et al. 2022
'SharkSafe' and similar exclusion barriers				
• Visual and/or electromagnetic stimuli. • Non-lethal control method.	• Non-lethal and no bycatch • SharkSafe barrier effective in small spatial scale experiments. • Improved performance of newer designs at larger spatial scales. • Limited operational costs • Not dependent on water clarity.	• Technology is still under development/testing and is not commercially available. • Not designed to cover large areas. • Potential conflict with other human use of area. • Set up cost: medium.		McPhee et al. 2021 O'Connell et al. 2014 O'Connell et al. 2022
Detection methods				
Aerial detection: blimp				
• Pre-emptive, non-lethal control method.	• Effective method with very high detection probability (>90% on sunny day; and >75% on cloudy days; in shallow waters). • Non-lethal method, no bycatch. • Non-invasive. • Continuous detection throughout the day. • Good publicity for the government/tourism. • Most efficient in swimming areas (vs surf or other water sports). • Detection can be automatic (AI). • No noise pollution. • Environmentally friendly with no battery power. • Commercially available. • Operational cost: low.	• Needs to be paired with lifeguard surveillance and alert system. • Could increase safety across all water-based activities in a location. • Water clarity needs to be high to moderate. • Set up cost: moderate.		McPhee et al. 2021 Adams et al. 2020

Management strategy	Positive consequences	Negative consequences	Notes	References
Aerial detection: drone or helicopter				
• Pre-emptive, non-lethal control method.	• Non-lethal method, no bycatch. • Non-invasive. • Most efficient in swimming areas (vs surf or other water sports). • Set up cost: low. • Operational cost: low (drone) to expensive (helicopter).	• Detection probability high in good weather conditions and with good water clarity. • Transects rather than providing visibility over whole area. • Needs to be paired with lifeguard surveillance and alert system (re: drone) • Noise pollution issues. • Potential negative response from public due to noise or privacy issues.		McPhee et al. 2021 Simmons and Mehmet 2018 Robbins et al. 2014 McPhee et al. 2022
Aerial detection: towers, beach level or headlands (shark spotters)				
• Pre-emptive, non-lethal control method.	• Non-lethal method. • No bycatch. • Non-invasive. • Set up cost: low • Operational cost: moderate • Most efficient in swimming areas (vs surf or other water sports).	• Detection probability only high in good weather conditions and with good water clarity. • High human resource needed. • Needs to be paired with lifeguard surveillance and alert system. • Potential negative response from public due to privacy issues.		McPhee et al. 2021 Simmons and Mehmet 2018 Robbins et al. 2014
Sonar (detection of sharks in water)				
	• Non-lethal method. • No bycatch. • Works in all sea states and clarity.	• Detection can be limited, or needing to cover large areas. • Still needs to be tested in terms of effectiveness. • Set up cost: high. • Operational cost: high.		McPhee et al. 2021 DeNezzo et al. 2019
Deterrence methods				
Individual shark deterrent (e.g. "shark shields")				
• Pre-emptive, non-lethal control method.	• Different types: electrical, magnetic, semiochemical, visual. • Electrical personal risk-reduction technology. • Easy to implement. • First-line-of-protection. • Take-up easily encouraged with govt tax exemptions.	• Not a stand-alone complete deterrent. • Effectiveness varies with model and activity of the user • Not 100% effective. • May encourage lax behaviour due to incorrectly assuming total protection is offered. • Set up cost: high for individuals USD 300-600 for electrical (XPF 10,000).		Huveneers et al. 2012 Huveneers et al. 2018 DeNezzo et al. 2019. O'Connell et al. 2014

*http://www8.austlii.edu.au/cgi-bin/viewdoc/au/cases/cth/AATA//2019/617.html
**https://www.globalmarineenclosures.com/aquarius-barrier-gen-2



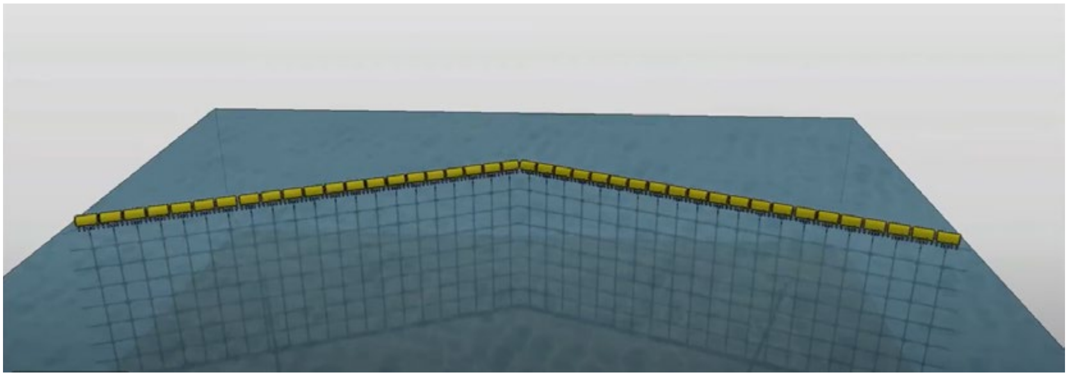


Figure 5. Examples of shark barriers for swimming enclosures.
Top: swimming enclosures in Hong Kong (adapted from McPhee 2012; Map data: Google, © 2023 Airbus);
Middle: Aquarius Gen 2 Barrier (https://www.globalmarineenclosures.com/aquarius-barrier-gen-2);
Bottom: newly-installed shark barrier enclosure at Baie des Citrons in Noumea, New Caledonia. ©Sophie Garioud

The need for continued research

While not an exhaustive list, Table 1 does illustrate the diversity of options available for minimising the risk of negative human–shark encounters. It is clear that shark hazard management strategies are evolving in concert with new technological developments and a greater public awareness of and support for conservation and non-lethal responses. That said, our literature review also indicated that a still often missing piece of the puzzle relates to our understanding of shark behaviour and biology, and the underlying causes of negative human–shark encounters. As programmes to reduce negative human–shark encounters are typically expensive, government priorities often appear to have been placed on the implementation of the management strategy itself, rather than invested in scientific programmes to understand the root cause of the encounters or to evaluate the environmental, social and political consequences of the different strategies.

This feels like an opportunity lost, since the implementation of shark hazard management strategies, either with lethal or non-lethal endpoints, can theoretically provide the perfect platform for gathering biological and ecological data on shark populations. For instance, despite little evidence of success in terms of reducing attack rates, and some shortcomings in scientific focus, the Hawaiian shark control programmes that ran between 1959 and 1976 generated crucial new information on the diet, reproduction and distribution of sharks around Hawaii (Wetherbee et al. 1994). Through science-led initiatives, taking advantage of recent advancements in electronic tagging technology, genetic methods, sonar and baited remote underwater video cameras (BRUVs), additional detailed data can be collected on site fidelity, large-scale movements, and population size and structure (Blaison et al. 2015; Taglioni et al. 2019; Drymon et al. 2021; Barnett et al. 2022). This information is doubly useful. First, it can help us better understand the drivers of human–shark interactions, and second, it can be fed back to update and optimise the design of the shark management strategies that generated the data in the first place.

In addition to the biological and ecological factors, the examples listed in Table 1 also reinforce the importance of considering the human dimension of human–shark interactions. They highlight in particular how engaging all stakeholders through effective education and communication programmes is a necessary ingredient in developing a "SharkSmart" understanding (https://www.sharksmart.nsw.gov.au/) among the general populace. This in turn allows management agencies to make the most informed, evidence-based policy decisions around what action to take to best mitigate risk, no matter if these decisions are made at local, state or national levels. The success of the current New South Wales Shark Management Strategy and Shark Program (McPhee et al. 2022) provides a good example of the advantages of this type of integrated approach, one that is adaptable to changing social perceptions around human–shark interactions and open to integrating new data as it comes to hand. Such programmes are increasingly acknowledging that humans and sharks will always share oceanic environments, and that strategies that promote coexistence rather than dominance will ultimately benefit both parties.

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