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Effects and effectiveness of lethal shark hazard management: The *Shark Meshing (Bather Protection) Program*, NSW, Australia

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Abstract

1. 'Shark attack' presents a considerable social-environmental challenge. Each year a small number of people are injured or killed by shark bite. Concurrently, sharks and other marine life are subject to unprecedented anthropogenic pressures.
2. Shark hazard management varies globally, but lethal strategies are common, with negative consequences for species and environments. Of particular concern are the effects for threatened species.
3. Lethal strategies have recently come under criticism, based on the negative effects for marine life, effectiveness for human safety and inconsistency with contemporary values. Moves to improve both safety and conservation can be hindered by polarized debate.
4. We present a case study of the world's longest-running lethal shark hazard management program, the *Shark Meshing (Bather Protection) Program*, New South Wales, Australia. We take an interdisciplinary approach to bring into conversation factors that contribute to safety and conservation outcomes. To date, most research focuses on one or other of these areas. We seek to synthesize the factors that are not previously considered in relation to each other.
5. Our aims were to: (a) identify and critique the diverse factors that determine the outcomes of the program; (b) assess the negative effects of the program for sharks and other marine life; and (c) assess the effectiveness of the program for reducing threat of shark interactions.
6. We find that: (a) multiple social and environmental factors contribute to program outcomes; (b) total shark numbers and populations of key target species – white shark (*Carcharodon carcharias*), tiger shark (*Galeocerdo cuvier*) and bull shark (*Carcharhinus leucas*) – have declined over the program's 80 years, as have a number of non-target species; (c) incidence of shark bite has declined since the program's introduction, but two external points warrant attention.
7. First, key factors influencing the shark bite incidence are frequently overlooked, namely changing cultures of beach- and ocean-use, advances in beach patrol, and emergency and medical response. Second, the proportion of bites leading to fatality has decreased significantly in recent decades.

8. Beach patrol and emergency response contribute to human safety and well-being without the negative consequences of lethal strategies. As such, they offer a focus for future shark hazard management and research.

KEYWORDS

beach patrol, human-wildlife conflict, shark attack, shark nets, threatened species

1 | INTRODUCTION

'Shark attack' presents a considerable social and environmental challenge. Each year a small number of human–shark encounters result in human injury or fatality. Although dangerous interactions are extremely rare, there is evidence that the global rate has increased over the past three decades (McPhee, 2014). Incidents invariably receive intense media attention, leading to highly divisive public and political debate. Concurrently, marine ecosystems and lifeforms are experiencing unprecedented pressures from human activity – chiefly, habitat degradation and overfishing (IPCC, 2014; United Nations, 2017). The sharks, rays and chimaeras (Chondrichthyan fishes) face significant threat (Dulvy et al., 2014).

Around the world, societies institute a range of techniques to avert dangerous human–shark interactions. They can be grouped into four broad categories: spatial deterrents; spatial observation; exclusion barriers; and personal deterrents (summarized in Figure 1). Strategies that rely on killing targeted species are common (Gibbs & Warren, 2015), including long- and short-term programs designed to control or reduce populations or kill individual animals. Such strategies have been adopted in Australia, South Africa, USA (Hawai'i), France (La Réunion), Egypt, Mexico, New Zealand, Russia, Seychelles (Dudley, 1997; Gibbs & Warren, 2015; Neff & Yang, 2013; Wetherbee, Lowe, & Crow, 1994). Growing criticism in recent years has seen innovation and development of non-lethal methods across all categories – SMART drumlines ('Shark Management Alert in Real Time'), tagging and satellite observation, new generation swimming enclosures and electrical deterrents.

Lethal strategies have negative consequences for marine life, including targeted species and other species and ecosystems (Cliff & Dudley, 2011; Office of Environment & Heritage, 2011). Shark hazard management exists in the context of unprecedented anthropogenic pressures on the oceans. The combined effects of warming, acidification, pollution and overfishing contribute to the

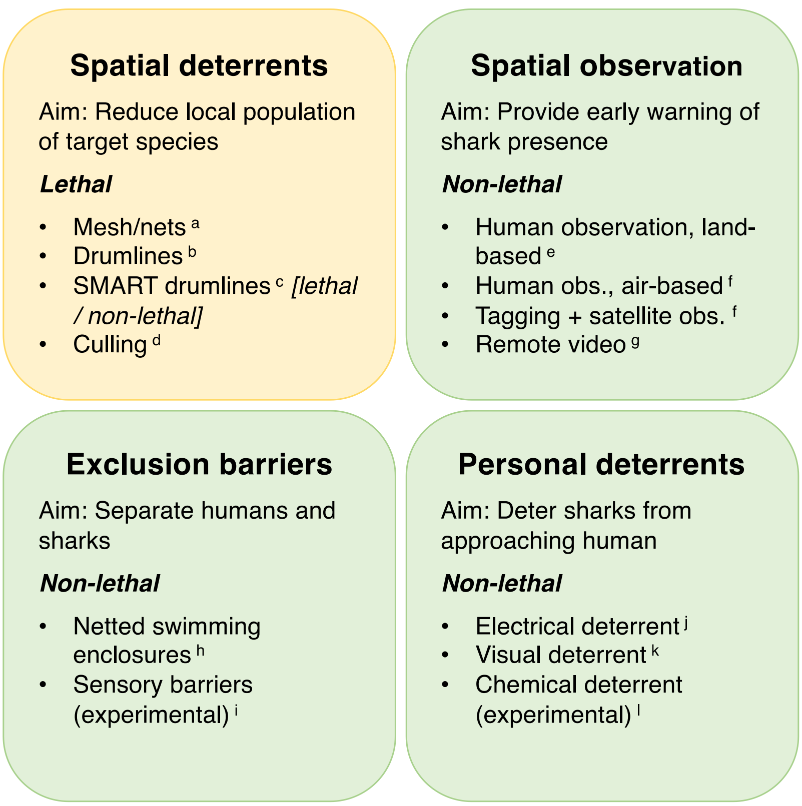


FIGURE 1 Summary of global shark hazard mitigation strategies. [a]Cliff and Dudley (2011); Department of Primary Industries (2017–18); Dudley (1997). [b]Cliff and Dudley (2011); Dudley (1997). [c]Department of Primary Industries (2017); Hazin and Afonso (2014). [d]Gibbs and Warren (2015); Wetherbee et al. (1994). [e]Shark Spotters (n.d.). [f]Department of Primary Industries (n.d.-b); McPhee and Blount (2015). [g]Department of Primary Industries (n.d.-b). [h]McPhee and Blount (2015); Shark Spotters (n.d.). [i]McPhee and Blount (2015); O'Connell, Andreotti, et al. (2014)). [j]Huveneers et al. (2013); O'Connell, Stroud, et al. (2014)). [k]McPhee and Blount (2015). [l]O'Connell, Stroud, et al. (2014)

destruction of ecosystems, radical shifts in habitats and reductions in number and range of many species (IPCC, 2014; United Nations, 2017). Chondrichthyan fishes are heavily impacted. A recent study found that of 1,041 species worldwide, more than half face elevated risk of extinction (Dulvy et al., 2014); many species are exceptionally vulnerable to overfishing (Worm et al., 2013). Implications extend beyond species, with far-reaching and unpredictable effects of removal of predators, such as sharks, from ecosystems (Burkholder, Heithaus, Fourqurean, Wirsing, & Dill, 2013; Ripple et al., 2014). The United Nations (2017, p. 17) notes that 'Adverse impacts on marine ecosystems come from the cumulative impacts of a number of human activities … Thus the cumulative impacts of activities that, in the past, seemed to be sustainable are resulting in major changes to some ecosystems'. They assert that coherent management of all sectors is essential to sustainable use of the ocean.

One specific concern is the effects of activities for threatened species. The three species identified as posing greatest potential threat to humans – white shark (*Carcharodon carcharias*), tiger shark (*Galeocerdo cuvier*) and bull shark (*Carcharhinus leucas*) – are also recognized as threatened or 'Near Threatened' by international and/or state institutions. White shark is listed on the IUCN Red List of Threatened Species as 'Vulnerable', and on the Convention on Migratory Species of Wild Animals/ Bonn Convention (CMS), and Convention on the International Trade in Endangered Species (CITES). It is protected in all four countries in which it is abundant: Australia, New Zealand, South Africa and USA (United Nations, 2017). In Australia, it is recognized as 'Vulnerable' under the *Environmental Protection and Biodiversity Conservation (EPBC) Act 1999* and is subject to a Recovery Plan. Tiger and bull sharks are listed on the IUCN Red List as 'Near Threatened', a category used to describe a species that 'does not qualify for Critically Endangered, Endangered or Vulnerable now, but is close to qualifying for or is likely to qualify for a threatened category in the near future' (IUCN, 2012, p. 15). Other listed whaler species include dusky whaler *C. obscurus* (Vulnerable) and bronze whaler *C.brachyurus* (Near Threatened). The IUCN identifies fishing and persecution/control as threats to all of these species (IUCN, 2018). The dual status of potentially threatening and threatened amplifies management challenges.

Established lethal methods for managing shark hazards have in recent years come under criticism, based on the concerns about their environmental effects, their effectiveness for improving human safety and their (in)consistency with contemporary societal values. Criticisms have emerged in the context of environmental change, growing scientific knowledge, shifting public sentiment and technological innovation. There is a move to re-assess how we manage shark hazards. Some governments explicitly aim to improve both human safety and marine conservation (e.g. Department of Primary Industries n.d.-b). But efforts are hindered because public discourse is often polarized (McCagh, Sneddon, & Blanche, 2015; Muter, Gore, Gledhill, Lamont, & Huveneers, 2013), and much research focuses on either marine conservation or human safety and public perception. Some research recognizes that management efforts must consider both (Ferretti, Jorgensen, Chapple, Leo, & Micheli, 2015; Hazin & Afonso, 2014) and that multiple disciplines are needed to address the problem (Chapman & McPhee, 2016; Lagabrielle et al., 2018). We seek to contribute to this work by bringing these two disparate realms into conversation, to inform development of effective and appropriate shark hazard management.

We approach this task through a case study analysis of Australia's *Shark Meshing (Bather Protection) Program* (SMP) in the state of New South Wales (NSW) – the world's longest-running lethal shark hazard management program (Dudley, 1997; Reid, Robbins, & Peddemors, 2011). Like numerous programs worldwide, the SMP targets three key groups. According to the NSW Government Department of Primary Industries (n.d.-a) 'Nearly all shark bites in coastal waters are attributed to just three species: White Sharks (also known as Great White Sharks and White Pointers), Bull Sharks and Tiger Sharks'. The Australian Government Department of the Environment and Energy (n.d.) lists these three species and other whaler sharks (*Carcharhinus* spp) as 'dangerous to humans'. The SMP aims to 'reduce the threat of shark interactions within the area of the SMP while minimizing its impacts on non-target species' (Department of Primary Industries, 2018–19, p. 1). The SMP has been identified by the Australian Office of Environment and Heritage (2011) as a *Key Threatening Process* due to its impacts on white shark (a target species) and grey nurse shark (*Carcharias taurus*; a non-target species). This local context combined with the global trends outlined above suggests that closer examination of the program is timely. We take an interdisciplinary approach (Huutoniemi, Thompson Klein, Bruun, & Hukkinen, 2010; Stock & Burton, 2011), drawing on analytical, interpretive and critical theoretical perspectives emerging from the physical sciences, social sciences and humanities (Castree et al., 2014; Moon & Blackman, 2014). We seek to synthesize the factors that have not previously been considered in relation to each other. Our aims were threefold, to: (a) identify and critique the diverse factors that together determine the outcomes of the SMP; (b) assess the negative effects of the SMP for sharks and other marine life; and (c) assess the effectiveness of the SMP for reducing the threat of shark interactions.

2 | METHODOLOGY

This project adopted an interdisciplinary methodology. Three very different disciplinary perspectives were brought to bear on framing the research problem, determining the methodological approach and analysing data (Stock & Burton, 2011, p. 1096); namely, human geography, marine biology and fisheries. The project 'integrate[s] different kinds of empirical data in order to investigate the relationships between phenomena observed in different fields' (empirical interdisciplinarity), and combines 'different methodological approaches … in a novel, integrated manner' (methodological interdisciplinarity; Huutoniemi et al., 2010, p. 84). This approach has allowed us to consider a wide range of factors shaping the outcomes of the SMP in relation to each other. Our mixed-methods approach involved the following elements.

First, we undertook a review of the literature. This allowed us to identify and critique the diverse social and biophysical factors that contribute to the outcomes of the SMP, including negative effects for sharks and other marine life, and effectiveness of the program to reduce the risk of shark interactions. The literature review was based on published literature about shark meshing and shark control and publicly available reports about the SMP (Supp. S1). We undertook a thematic analysis to identify the factors contributing to negative impacts on sharks and marine life and changing incidence of shark bite.

To assess the negative effects of the SMP for sharks and other marine life, we drew on our review of the literature and analysis of SMP catch data. Shark catch data from the SMP have previously been published for 1950–2010 (Reid et al., 2011). We sought to update data and analysis to 2018. To do so, we compiled catch data from SMP annual and other reports (Department of Industry & Investment, 2011; Department of Primary Industries 2012a, 2013a, 2013b, 2014, 2015, 2015–16, 2016–17, 2017–18). Format and presentation of data in publicly accessible reports is inconsistent and incomplete across years, presenting challenges for compilation and analysis (see also Dudley, 1997). Shark catch data post-1950 is publicly available; however, data collection methods and reporting have differed through the Program's history. Early records (pre-1950) are not publicly accessible. Data are currently made public each year in non-machine-readable pdf format. Effort data are not publicly available prior to 1992; however, Reid et al. (2011) found that standardized catch per unit effort (CPUE) closely mirrored overall trends in catch data. From these sources we compiled total catch data for each season between 1950 and 2018 (Fetterplace, Gibbs, & Rees, 2018). To standardize the effort across years, we converted our data to mean CPUE (number of sharks per 100 net-days), basing 1950–2010 effort on Reid et al. (2011), and post-2010 effort on information in SMP reports (Department of Industry & Investment, 2011, Department of Primary Industries 2012a, 2013a, 2013b, 2013b, 2015, 2015–16, 2016–17, 2017–18). This is the first study to use CPUE for 1950–2018.

We used generalized additive mixed effects models (GAMMs) to examine the trends in CPUE of all sharks, and of tiger, white and whaler sharks over time. GAMMs were employed as they can: (a) account for data that are not normally distributed, (b) model nonlinear relationships, and (c) address non-independence in the data using correlation structures (Zuur, Leno, Savelier, & Smith, 2009). For each response measure, three models were constructed. All models included 'Year' with a smoothing function as an explanatory variable; the second and third model also included an auto-regressive moving average (ARMA 1 or 2) error structure (Zuur et al., 2009). ARMA error structures were included to account for the potential temporal autocorrelation in the datasets. Akaike Information Criterion (AIC) was used to select the best fitting model for each response measure (Burnham & Anderson, 2002; Supp. S2). All models were fitted with a quasi-poisson distribution constructed in the statistical platform R (R Development Core Team, 2017) using the 'mgcv' package (Wood, 2006).

To assess the effectiveness of the SMP for reducing the threat of shark interactions, we drew on the literature review and analysed data from the Australian Shark Attack File (ASAF) and Australian Bureau of Statistics (ABS). The ASAF provides the most complete record of dangerous human–shark incidents in Australia since colonization (West, 2011). It does not claim to provide a complete record, but has systematically sought to compile all cases of 'shark attack'. Method of recording incidents and collecting data has changed over time, and a variety of methods has been used by the curators to gather data, including historical research and self-reporting (West, 2011). Cases are categorized as 'provoked' or 'unprovoked' and 'fatal', 'injured' or 'uninjured'. We analysed the ASAF for all recorded shark bite incidents in NSW (Taronga Conservation Society Australia, n.d.). The first was 1791. We limited our analysis to the past 150 years (1868–2017 inclusive). Our rationale was twofold: only three injuries and six fatalities are recorded in the first eight decades to 1870; and public bathing during daylight hours was prohibited in NSW before 1903 (Metusela & Waitt, 2012), suggesting few people entered the water at the beach before the turn of the century. We omitted incidents that led to no injury; we concluded that record of such events is more likely to be incomplete than those resulting in injury, introducing greater uncertainty to analysis (see also West, 2011 on the rise in reported 'non-injury attacks'). Growth in social media and mobile telecommunication in the past decade is likely to have continued to influence rates of reporting. We plotted fatal and non-fatal shark bite incidents in NSW by year and by decade.

To estimate the numbers of people entering the water at NSW beaches, we analysed ABS data, using Australian Historical Population Statistics (Australian Bureau of Statistics, 2014) and Australian Demographic Statistics (Australian Bureau of Statistics, 2017). We plotted fatal and non-fatal shark bite incidents in NSW per million people per decade. Literature suggests that beach- and ocean-use in Australia have changed substantially over time (Cushing & Huntsman, 2007; Ford, 2014; Metusela & Waitt, 2012; West, 2011). However, no complete record exists for Australia or the state of NSW. To develop a more nuanced picture of changing beach- and ocean-use than is provided by ABS data alone, we investigated other social and cultural factors influencing the incidence of human–shark encounter identified in the literature review.

3 | RESULTS AND DISCUSSION

3.1 | Diverse factors determine outcomes of the SMP

Our research identified a suite of interacting factors that contribute to the outcomes of the SMP, including negative effects for sharks and other marine life and effectiveness for reducing human–shark interactions (summarized in Figure 2). At present, marine protection and human safety are commonly discussed in isolation, contributing to highly divisive public and political debate, and an impasse in decision-making. Multiple factors are reported in SMP annual reports, including: shark bite incidents; catch data of target, non-target and threatened species; and estimated beach use numbers. However,

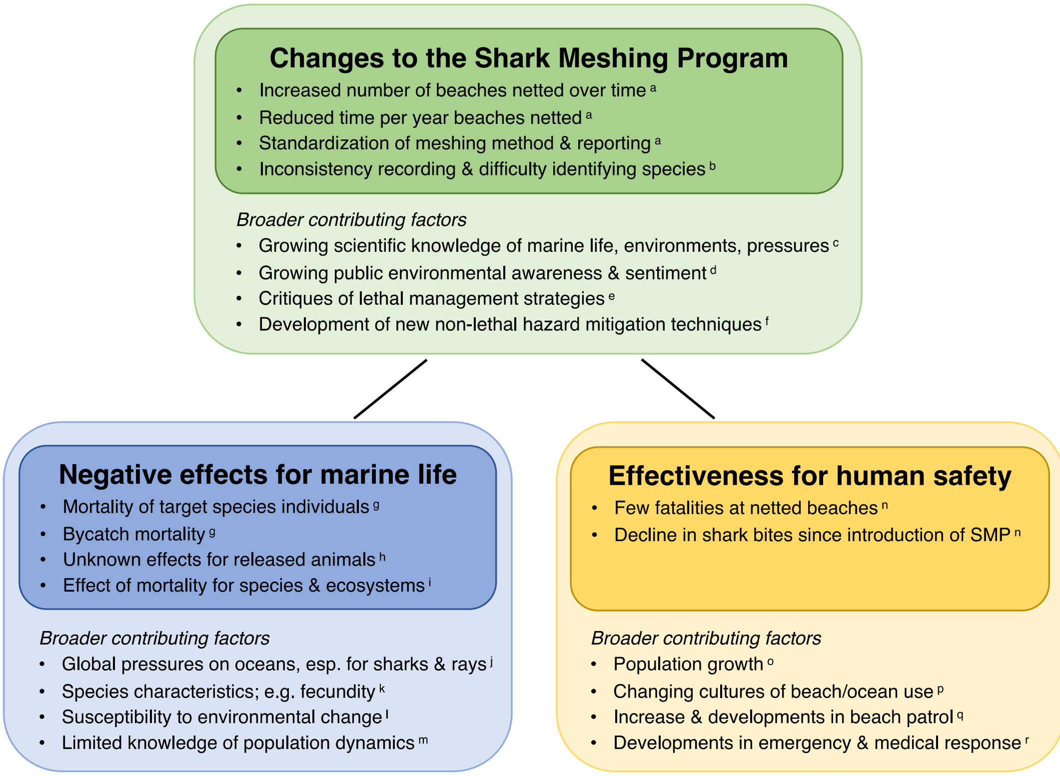


FIGURE 2 Factors determining the outcomes of the *Shark Meshing (Bather Protection) Program*. [a]Green et al. (2009); Krogh and Reid (1996); Reid et al. (2011). [b]Duffy and Gordon (2003); Stewart et al. (2015). [c]IPCC (2014); United Nations (2017). [d]Carson (1962); United Nations (n.d.); World Commission on Environment and Development (1987). [e]Gibbs and Warren (2014, 2015); McPhee (2012); Meeuwig and Ferreira (2014); Pepin-Neff and Wynter (2018); Simpfendorfer et al. (2011). [f]Department of Primary Industries (n.d.-b); Hazin and Afonso (2014); Huveneers et al. (2013); McPhee and Blount (2015); O'Connell, Stroud, et al. (2014)). [g]Department of Industry and Investment (2011); Department of Primary Industries (2012a, 2013a, 2013b, 2014, 2015, 2015–16, 2016–17, 2017–18): Krogh and Reid (1996). [h]Adams et al. (2018); Guida et al. (2017); Malcolm et al. (2001). [i]Office of Environment and Heritage (2011); Stewart et al. (2015). [j]Dulvy et al. (2014); IPCC (2014); United Nations (2017). [k]Duffy and Gordon (2003); Fergusson et al. (2009); Hillary et al. (2018); Malcolm et al. (2001); Musick et al. (2009). [l]Duffy and Gordon (2003); Espinoza et al. (2016). [m]Blower et al. (2012); Bruce (2008); Fergusson et al. (2009); Hillary et al. (2018); Holmes et al. (2012); Simpfendorfer and Burgess (2009); Smoothey et al. (2016); Stewart et al. (2015). [n]Australian Shark Attack File (Taronga Conservation Society Australia n.d.). [o]Australian Bureau of Statistics (2014, 2017); Gurran et al. (2006); Hugo and Harris (2013); West (2011). [p]Cushing and Huntsman (2007); Ford (2014); Metusela and Waitt (2012); West (2011). [q]Brawley (2007); Cushing and Huntsman (2007); Ford (2014); Metusela and Waitt (2012), Surf Life Saving Australia (n.d.). [r]Ricci et al. (2016); Rtshiladze et al. (2011)

the interplay of these factors does not currently translate to public debate. Here we seek to bring the diverse factors shaping program outcomes into conversation.

A key factor determining the outcomes of the SMP is the operation of the Program itself. The SMP has undergone significant change since its implementation, posing challenges for measuring outcomes over time. Changes to the Program have included: number of beaches netted; times of year and duration of nets in the water; netting materials; and requirements for setting and checking nets and reporting. At the Program's implementation in 1937, nets were set year-round at 18 Sydney beaches. Today, 51 beaches between Newcastle in the north and Wollongong in the south are netted during September–April; peak beach season (Table 1). Overall, these changes have led to an increase in effort over time (Reid et al., 2011). Standardization of netting materials and technique began in 1972 (Green, Ganassin, & Reid, 2009; Krogh & Reid, 1996); however, recent reports suggest it has not yet been achieved (Department of Primary Industries, 2016). The importance of standardization was highlighted in the 2009–2010 annual report, which recognized its necessity for assessing the status of shark catch by CPUE methodologies. The SMP is significant in this regard as it is 'the only long-term coastal shark fishery in NSW' (Department of Industry & Investment, 2011, p. 21). Lack of consistency presents challenges for comparing data between years, and thus determining trends in catch and effectiveness of the program in achieving its goals.

A specific challenge for assessing the Program is the difficulty and inconsistencies identifying and recording species. Methods of data collection and record-keeping were inconsistent and incomplete pre-1972 (Dudley, 1997) and challenges remain. According to Reid et al. (2011), most species are accurately identified by contractors; however, *Carcharhinus* spp are difficult to distinguish (Stewart, Hegarty, Young, Fowler, & Craig, 2015), and until 1998 were recorded simply as 'whaler'. Since 1998, the Program has required contractors to retain heads of whaler sharks for identification. DNA testing has identified at least seven species caught in the nets (Reid et al., 2011). Thus, identifying long-term effects on individual whaler species is not possible.

TABLE 1 Changing spatial and temporal distribution of the *Shark Meshing (Bather Protection) Program* (SMP)

Year	Netting season	Nets in water	Regions
1937–1949	Year round	18	Sydney (Palm beach to Cronulla)
1949–1972	Year round	31	Sydney, Newcastle, Wollongong
1972–1983	Year round	40	Sydney, Newcastle, Wollongong
1983–1987	Aug–May	40	Sydney, Newcastle, Wollongong
1987–1989	Aug–May	49	Sydney, Newcastle, Wollongong, Central Coast
1989–1992	Sept–April	49	Sydney, Newcastle, Wollongong, Central Coast
1992–ongoing	Sept–April	51	Sydney, Newcastle, Wollongong, Central Coast
2016–2017	*Dec–May*	*+5*	*North Coast trial*[b]
2017–2018	*Nov–* [a]	*+5*	*North Coast trial*

Note: A complete list and map of 51 beaches can be found in SMP Annual Reports (e.g. Department of Primary Industries, 2017–18).

[a]The 2017–2018 North Coast trial was to run for 12 months. Nets could be used for a total period of 6 months, which need not run as an uninterrupted sequence (Department of Primary Industries, 2017).

[b]Two trials, involving nets and drumlines, were conducted on the North Coast of NSW, representing the first significant proposed change in geographical extent of the SMP. The northern program has not been continued.

Further to changes in the Program itself, significant social change has occurred since the SMP was established (see Figure 2). Changes to netting season and technique in the 1980s were influenced by the scientific findings and public concern about entanglement of non-target animals including cetaceans, turtles and sea birds. Growing concern contributed to the introduction of acoustic deterrent devices. Scientific research is demonstrating unprecedented pressures on marine and coastal environments (Dulvy et al., 2014; IPCC, 2014; United Nations, 2017), and public awareness and sentiment has increased substantially in recent decades (Carson, 1962; United Nations n.d.; World Commission on Environment & Development, 1987). Concern for well-being of species and individual animals of non-target and target species has grown substantially since the Program's introduction 80 years ago, reducing public support for lethal strategies (Gibbs & Warren, 2014, 2015; Gray & Gray, 2017; Pepin-Neff & Wynter, 2018). Critiques of negative effects, effectiveness and appropriateness of lethal strategies are becoming more widespread (e.g. Gibbs & Warren, 2014, 2015; McPhee, 2012; Meeuwig & Ferreira, 2014; Pepin-Neff & Wynter, 2018; Simpfendorfer, Heupel, White, & Dulvy, 2011). Concurrently, related concerns are driving innovation and investment in non-lethal techniques, including personal electrical and visual deterrents, underwater barriers and deterrents using light, sound, air and magnet technologies, and underwater and aerial surveillance (Department of Primary Industries n.d.-b; Hazin & Afonso, 2014; Huveneers et al., 2013; McPhee & Blount, 2015; O'Connell, Stroud, & He, 2014; see Figure 1). Scientific and technological development and changing attitudes exert new pressures, which will inevitably continue to change the Program's form. Together, changes to the SMP and broader social change shape the outcomes of the Program for marine life and human safety.

3.2 | Negative effects of the SMP for sharks and other marine life

The SMP seeks to improve human safety by catching potentially dangerous sharks in nets. Our review finds that direct effects include: mortality of individuals of target species; mortality of non-target species (bycatch); impacts on animals caught and released; and impacts for species and ecosystems. Broader contributing factors further influence the Program's negative effects for marine life (see Figure 2). Here we discuss each of these direct and broader factors in turn.

First, the SMP targets a list of potentially dangerous species. The list has changed over time; rationale is not presented in annual reports. For example, the 2016–2017 and earlier reports list ten target species, including white shark, tiger shark, six *Carcharhinus* species and at least two species never recorded in a shark bite incident in Australia; namely broadnose sevengill shark (*Notorynchus cepedianus*) and shortfin mako (*Isurus oxyrinchus*) (Department of

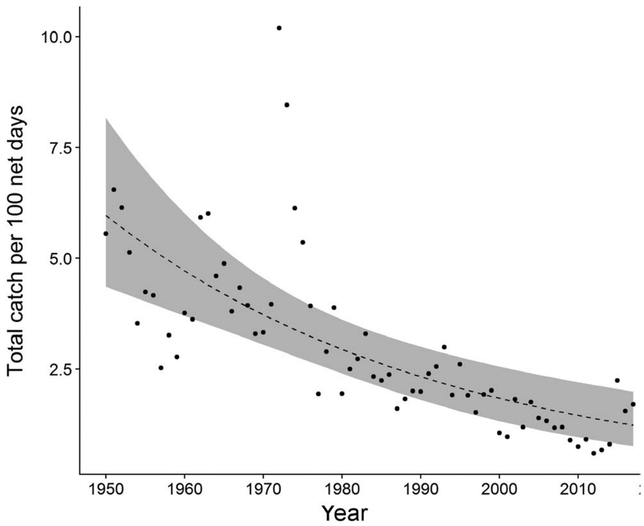


FIGURE 3 Catch per unit effort of sharks caught in the *Shark Meshing (Bather Protection) Program* per year, 1950–1951 to 2017–2018 seasons. Dashed trend line calculated using a generalized additive mixed model. Regions in grey represent 95% confidence intervals. Source: Fetterplace et al. (2018); catch data (Department of Industry & Investment 2011; Department of Primary Industries 2012a, 2013a, 2013b, 2014, 2015, 2015–16, 2016–17, 2017–18; Green et al., 2009); effort data based on Reid et al., 2011)

Primary Industries, 2016–17). In 2018, the number of target species was reduced to three: white, tiger and bull sharks (Department of Primary Industries, 2017–18). The Program does not discriminate based on animal size. In contrast, Western Australia's (WA) drumline trial of 2013–2014 targeted animals over 3 m (Gibbs & Warren, 2015), based on the rationale that smaller sharks feed on fish and small animals and do not generally pose a threat to humans. As such, recorded figures for target species caught in SMP nets include animals – of species and size – unlikely to be dangerous to people.

Numbers of target and non-target animals caught in nets vary greatly year-to-year. Our analysis shows long-term reduction in total shark catch (Figure 3) and catch of the three key target groups (Figure 4). These declines are notwithstanding changes in fishing method and effort. According to Reid et al. (2011, p. 676), 'Large-scale, ongoing fishing programs deploying shark nets', including those in NSW, the state of Queensland, and the city of Durban (South Africa), 'represent an extended sampling period of coastal waters in the regions they operate. Thus, they provide a reliable record of the long-term trends in abundance and distribution of regional shark species'. Given this observation, the decline in catch suggests long-term decline in overall shark abundance and abundance of three key species and genus in NSW coastal waters. This downward trend is consistent with other studies that report declines in marine species populations (Dudley, 1997; Malcolm, Bruce, & Stevens, 2001; Roff, Brown, Priest, & Mumby, 2018; United Nations, 2017).

The 2015–2016 season saw the largest number of white sharks (31) caught in any single year. All were under 3 m; and the majority

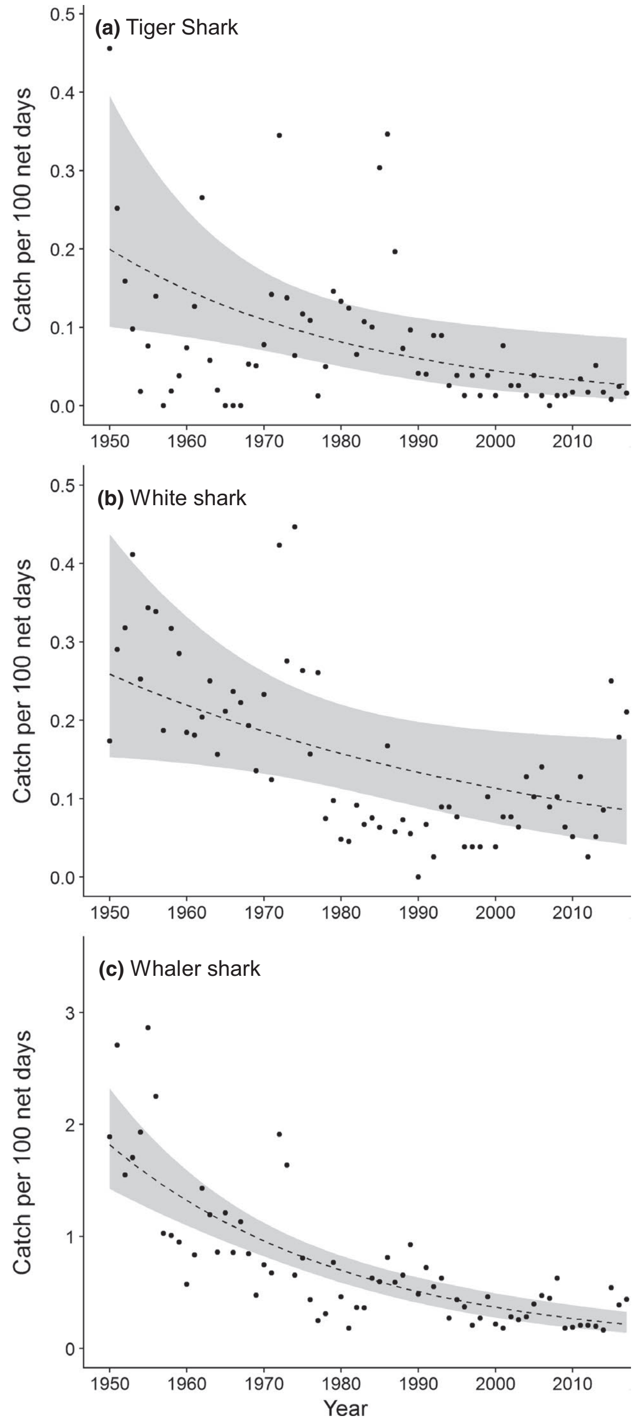


FIGURE 4 *Shark Meshing (Bather Protection) Program* catch per unit effort of three key target species or groups per year, 1950–1951 to 2017–2018 seasons. (a) Tiger shark, (b) white shark and (c) whalers. Dashed trend line calculated using a generalized additive mixed model. Regions in grey represent 95% confidence intervals. Source: Fetterplace et al. (2018); catch data (Department of Industry & Investment, 2011; Department of Primary Industries 2012a, 2013a, 2013b, 2014, 2015, 2015–16, 2016–17, 2017–18; Green et al., 2009); effort data based on Reid et al., 2011)

(20) were under 2 m, indicating all were juveniles (Bruce et al., 2013). Twenty were caught at beaches in the Hunter and Central Coast North regions, close to a known white shark nursery (Bruce et al.,

2013). The 3 years to 2018 have each seen white shark catches higher than in the previous four decades. Long-term decline is still significant despite the recent increase.

Second, bycatch is a significant effect of the SMP (Krogh & Reid, 1996). Non-target species consistently represent the vast majority of animals caught in nets. Catch and mortality of non-target species are reported in detail in annual reports, and efforts have been made over time to reduce bycatch, including through bottom-setting nets and introducing acoustic deterrents. Of particular concern is mortality of threatened species, including target and non-target species. In 2015–2016, the nets caught 19 grey nurse sharks – critically endangered on the east coast. Five were found dead, 14 released alive, their long-term survival unknown. This catch was much higher than in the previous four decades. It raised concern but did not trip the 'trigger point' for 'minimising the impact on non-target species and threatened species', which would have demanded further review (Department of Primary Industries, 2015–16, p. 22). In 2017–2018, 20 grey nurse sharks were caught; ten were found dead, tripping the trigger point (Department of Primary Industries, 2017–18).

Third, the 2009 review of the SMP prescribed all animals found alive in nets, 'with a reasonable chance of recovery from injuries', be released (Green et al., 2009, p. 12). All sharks (excluding grey nurse sharks), rays and turtles are to be tagged and released 'where safe to do so', as part of an education program developed by the NSW Government in collaboration with KwaZulu-Natal Sharks Board (Department of Industry & Investment, 2011). Long-term survival and effects of catch and release are largely unknown, but recent research found capture-induced parturition (premature birth or abortion; Adams, Fetterplace, Davis, Taylor, & Knott, 2018) and other sub-lethal effects of capture stress (Guida, Awruch, Walker, & Reina, 2017). Effects for populations, species and ecosystems remain poorly understood (Bruce, 2008; Fergusson, Compagno, & Marks, 2009; Hillary et al., 2018; Holmes et al., 2012; Simpfendorfer & Burgess, 2009), especially for species whose overall stock status is unknown, including tiger and whaler sharks (Stewart et al., 2015).

In addition to these direct, reported effects of the SMP, broader factors contribute to the Program's environmental impacts. Since its introduction in the 1930s, pressures on marine environments have increased dramatically. Global research shows that dominant industrial practices exploit marine resources at unprecedented rates, and oceans receive waste materials of increasing complexity at ever-growing rates and scales (IPCC, 2014; United Nations, 2017). Research has found sharks and rays are at increased threat of extinction, due to direct fishing pressure and dramatically reduced prey species populations (Dulvy et al., 2014; Worm et al., 2013). Among these are species targeted by the SMP.

Physiological characteristics shape response to pressures. Late sexual maturity and low fecundity among some species, including white sharks, lead to slow recovery following disturbance (Bruce et al., 2013; Fergusson et al., 2009; Hillary et al., 2018; Malcolm et al., 2001; Musick, Grubbs, Baum, & Cortés, 2009; Towner, Wcisel, Reisinger, Edwards, & Jewell, 2013). Location of habitat relative to human activity makes some species especially susceptible to anthropogenic pressures, for example coastal development can significantly impact *Carcharhinus* species habitat (Duffy & Gordon, 2003; Espinoza, Heupel, Tobin, & Simpfendorfer, 2016). Knowledge of target shark species abundance, distribution and population trends is generally limited. Globally, white shark abundance, population structure, genetic diversity and population trends are largely unknown (Blower, Pandolfi, Bruce, Gomez-Cabrera, & Ovenden, 2012; Bruce, 2008; Fergusson et al., 2009; Hillary et al., 2018). Existing data suggest slight declines or zero population rate of change (Hillary et al., 2018). Scarce information limits reliable assessment of tiger shark population and exploitation status (Brown & Roff, 2019; Holmes et al., 2012; Stewart et al., 2015), but recent studies suggest population decline across eastern Australia (Brown & Roff, 2019; Holmes et al., 2012; Reid et al., 2011). Population size, structure and trends are largely unknown for bull sharks (Simpfendorfer & Burgess, 2009; Smoothey et al., 2016) and other *Carcharhinus* species, including dusky (Musick et al., 2009) and bronze whalers (Duffy & Gordon, 2003). Reported landings of whaler species have declined in recent years (Stewart et al., 2015). Limited knowledge hampers the ability to assess the effects of management.

Our analysis shows decline in total shark catch and catch of key species targeted by the SMP over the period of the Program's operation. This may mean the SMP has contributed to population decline – given sustained fishing effort, numbers of animals caught over time and low fecundity among some species – and/or it may reflect broader trends in species declines, indicated by catch data and research around the world. Irrespective of the cause, reduced catch combined with increased effort suggests reduced abundance of sharks in the region of the SMP.

3.3 | Effectiveness of the SMP for human safety

The SMP is frequently described as the key factor responsible for reducing the risk of shark bite in NSW. The 2009 review explicitly states 'the SMP has been effective in reducing incidences of fatal shark attack' (Green et al., 2009, p. v). There are two major arguments for the SMP, namely few fatalities at meshed beaches and a reduction in the incidence of shark bite since the Program's introduction (Department of Primary Industries, 2012b; Green et al., 2009). Here, we present analysis of ASAF data for NSW, focusing on fatalities and non-fatal injuries. We then discuss four broader social-cultural factors that contribute to the incidence and outcomes of human–shark encounter: increase in population and beach use; changes in cultures of beach- and ocean-use; developments in beach patrol and surveillance; and improvements in emergency and medical response (see Figure 2). We argue that the claim that the SMP is effective in reducing shark interactions conflates correlation with causation, oversimplifying or overlooking key social factors.

Only one fatality has occurred at a meshed beach – Merewether Beach, Newcastle, in 1951. A further 24 bites resulting in injury are recorded at netted beaches over the eight decades of the SMP (Department of Primary Industries n.d.-c). These incidents demonstrate that the SMP does not prevent shark bite; a point made explicitly by the NSW government.

To determine the change in shark bite incidence over time, we plotted fatal and non-fatal incidents per year (Figure 5) and per decade (Figure 6). From this analysis, we make three observations. First, shark bite is very rare, both in absolute numbers and in relation to other beach and ocean accidents. In 150 years, 204 shark bite incidents have been reported, leading to 66 fatalities. Total incidence has varied between 0 and 9 per year (0–4 fatalities). In relation to other beach accidents, on average 92 people drown each year in Australian coastal waters, and NSW accounts for almost half this toll (Surf Life Saving NSW, 2013).

Second, the raw data show two clusters of incidents. The first during the early 20th century; the second from the mid-1990s. The early cluster is frequently interpreted in relation to the decade that followed; that is, as evidence that shark bite incidence declined following, and due to, the introduction of the SMP. We argue that this interpretation conflates correlation with causation, is an over-simplification of the social context of the time, and that multiple other factors must be considered when interpreting the data; we expand below. The later cluster occurs in the context of a relatively stable SMP, suggesting other factors influence incidence. Our third observation is that despite the cluster of incidents since the mid-1990s, fatalities remain very low. This point is largely overlooked in public discourse of shark hazards in Australia.

We argue that multiple factors influence the incidence of shark bite (see also Chapman & McPhee, 2016). In the remainder of this section we examine four key socio-cultural factors, external to the SMP, that should be taken into account when assessing its effectiveness. First, population growth in Australia, the state of NSW and coastal NSW, suggests more people entering the water. We used NSW population data to determine the number of shark bites per million people per decade (Australian Bureau of Statistics, 2014, 2017; Figure 7). Relative to population, total incidence decreases markedly from the 1940s and is lower overall in the second half of the 150-year record. Research in California finds consistent results (Ferretti et al., 2015).

Through analysis of bite incidence relative to population, the cluster from the mid-1990s observed in the raw data (Figures 5 and

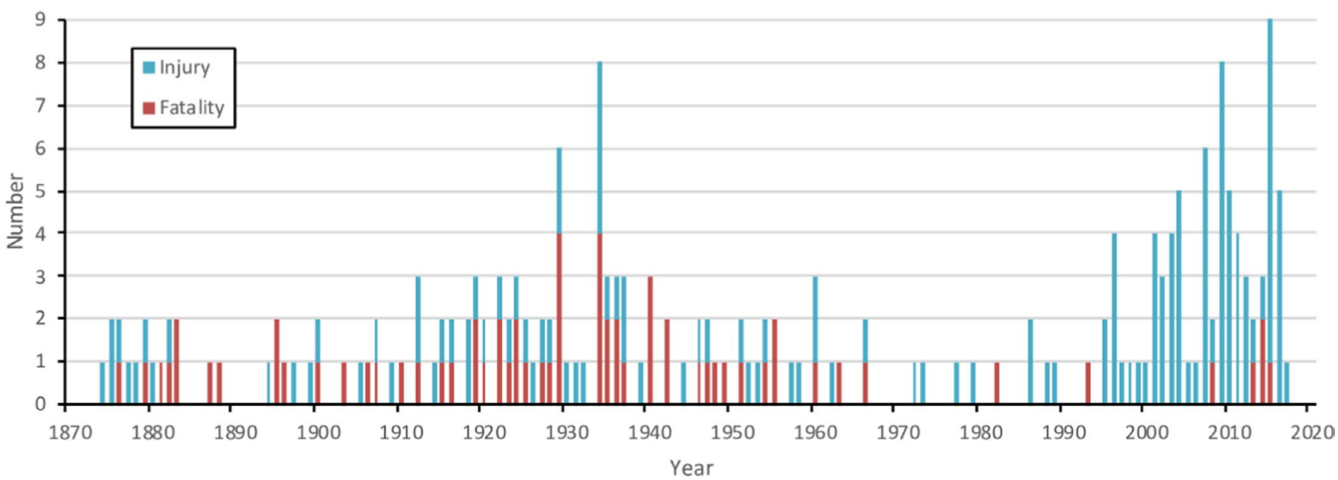


FIGURE 5 Shark bite incidents in New South Wales by year, including incidents leading to fatality and non-fatal injury. Source: Australian Shark Attack File (Taronga Conservation Society Australia n.d.)

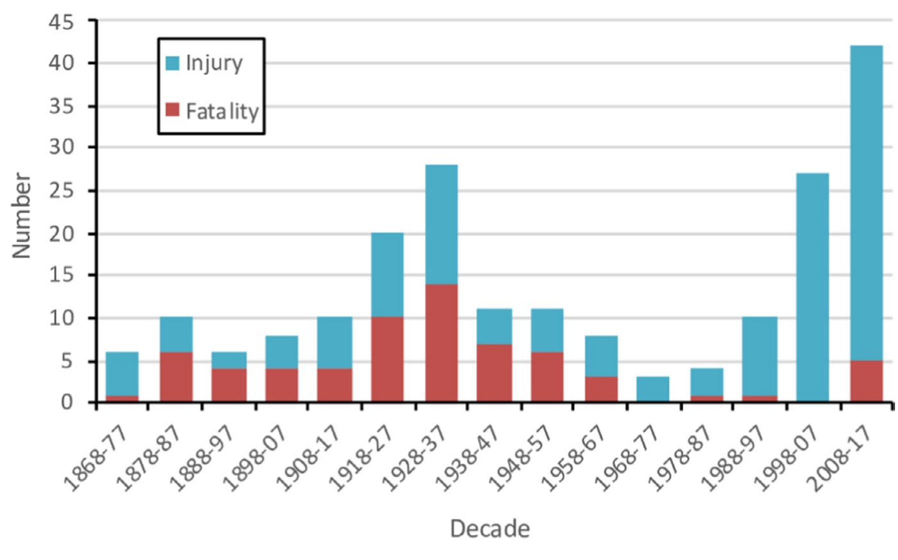


FIGURE 6 Shark bite incidents in New South Wales by decade, including incidents leading to fatality and non-fatal injury. Decades selected to highlight the introduction of the *Shark Meshing (Bather Protection) Program* in late 1937, and to include publicly available data to 2017. Source: Australian Shark Attack File (Taronga Conservation Society Australia n.d.)

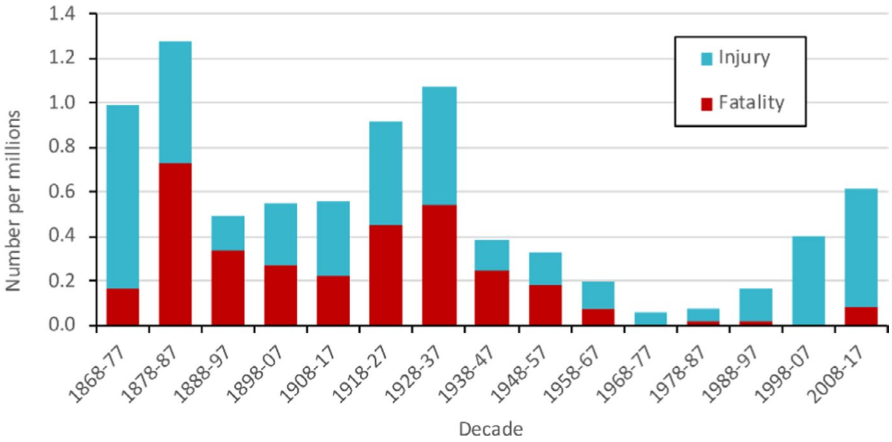


FIGURE 7 Shark bite incidents in New South Wales per million people per decade, including incidents leading to fatality and non-fatal injury. Decades selected to highlight the introduction of the *Shark Meshing (Bather Protection) Program* in late 1937, and to include publicly available data to 2017. Source: Australian Bureau of Statistics (2014, 2017); Australian Shark Attack File (Taronga Conservation Society Australia n.d.)

6) becomes far less pronounced (Figure 7). Analysis of coastal population would further reduce the apparent spike. Coastal NSW saw a sharp rise in population growth from the 1980s (Gurran, Squires, & Blakely, 2006). Since 1991, growth has been fastest near the coast, and a stronger trend during 2011–2014 indicates growth is accelerating. Signs of rapid growth c. 30 km from the coast suggest growing suburban areas near coastal cities (Commonwealth of Australia, 2017). Further, Hugo and Harris (2013) discussed the significance of Australia's growing temporary coastal population. Based on three NSW coastal localities (Byron Bay, Shoalhaven and Eurobodalla), they estimated the combined effect of holiday-home-owners and tourists would add 24.9% to the 2011 effective full-time resident population. In his global study of unprovoked shark bite, McPhee (2014) found total incidence and fatalities increased over the 30 years to 2011, and argued population growth plays a role but does not alone account for the rise (see also Chapman & McPhee, 2016). We agree that population paints an incomplete picture of change in shark bite incidence, but suggest that growth in permanent and temporary coastal population provides an as yet unaccounted for portion of the increase in incidence in NSW since the mid-1990s.

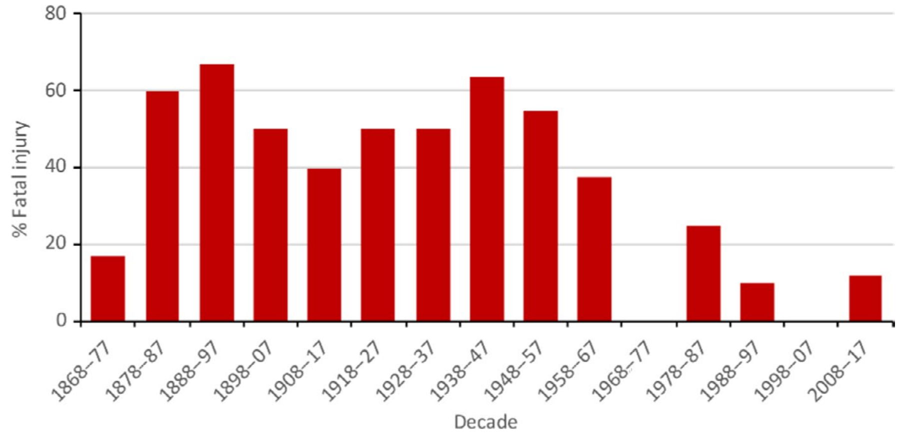
The second key factor influencing shark bite incidence is cultures of beach- and ocean-use, which have changed dramatically over time. From the early 1830s until around 1903, public bathing during daylight hours was officially prohibited (Ford, 2014; Metusela & Waitt, 2012). Metusela and Waitt (2012) noted 'under the Bathing Regulation Bill [1894] *all* aspects of bathing were legislated' (p. 27), and 'surf-bathing naked or semi-naked in *public* was considered by many of those in positions of colonial authority as immoral' (p. xviii). Ford (2014) argued the shift towards daylight surf-bathing was a response to broad cultural change and new by-laws. Together, these factors led to 'a rapid influx of surf bathers who were not familiar with the surf and in many cases could not even swim, putting their own safety and that of their rescuers in danger' (Ford, 2014, p. 50). Popularity of the beach and surf grew rapidly: 'The 1920s and 1930s are renowned for the huge crowds that flocked to Sydney's beaches each summer' (p. 165). As WWI ended many people began to enjoy economic prosperity and increased leisure time; beaches 'became a favourite resort, many easily reached by ferry, train or tram' (Cushing & Huntsman, 2007, p. 9). From the late 1920s, public appeals were increasingly made for new members of surf clubs, based on 'the moral ground of self-sacrifice and civic duty', and by the 1930s competitive surf carnivals were popular (Metusela & Waitt, 2012, p. 92). This history suggests the increase in shark bites in the early 20th century is likely due, in part, to cultural and social changes that saw massive growth in popularity of the beach and surf.

In recent decades, Australian beach use has again grown dramatically (West, 2011). In the absence of a complete record, West (2011, p. 745) adopted 'a conservative figure of a 20% annual increase' in beach visitation and water-based activities over the preceding decade. He derived this figure from 'an average of the Australian population increase of 15% and an increase in surf life-saver beach rescues of 29%' over the same time period. West (2011, p. 744) noted the greater number of shark bites from the 1990s 'coincides with an increasing human population, more people visiting beaches, a rise in the popularity of water-based fitness and recreational activities and people accessing previously isolated coastal areas'. He argued the increase in incidence is due to larger numbers of people in the water; others have described this as a major factor (Chapman & McPhee, 2016; McPhee, 2014).

The third key factor, frequently overlooked in debates about effectiveness of shark hazard management, is beach patrol. In Australia, popular beaches are patrolled by professional lifeguards and volunteer surf lifesavers. These activities developed from the early 20th century with the rising popularity of surf-bathing. Australia's earliest beach patrols began in the late 19th century (Brawley, 2007; Ford, 2014), and the precursor to today's Surf Life Saving Australia (SLSA) formed in 1907 (Ford, 2014). The surf life saving movement grew rapidly through the 1920s and 1930s, especially in NSW, Queensland and WA (Cushing & Huntsman, 2007). By the late 1930s, the importance of bathing 'between the flags' – that is, in the patrolled area of the beach – was widely promoted (Metusela & Waitt, 2012).

Establishment of beach patrol across Australia's popular beaches broadly corresponds with introduction of the SMP. Beach safety improved substantially through the development of beach patrol. Today, 50 of the 51 beaches netted through the SMP are also patrolled beaches (Surf Life Saving Australia n.d.). Yet in public discourse and policy debate about shark hazard management, improved safety is generally attributed to the SMP; the role of beach patrol is largely

FIGURE 8 Proportion of shark bite incidents resulting in fatality in New South Wales by decade. Decades selected to highlight the introduction of the *Shark Meshing (Bather Protection) Program* in late 1937, and to include publicly available data to 2017. Source: Australian Shark Attack File (Taronga Conservation Society Australia n.d.)



overlooked. We argue beach patrol has historically played, and continues to play, a significant role in reducing shark hazards in Australia.

The fourth and final key factor frequently overlooked in debate about the effectiveness of shark hazard mitigation is improved emergency and medical response. Beach patrol plays a central function in emergency response to any beach hazard, including shark bite. In addition, generic improvements in medicine post-WWII, and specific knowledge of response to shark bite, have grown substantially. Ricci, Vargas, Singhal, and Lee (2016, p. 112) stated: 'due to advancements in medical care and earlier access to treatment, the percentage of fatal attacks has decreased'. Regarding shark bite incidents in Sydney in 2009, Rtshiladze, Andersen, Nguyen, Grabs, and Ho (2011, p. 350) found 'Recent advances in the management of major trauma patients has led to a greater understanding of the role of pre-hospital tourniquets, rapid transit to the operating suite and damage control surgery'.

Returning to our analysis of the ASAF, we argue that the proportion of incidents resulting in fatality is an important and under-emphasized change in the record (Figure 8). From mid-20th century – approximately the end of WWII – this proportion declines markedly. If we split the 150-year dataset into two equal periods, the number of incidents is approximately equal. However, the proportion of shark bites leading to fatality prior to the end of WWII (1874–1945; there are no recorded shark bites 1868–1873) is 51% (of a total 95 bites), and in the post-War period (1946–2017) the proportion is 17% (*n* = 109). West (2011) suggested the early record is likely incomplete. To address this limitation of the data, we considered two decades before the end of WWII (1926–1945) and prior to today (1998–2017). Doing so, an even more pronounced trend emerges; the proportion of fatalities in the earlier period is 53% (*n* = 38) and in the recent period 7% (*n* = 69). We argue that effective emergency response and medical treatment, combined with beach patrol, are clear contributors to the low proportion of fatalities following shark bite in recent decades.

4 | CONCLUSIONS

Shark bite is extremely high profile in Australia and globally. Lethal strategies for managing shark hazards are used in many parts of the world, including eastern Australia. The NSW *Shark Meshing (Bather Protection) Program* is the longest-running lethal program in the world. However, since its introduction in 1937, many things have changed. Oceans and marine ecosystems have come under combined pressures of warming, acidification, overfishing and pollution; scientific understanding has increased substantially; and environmental awareness among broad publics has grown. In the context of these biophysical and socio-cultural changes, lethal strategies are subject to increasing public and scientific criticism and critique, and new non-lethal approaches are being developed. This paper contributes to this shift by developing a fuller account of the negative effects for sharks and the effectiveness for human safety of a prominent, long-standing lethal shark management program.

Numbers of animals caught in the nets of the SMP, including target species and bycatch, have varied greatly year-to-year. Our analysis shows long-term decline in total shark catch and catch of three key target species and genus – white shark, tiger shark and whaler species – to 2017. Declines in catch suggest reduced abundance in the region of the SMP. This may indicate the Program has contributed to population decline, given sustained fishing effort, and/or it may reflect broader trends in abundance observed globally. Irrespective of the cause, reduced catch coupled with increased effort suggests smaller numbers of sharks, including species identified as threatening and threatened, which is a cause for concern. Further, despite efforts to reduce bycatch, non-target species represent the vast majority of animals caught in SMP nets. Long-term effects of catch and release are poorly understood, but recent research indicates catch-related stresses. In the context of broader pressures on marine environments, the large sharks are at heightened risk of extinction. Together these factors suggest the rationale and justification for the SMP, and other lethal strategies, might be revisited to reduce pressures on vulnerable species and ecosystems.

The SMP is frequently presented as the key or sole factor responsible for reducing shark bite incidence in NSW. However, the evidence does not support this claim. Our analysis demonstrates several factors external to the Program are key. Coastal population growth, combined with changing cultures of beach- and ocean-use, has led to rapid increases in numbers of people entering the water. This has played an important role in changing shark bite incidence over time, including observed spikes in the early 20th century and in recent years. Establishment of beach patrol from the 1920s and 1930s led to improved overall beach safety. Today 50 of the 51 beaches meshed through the SMP are also patrolled. As such, findings that shark bite incidence are reduced at *meshed* beaches might alternately be interpreted as reduced incidence at *patrolled* beaches. The contribution of beach patrol to shark hazard management warrants further study. Finally, analysis of ASAF data shows the proportion of shark bites leading to fatality has decreased significantly in recent decades; from 51% in the pre-War era to 17% post-WWII. This improvement in survival rate is likely a result of investment in public services and advances in medicine since the mid-20th century.

These social and cultural factors have largely been overlooked in assessments of the effectiveness of shark hazard management. Substantial financial and human resources are invested in beach patrol and emergency and medical response. Positive effects of these investments and this work could be more widely acknowledged and celebrated. In addition, these factors provide major contributions to human safety and well-being, without any of the negative consequences for sharks and other marine life – including threatened species – caused by lethal strategies. These areas offer a focus for future efforts to further improve human safety.

Attributing reduced risk of dangerous shark encounter to the SMP, or to any single strategy, seriously over-simplifies the available data and understates the significance of the broader biophysical and social context. We have shown that multiple factors come together to determine the effects and effectiveness of shark hazard management. We argue more interdisciplinary work is needed to bring these factors into conversation, to make appropriate, informed decisions. Only in doing so can we hope to move away from simple cause-and-effect stories, and beyond polarized debates that erroneously pit human safety and marine conservation against one another.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHORS' CONTRIBUTIONS

L.G., L.F., M.R. and Q.H. conceptualized the study. L.G., L.F. and M.R. developed the methodology, gathered the data and conducted analysis. L.G. managed the project and prepared the original draft. All authors contributed critically to the drafts and have given final approval for publication.

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DATA AVAILABILITY STATEMENT

All shark catch data, estimates of netting effort and catch per unit effort in the *Shark Meshing (Bather Protection) Program* NSW, for netting seasons 1950–2017, are available from the Figshare database https://doi.org/10.6084/m9.figshare.6222155 (Fetterplace et al., 2018).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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