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Selective removal of problem individuals as an environmentally responsible approach for managing shark bites on humans

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ABSTRACT

Selective removal of problem individuals following shark bite incidents would be consistent with current management practices for terrestrial predators, and would be more effective and more environmentally responsible than current mass-culling programs. In parallel, and in addition to traditional forensics analysis, we recommend the routine collection of shark DNA from wounds or devices following shark bite incidents in order to genetically identify the individual responsible. This approach would require creating an extensive database of shark identities in high-risk areas against which to compare DNA forensically recovered from shark bite incidents. At a local and regional scale, we propose utilizing existing shark tagging programs and artificial shark aggregation sites to collect DNA, behavioural and morphological data for the database, and to facilitate removal of problem individuals. In several places around the world, selective removal of problem individuals would not be significantly more expensive and definitely less environmentally-destructive than traditional approaches and would also help reconcile people and sharks by underlining individuality in shark behaviour.

1. Introduction

Although very rare with an average of <10 human fatalities per year (ISAF, 2020), shark bites generate strong emotional reactions among the public that pressure decision-makers to implement reactive mitigation strategies (Meeuwig and Fereira, 2014). Mass shark culling campaigns, such as those recently implemented in Australia and La Reunion island (Clua and Linnell, 2018), have been the most common management response to fatal shark bites on humans. These campaigns have detrimental effects on the status of already threatened species and their effectiveness is questionable (Ferreti et al., 2015). The few analyses suggesting culling campaigns improve human safety (e.g. Dudley, 1997; Cliff and Dudley, 2011) lack controls and show apparent trends that may simply reflect the natural rarity and stochasticity of fatal bites on humans. Analyses of other culling campaigns show they do not reduce shark bites. One of the most comprehensive studies conducted on a shark control programs shows how 4668 sharks (including 554 tiger sharks *Galeocerdo cuvier* considered to be the species responsible for lethal bites on surfers) were killed in Hawaii between 1959 and 1976, with “no measurable effects on the rate of shark fatalities in Hawaiian waters” (Wetherbee et al., 1994). In this study an average rate of 0.6 fatal ‘attacks’ per year was recorded before and persisted during the culling, with an increase to 1.4 per year during the years following the program. An ongoing culling campaign around La Réunion Island (Indian Ocean), removed 33 bull sharks *Carcharhinus leucas* and 122 tiger sharks *Galeocerdo cuvier* between March 2018 and December 2019, yet two human fatalities (among a total of five around the world) were still experienced in January and May 2019, respectively (IR, 2020).

Compared to the very few fatal bites, on a global basis there are hundreds of non-lethal shark bites on humans, most of them unreported, perpetrated by many shark species potentially driven by many different motivations including self-defense (Balbridge, 1988; Gruber, 1988), territoriality, hunger or competition (Johnson and Nelson, 1973; Gruber, 1988; Jublier and Clua, 2018) or misidentification of prey (Clua, 2018). However, these agonistic behaviours usually only cause non-fatal superficial wounds and do not trigger the initiation of unselective culling campaigns and are therefore not the priority focus of our discussion. Instead, we are focusing on fatal or near-fatal bites that probably result from feeding attempts by larger species (Clua and Reid, 2018). Three shark species (white shark *Carcharodon carcharias*, tiger shark and bull

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shark *Carcharhinus leucas* collectively account for most of the worlds' serious and fatal shark bite incidents (ISAF, 2020). The first two species are considered highly migratory (Bonfil et al., 2005; Meyer et al., 2009), an ecological trait that could partially explain why blind mass culling campaigns, that are based on a simple density-dependent hypothesis, often fail because they do not remove the very few animals within the population that constitute a potential threat to humans. This mass predator culling approach is completely at odds with methods used in terrestrial settings where considerable efforts are made to carefully identify and selectively remove only problem individuals associated with negative interactions with humans (Linnell et al., 1999; Packer et al., 2019), and there is no *a priori* reason why this selective approach cannot be extended to sharks (Clua and Linnell, 2018).

Shark bites on humans are very rare, hence the numbers of sharks biting people must be very low (i.e. it cannot exceed the number of people bitten). However, these rare incidents often cluster in space and time, making it possible that a few individual sharks are responsible for multiple bites, as was recently concluded in Cocos island (Costa Rica), where a 3.5 m Total Length (TL) female tiger shark was responsible for a fatal bite on a US diver in November 2017, a non-fatal bite on a German diver in April 2018 and subsequent aggressive interactions with divers (EC Pers. Obs.). Concerning the eight bites occurring around La Reunion iland (Indian Ocean) between April 2015 and February 2018, forensic analyses identified four times a bull shark as the species involved, which on three occasions was around 2.5 m TL in size (IR, 2020). Neither of these case studies alone can prove or disprove either of the competing hypotheses behind shark fatalities. However, they do illustrate that, compared to usual environmentally-based drivers of shark bites (Chapman and McPhee, 2016), the behavioral hypothesis (Clua and Linnell, 2018) is an equally, or even more, plausible explanation of the events, and that it therefore deserves due consideration. This hypothesis states that some animals with specific behaviors (including boldness and aggressiveness) may potentially pose a higher risk than conspecifics. Under this scenario the risk of a shark 'attack' in a given area would relate to the presence of a limited number of high-risk individuals rather than for example shark density or habitat parameters. Such hypothesis should not be confused with the controversial 'rogue' shark hypothesis (Neff, 2015). While our 'problem individual' and a 'rogue' shark would both tend to repeat strikes on human beings, as potential prey, in our perspective, the latter would develop an aggressive and targeted preference for humans as embodied by films such as “Jaws”. It would also imply a high degree of individual aggression, whereas the current ethology literature on which we base our hypothesis underlines individual differences along a shyness-boldness gradient (Clua and Linnell, 2019). As a matter of fact, given the conservation status and ecological importance of sharks, there is currently not enough convincing scientific basis for mass unselective culling campaigns which may completely fail to capture the “problem individual” while simultaneously inflicting damage on the marine ecosystem

Thus far, alternative strategies and possible improvements to large scale and non-selective shark culling include (i) in-depth analysis of available attack data to uncover spatio-temporal patterns of 'attacks' and inform management strategies to enhance public safety and risk perception (Sprivulis, 2014; Ferreti et al., 2015), (ii) the improvement of beach safety with smart drumlines (Guyomard et al., 2019), nets and/or shark spotters (Curtis et al., 2012), (iii) the use of telemetry protocols to set up warning systems (Curtis et al., 2012; Meeuwig and Ferraira, 2014; McAuley et al., 2016), (iv) the development of effective shark personal or barrier deterrents or repellents (Huveneers et al., 2013, 2018; O'Connell et al., 2014, 2018; Stroud et al., 2014), (v) the use by sea users of novel fabrics to resist punctures and lacerations from large sharks (Whitmarsch et al., 2019), and vi) the enhancement of first aid skills among the public and first responders for the efficient medical care of shark 'attack' victims (Curtis et al., 2012). In the case of beach nets that were thoroughly documented in South Africa, such strategies might appear effective but are economically expensive (US$ 7 million per annum) and also have an ecological cost in terms of dead sharks and other by-catches resulting from entanglement (see Cliff and Dudley, 2011), which appears less and less acceptable to a large portion of our societies (Swan et al., 2017). None of these strategies consider whether the identification and selective removal of problem individuals would provide an effective alternative way to prevent shark 'attack' outbreaks with minimal ecological cost.

In this paper, we propose a new approach for increasing ocean-users' safety that is based on improved forensic analysis for individual shark profiling, combined with existing or new underwater studies to identify individual sharks in order to selectively remove the 'problem' animals after the confirmation of their involvement in a human fatality. This approach has the potential to reduce the negative ecological effects currently posed by non-selective shark culling campaigns, and to alleviate the conflicts with stakeholders opposed to them.

2. Profiling of “problem individuals” after a bite on humans

In practice, the success of management approaches based on selective shark removal will depend on the development of protocols that enable the reliable identification and targeted removal of 'problem individuals' (Linnell et al., 1999; Swan et al., 2017). To significantly improve the management of these events in a given area, we propose to (i) improve the speed and effectiveness of forensic analysis that follows a shark fatality to profile the problem animals and, (ii) broaden the access to sharks in order to set up a database of sharks against which to compare DNA recovered from shark bite incidents and to access the animals to individually identify them and to manage the risk. This database could be compiled from innovative shark aggregating and/or existing mark-release fishing operations.

Although we already have several forensic techniques already available for identifying the species and size of shark responsible for bite incidents (Lowrie et al., 2009; Clua and Reid, 2018), these are not being used consistently and none of them are as precise or definitive as the use of DNA techniques which hold potential to definitively identify species, sex and the individual responsible for the incident. For example, Inter-Dental Distance (IDD) measurements and other features of the wounds, combined with ecological knowledge of the suspected shark species and witness accounts, can help to accurately profile the incident perpetrator (Lowrie et al., 2009; Clua and Reid, 2018) (Fig. 1) yet these techniques are not always fully applied.

Systematic attempts to accurately profile a shark and recommend appropriate management actions should be undertaken as soon as possible (within a few hours, through use of the internet and based on adequate photographic documentation) after the incident. The victim and associated accessories (e.g. surfboard, wetsuit) should be swabbed for transfer DNA as soon as possible after the bite occurs. Ocean lifeguards and other emergency personnel could be issued simple swab kits to collect samples from accessories at the beach, or medical personnel could swab wounds once the patient has been stabilized. DNA barcoding to identify the shark species involved in the incident is easy and inexpensive with readily available primers (Fields et al., 2015) and studies have demonstrated that it works with DNA collected from flesh (Fotedar et al., 2019). However, as a first step forward for managing fatal bites, DNA fingerprinting using microsatellite repeat sequences would allow the identification of an individual among a given species (Chambers et al., 2014). DNA barcoding could be skipped if other forensic analysis methods (see above) could reliably identify the species of shark (Fig. 1).

3. Spotting and profiling the pool of potential “problem individuals”

Identifying individuals responsible for shark bites is a first critical step but finding them in the wild still poses a great challenge as large sharks are elusive and mobile animals. We need a library of DNA samples large enough to include the potential problem individuals within

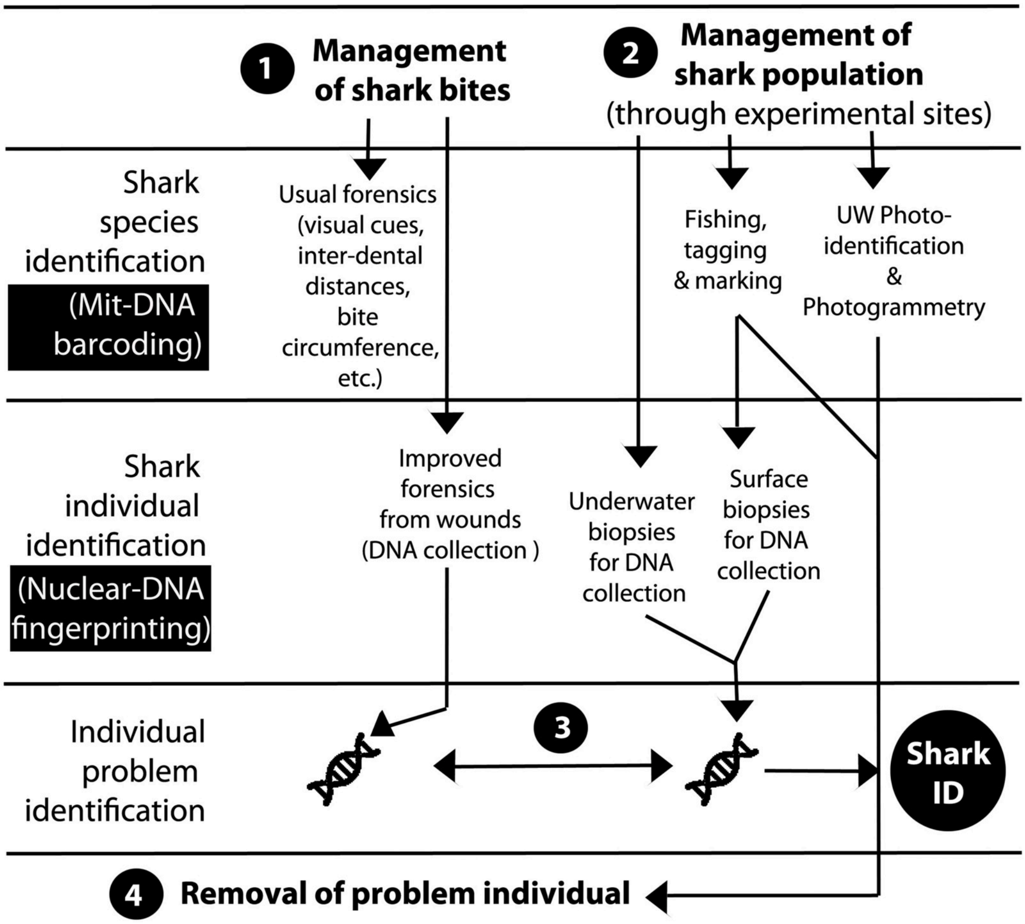

Fig. 1. General management of problem individuals that would rely on (1) the critical step of collecting DNA fragments in the framework of an improved forensic analysis following a shark strike on a human, (2) the parallel setting up of a genetic fingerprinting database of potential perpetrators (using experimental aggregation sites or other capture-recapture studies) which is also linked to a photographic image database, in order to (3) obtain the match between fingerprints and (4) the potential selective removal of a problem individual that would be spotted either on an experimental aggregation site again or through a tagging program, locally or at a regional level, days or even months after the strike. NB: Shark DNA could also be collected from personal accessories such as surfboards following bite incidents.

the larger population and we need a method of rapidly and definitively identifying those sharks in the field if removal is warranted. We propose a two-fold strategy to achieve this: (1) Leveraging existing shark tagging programs to obtain DNA profiles from individuals marked with external identification tags, and (2) Create temporary shark aggregation sites by using attractants (bait, blood etc.) in order to photograph (for visual identification purposes) and biopsy attendant sharks. Shark aggregation techniques are usually used for ecotourism purposes but could easily become management tools for profiling and removing problem individuals (Fig. 2). Individual identification among species with polymorphic color patterns such as those found on white and tiger sharks is effective and has proven to be reliable (Domeier and Nasby-Lucas, 2007). While more complicated, individual identification is also possible for those with uniform color patterns such as the bull shark (Brunnschweiller and Barnett, 2013). Problem animals could be ideally identified through genetics (by crossing the DNA fingerprinting results of forensics and underwater DNA sampling).

Such observation and management (sampling and occasional removal) sites could be implemented in remote and confined areas, for example offshore where ocean users are not likely to be accidentally involved. However, these areas would need to be sufficiently spatially connected to sites, like popular swimming or surfing beaches, where protection is essential. As a point to support the strong attractiveness of these artificial provisioning sites as compared to the locations of traditional fishing removal sites, acoustic-tagged bull sharks that were aggregated at a feeding site in Fiji were locally detected regardless of whether it was a feeding or a non-feeding day (Brunnschweiler and Barnett, 2013). Given the strong attractiveness of odor stimuli, we strongly believe that such experimental sites would provide suitable access to both transient animals, such as white and tiger sharks that are known for their high mobility and more resident species like bull sharks.

This two-fold approach based on fishing and/or diving appears necessary as (i) not all regions allow shark chumming, (ii) mark-recapture fishing can sample much more extensive areas than the aggregation method.

4. LARGE-SCALE regional cooperation for managing migratory species

Two studies have shown a relatively high site fidelity of satellite-tagged bull sharks and tiger sharks that have moved over hundreds of kilometers in the Pacific (Brunnschweiler et al., 2010) and thousands of kms in the Western Atlantic (Hammerschlag et al., 2012), respectively, before returning to artificial provisioning sites. Such information supports the utility of setting up a genetic database based on aggregation sites. However, the highly migratory behaviour of some individuals poses two main problems for our proposed method. Firstly, an unknown, unsampled and therefore unidentifiable transient shark could bite someone. Secondly, a known shark considered locally resident could bite someone and then leave the area. This could be overcome by creating a regional database of individual genetic profiles, identification photos and tags from potentially dangerous species. This database could be consulted whenever DNA is recovered from a shark bite incident in order to allow the identification of locally-unknown problem individuals. Following conclusive identification, the removal of the animal could then happen in a different place and at a different time, including several months after a shark incident, including fatal but also serious non-fatal bites.

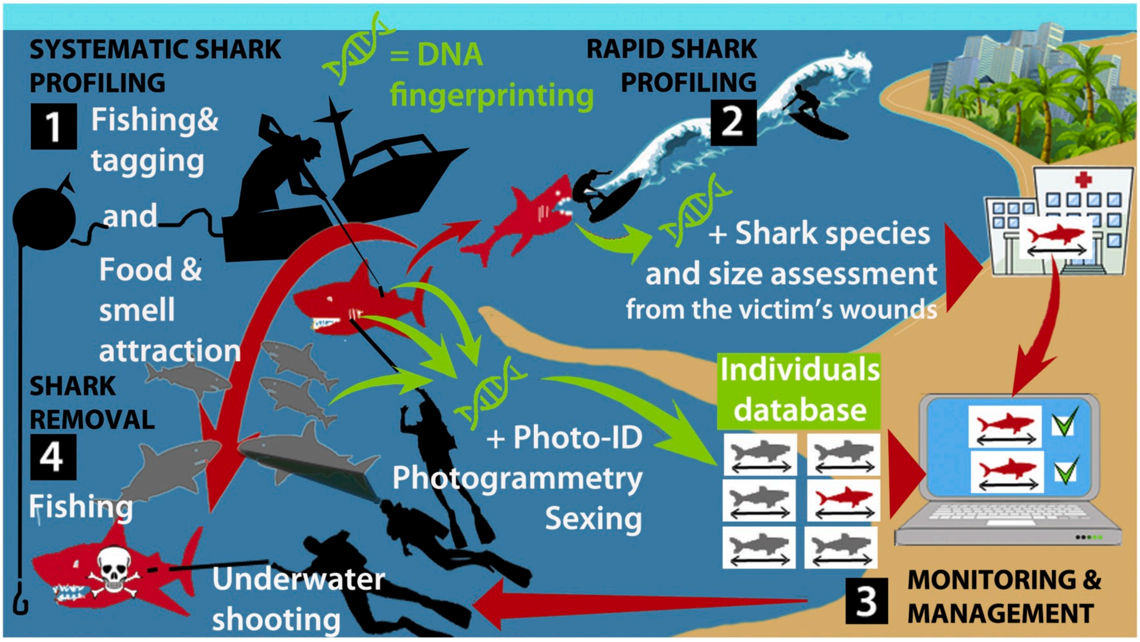

Fig. 2. Schematic representation of the proposed management system for managing shark fatalities. 1: Systematic and large-scale shark profiling should be undertaken through existing fishing-based capture-recapture operations and/or artificial provisioning sites that would be organized in a remote (offshore) site at a suitable distance from exposed beaches in order to aggregate all large sharks potentially dangerous for humans. In both approaches, systematic DNA sampling would be conducted for individual fingerprinting. This individual genetic profiling would be complemented by any means allowing the identification of the shark afterwards such as tagging and photo-identification, including for photogrammetry (with calibrated lasers) performed by expert scuba-divers allowing an accurate individual identification of sharks, whatever their species. The objective is for any shark to be individually identifiable for removal. A local database of individual sharks would be maintained, possibly enriched by data from other sites and countries. 2: Any incident with humans would be followed by a quick and efficient forensic process aiming at collecting DNA fragments in the victim's wounds and assessing the shark species and length whenever possible. In an ideal scenario, a DNA fingerprinting analysis would allow the identification of the problem individual. 3: The information (species, size and individual DNA identity) would be crossed with the local database of sharks potentially dangerous for humans. A match would designate the identity of the shark involved in the incident. 4: Based on full (through DNA identification) or basic (through only species and length assessment) profiling, the (few) potential candidate(s) would be removed either through a fishing process or an underwater shooting. This approach would also work with a transient shark that never came to the observation site before causing a human fatality. Such a shark could be DNA sampled at the neighboring aggregation site (or another one) after the incident and still be removed if it is spotted again after being positively identified as a problem individual.

5. Public acceptance and safety concerns regarding the feeding sites

The potential deleterious effects of such artificial food provisioning (see Brena et al., 2015) appear as a more acceptable ecological risk than the large-scale non-selective culling of threatened animals. Unlike for terrestrial predators such as bears (Floyd, 1999), it has never been shown that such artificial provisioning with the associated risks of food conditioning increase the risk of human fatalities in the vicinity of the activity. Empirical data from a feeding site set up in the 1990s' in Fiji and involving more than 50 bull sharks (considered as a potentially dangerous shark species for humans) has had no incidents in 28 years, in spite of many ocean users (in addition to scuba divers) being in the vicinity of the feeding spot on a daily basis (M. Neumann, Pers. Comm.). Beside the example of Fiji, figures show that other places where artificial provisioning is usually implemented (without culling) such as Tahiti (French Polynesia), Playa del Carmen (Mexico) or Tiger beach (Bahamas) have a very low rate of (if any) shark fatalities whereas places with no feeding activities (and regular blind fishing campaigns) such as Western Australia, Brazil or La Reunion account for the most human fatalities (ISAF, 2020). Furthermore, such a scientific framework would only involve a few expert divers with controlled procedures to decrease the link that animals may make between feeding stimuli and humans.

6. Scientific monitoring of shark movements and behavior to prevent attacks

With the exception of ending the non-selective culling campaigns, our proposal for selective management through individual shark profiling does not aim, at least in the short term, to replace the traditional management measures for shark attack mitigation. Those involving the VR4 receivers that are able to spot an acoustic tag on a given shark as implemented in south-western Australia (McAuley et al., 2016), would actually be very complementary to the individual profiling approach. The monitoring of feeding sites could be used, not only for photo-ID, sizing and DNA sampling, but also for acoustic tagging of the sharks. The acoustic arrays would then provide valuable information about shark movements, including locating forensically-identified problem individuals; the presence of such an animal in the vicinity of a populated beach properly equipped with VR4 receivers could constitute a high level of risk with a proportionate response through a management risk protocol, such as a temporary beach closure. Such a process would ease the short-term risk from this individual, before it was selectively removed. Furthermore, studies of individual shark behaviour (i.e. boldness or aggression) at aggregation sites over time, and with links to investigation of non-fatal bites or aggressive approaches (using DNA and/or photographic approaches) could be used to increase knowledge of behavioural individuality in sharks, and potentially develop protocols for pre-emptive removal of individuals with risky behaviour.

7. COST-EFFECTIVENESS in comparison to current practices

The Hawaii shark culling programme (from 1956 to 1974) came up with an average cost of US$182 per shark killed. If we use the 1969 inflation rate as the reference date, the cost in 2019 per shark culled would be US$1228 for a total expense of US$2,123,095 to kill 4668 sharks and without a detectable impact on shark bite numbers (Wetherbee et al., 1994). In fact, two shark bites occurred right toward the end, and immediately after, the largest culling program (1967–1969). One of those bites occurred at a beach from where 33 tiger sharks had been culled (CM Pers. Comm.). In March 2018, the French Ministry of Oversea Territories declared an increase in the government subsidies to La Reunion island up to US$2,200,000 per year for shark crisis management (LINFO, 2020). Among the global budget involving several prevention actions, a US$660,000 culling campaigns allowed the removal of 80 (65 tiger and 15 bull) sharks, i.e. US$8250 per shark culled, while two fatal bite still took place in January and May 2019 (IR, 2020). Once genetic reference databases already exist for the three main targeted shark species, a continuing fingerprinting analysis (involving an average of 20-loci as we suggest it) would cost US$40–50 per shark. The exhaustive genetic referencing of the bull shark population of a place like La Reunion island, which would include a maximum of 1200 individuals as estimated by the CHARC project (2015), would then cost < US$660,000 over several years, probably not involving (much) more running costs than present activity in terms of operations aiming at collecting shark DNA. The surface fishing operations are already implemented and funded (<30% of the total yearly amount dedicated to the shark crisis management of US$2,200,000 per year); they could be maintained but instead of culling shark, they could focus on DNA sampling. The complementary underwater operations suggested in this paper may indeed represent an extra and significant cost; but given what is at stake, it should be arbitrated with other significant expenses that are made with likely limited direct impact on public safety, such as a 3-D sonar with a 165-m range for shark detection on a single beach that cost US$770,000 for setting up in 2019 with an average running cost of US $375,000 per year (Anonymous, 2019). Based on these figures, the potential of gaining more efficiency in terms of public safety while sparing the lives of hundreds of sharks, should not be jeopardized based on financial arguments. In addition, these genetic databases could be used for other scientific purposes (such as the monitoring the genetic diversity or population trends for a given species) in addition to identifying a problem individual.

8. Conclusions

Although our management perspective does not resolve the issue of the mechanism behind shark incidents it offers more effective (in terms of improving human safety) and less ecologically damaging responses to these incidents. Furthermore, focusing management on individual animals would take the blame away from sharks in general and could help to improve the reputation of sharks worldwide (Swan et al., 2017).

Declaration of competing interest

We declare that we do not have any conflict of interest.

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