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Review article

Global systematic review of the factors influencing shark bites

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ABSTRACT

Shark bites can cause substantial socio-economic and ecological challenges, including debates about bite-mitigation policies, economic impacts for tourism-dependent communities, and increased fear among beachgoers. The growing frequency of shark bites globally has not only raised public concern but also intensified the need for comprehensive research into their causes. Using the 2020 PRISMA standards, we conducted a systematic review to synthetize current knowledge on factors influencing shark bites. We found that research on shark-bite determinants began in 1948 and has gained increased attention since the mid-2000s. Our search protocol identified 61 peer-reviewed articles proposing 40 factors likely influencing shark bites. These factors included 22 short-term factors, *e.g.* likely explaining short spates of shark bites, 13 long-term factors, *e.g.* addressing changes in the number of shark bites over decades, and 5 factors influencing both short- and long-term scales. Key suggested factors were changes in human and shark population dynamics, environmental conditions, prey availability, shark-bite mitigation measures, and coastal urbanization. However, most factors were speculative, with only five studies since 1948 statistically testing the correlation between shark bites and merely eight factors. Furthermore, there was a lack of consensus among studies on the effects of most factors. Our review therefore highlights the wide range of factors potentially influencing shark-bite occurrences worldwide while revealing a paucity of rigorous scientific evidence. It emphasizes the critical need for further studies to formally test shark bite determinants, providing decision-makers actionable insights to develop effective strategies that reduce shark-bite risks while enhancing both human safety and shark conservation.

1. Introduction

Sharks are a diverse group of cartilaginous fishes that have drawn considerable scientific and popular interest. As key predators, some sharks exert strong top-down effects on ecosystems, influencing food-web dynamics, regulating the abundance and distribution

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of mesopredators and primary consumers, and facilitating nutrient transfer and energetic linkages among habitats (Barnett et al., 2017; Dedman et al., 2024; Ferretti et al., 2010; Heithaus et al., 2022). Moreover, sharks are often caught and consumed because of their palatability, nutritional benefits, and relative affordability (Barreto et al., 2017; Clarke, 2006, 2004; Dent and Clarke, 2015; Hasan et al., 2023; Muttaqin et al., 2019). In some countries, the high value of shark parts, such as fins, has resulted in a rapid escalation in the global exploitation of shark stocks (Clarke et al., 2006; Worm et al., 2013). In many Pacific Island nations, sharks are revered as deities and guardian spirits, seen as manifestations of ancestors, guides to travelers, and the subjects of countless tales and proverbs (Dell'Apa et al., 2014; Jøn and Aich, 2015; Taylor, 1993; Techera, 2012; Torrente et al., 2018). However, sharks can also evoke fear as they represent one of the few animal groups that pose a threat to humans.

Despite their relative rarity, shark bites have become a societal phenomenon that draws intense public interest in mass and social media (Le Busque et al., 2021; McCagh et al., 2015; Muter et al., 2013; Sabatier and Huveneers, 2018). Often occurring within a short timeframe — ranging from a few weeks to a few days (Lagabrielle et al., 2018; MAILLAUD et al., 2022; Riley et al., 2022; Ugoretz et al., 2022) —shark bites can be highly traumatic for local communities and may lead to a decline in water sports participation and tourism (Muter et al., 2013), with negative economic impacts. These concerns often prompt management agencies to implement measures aimed at reducing perceived risk, reassuring the public, or providing information to help water users make more informed decisions about using specific areas and times. However, identifying high-risk areas and periods is challenging due to a limited understanding of the factors influencing shark bites. While various factors seem to play a role, the scientific community lacks a clear comprehension of their number and impact. To address this knowledge gap, researchers rely on two global repositories: the International Shark Attack File (ISAF; http://www.flmnh.ufl.edu/fish/sharks/isaf/isaf.htm) and the Global Shark Attack File (GSAF; https://www.sharkattackfile.net/incidentlog.htm). ISAF records only verified, unprovoked bites on living humans, whereas GSAF logs every documented human-shark interaction and assigns each a confidence level. Together, these databases provide the temporal and spatial context needed to analyze shark bites.

A recent analysis of the ISAF database revealed a global increase in shark bites over the past three decades (ISAF, 2023). Several hypotheses have been proposed to explain this upward trend, including population growth, habitat destruction or modification, climate change, alterations in water quality, and shifts in the distribution and abundance of prey (Chapman and McPhee, 2016). However, the rarity of shark bites makes it difficult to empirically evaluate the relative importance of causal factors that might have contributed to their global rise. Furthermore, each region seems to have different trends in shark bites, with, for example, an upward trend in the USA and Australia and a downward trend in Brazil since the mid-2000s (Chapman and McPhee, 2016; Hazin et al., 2013; Riley et al., 2022; Ugoretz et al., 2022). This highlights that shark-bite risk and its underlying factors can vary on a regional level and are context-specific.

One study attempted to synthesize factors likely contributing to the upward trend in shark bites, focusing on six primary hotspots: USA, Australia, South Africa, Brazil, Reunion Island, and the Bahamas (Chapman and McPhee, 2016). The authors suggest that local rises in shark bites were attributable to intersecting pressures, including changes in coastal populations, habitat alteration, declining water quality, climate-driven and weather anomalies, and shifts in prey distribution, which together destabilize local and regional ecosystems (Chapman and McPhee, 2016). However, no study to date has systematically reviewed and quantified the contribution of the underlying factors to shark bites in the scientific literature. Moreover, it is crucial to highlight whether such factors have been empirically tested and validated or if they remain speculative hypotheses. This systematic review aims to compile current knowledge on the factors that may influence shark bites on a global scale and assess whether they have been formally tested. Specifically, we explore the following research questions: (i) which factors are thought to influence shark bites across various spatio-temporal scales; (ii) have the proposed factors been empirically tested or are they speculative; (iii) is there consensus in the scientific literature regarding the effects of these factors on shark bites; and (iv) do the suggested factors affecting the number of shark bites vary between species. While "shark attack" is often used in the media and some of the earlier literature, we instead used "shark bites" throughout this review (Neff and Hueter, 2013), but included studies referring to either term.

2. Methods

2.1. Search strategy

Our review followed the 2020 Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) standards (Page et al., 2021). The PRISMA 2020 framework guides the planning, conduct, and transparent reporting of systematic reviews. It encompasses a 27-item checklist that informs a review's content and a flow diagram detailing study selection, thereby enhancing reproducibility and minimizing bias throughout the process. We used search engines including *Web of Science*, *Scopus,* and *Google Scholar* to systematically search combinations of the following terms within publications titles, abstracts, and key words: "shark" and at least one of the following six words: "attack", "bite", "interaction", "incident", "risk", or "encounter". These specific keywords were determined through a preliminary survey of the literature on shark bites. We also examined reference lists within relevant literature to locate additional sources. We included literature from all years until December 2023, without setting any earliest-year cutoff.

2.2. Study selection and eligibility criteria

We screened the title and abstract of each record and only kept studies published in peer-reviewed journals that suggested factors potentially explaining variations in the number or risk of shark bites. Therefore, we only included studies that focused on the factors influencing the number of shark bites and excluded studies that only mentioned them in the introduction. We also excluded abstracts, editorials, letters, opinions, position statements, proceedings papers, book chapters, theses, and gray literature. We restricted our analysis to peer-reviewed literature as it provides a reliable, expert-validated information base and is generally easier to find than some gray literature.

2.3. Data extraction and categorization

We extracted information from all publications into a standardized spreadsheet containing the following information: author(s), publication type (*e.g.* case report, research paper, or review) and year, country of study, shark bite database used, shark species considered, factors proposed to explain variations in the number or risk of shark bites, the direction of the correlation or relationship between those factors and trends in shark bites (*positive/increase*, *negative/decrease*, or *neutral*), and whether the factors were statistically tested (*tested*) or only suggested in the discussion *(suggested*). Publications were classified as a review if they were identified as narrative reviews, systematic reviews, or meta-analyses. Peer-reviewed publications solely describing shark bites without a specific research question constituted case reports. When a clear research question was present and addressed through quantitative analysis, statistical methods, or modeling, the peer-reviewed publication was classified as a research paper. The correlation was considered *positive* if an increase in the factor was believed to increase the number of shark bites, and *negative* if the factor was assumed to decrease the number of shark bites. Factors were classified as either *short-term* if they referred to fast changes, *e.g.* short spate of shark bites or changes over a few years, or *long-term* if they were proposed to explain changes in the number of shark bites over decades. Factors were further subdivided into seven categories based on whether they implied changes in human population (*human*), shark population (*shark*), prey populations (*prey*), environmental conditions (*environment*), coastal urbanization (*urbanization*), shark-bite mitigation measures (*mitigation*), or information reporting (*media*).

2.4. Data analysis and percentage calculations

This review specifically examined: (1) the spatial distribution of study areas; (2) how the number of publications citing explanatory factors has changed over time; (3) the type of factors proposed; and (4) the nature of correlations reported. Changes over time in publications citing the three species responsible for the most severe shark bites, i.e., white, tiger, and bull sharks, were evaluated. The short-term factors used to explain patterns in shark bites for each of these species were analyzed. Species-specific analyses for long-term factors could not be performed due to limited data.

All results are presented as percentages of either the total number of reviewed publications (N_{tot}), the number of studies addressing short-term (N_{ST}) or long-term factors (N_{LT}), their respective counts within specific time periods (*e.g.*, $N_{ST\ 48\text{–}70}$ for the number of studies addressing short-term factors between 1948 and 1970), or the number of publications referring to white (N_W), tiger (N_T), or bull (N_B) sharks. Because a single publication can mention multiple countries, factors, or species, percentages often add up to more than 100 %.

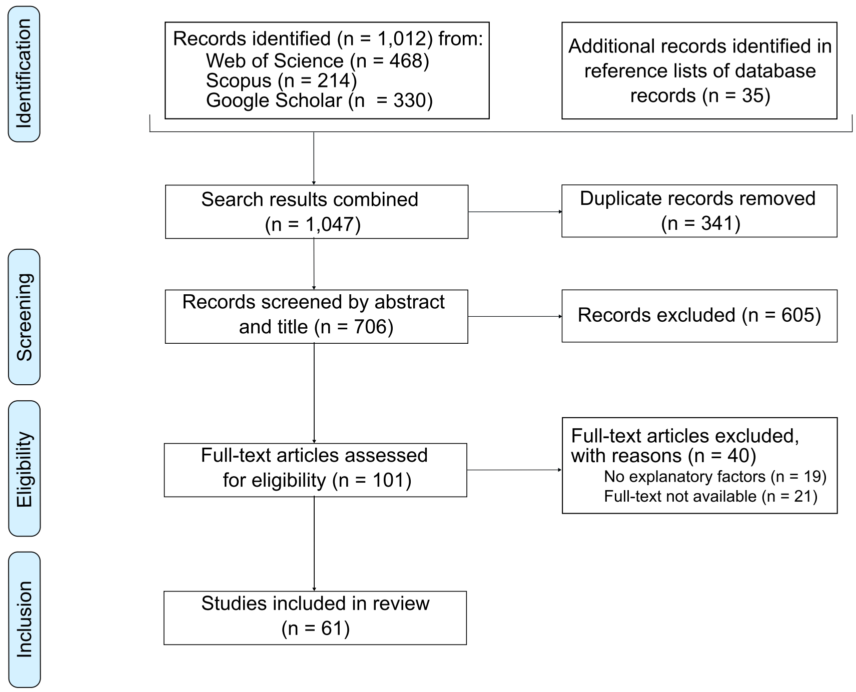


Fig. 1. Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) flow diagram, detailing the process of record collection and study elimination for this systematic review.

In contrast, when each publication is assigned to only one category (*e.g.* publication type), the percentages sum to 100 %.

Data analysis was done in R (R Core Team, 2023) version 4.3.1 using the tidyverse package set (Wickham et al., 2019).

3. Results

Searches across the three databases returned 1012 papers, which increased to 1047 after screening references cited in these papers (Fig. 1). After removing duplicates, 706 papers remained. Title and abstract screening further excluded 605 articles. Full-text screening of the remaining 101 publications resulted in 61 articles being eligible for this review and included in the analyses (S1 Appendix). Forty (65.6 %) were classified as original research papers, 16 (26.2 %) as case reports, and 5 (8.2 %) as reviews.

3.1. Spatio-temporal trends in research

Most of the N_{tot}= 61 studies focused on five global hotspots of shark bites: the United States (n = 18 papers, 29.5 % of N_{tot}), French overseas territories (n = 16, 26.2 %), Australia (n = 12, 19.7 %), South Africa (n = 7, 11.5 %), and Brazil (n = 7, 11.5 %; Fig. 2). None of the other 14 study countries were the focus of more than four (6.6 %) studies. In most countries, over 50 % of the studies were original research papers, except for the Bahamas (one review, one case report, two research papers), the Marshall Islands (one case report, one research paper), and Iran (one case report).

Publications identifying factors likely to influence shark bites were sparse between 1948 and 2006 (Fig. 3) and primarily focused on the USA (n = 6, 35.3 % of the $N_{tot\ 48–06}$ = 17 papers published between 1948 and 2006), South Africa (n = 4, 23.5 %), and Australia (n = 2, 11.8 %). Their number has increased since 2007, albeit with high interannual variability. The scope of research broadened to encompass other countries, including Brazil (since 2003) and French overseas territories (since 2009). White, bull, and tiger sharks have been equally studied in the literature since the 1950s (Fig. A.1). The first studies mentioning white and tiger sharks appeared in 1948, while bull sharks were first cited in 1971. Research on all three species remained sparse until the mid-2000s, after which they attracted growing research interest.

Overall, from 1948 to 2023, a total of 40 factors were cited in the scientific literature. These factors were suggested to have an impact either in the short-term (n = 22), the long-term (n = 13), or both (n = 5). Since 1948, factors suggested to explain variations in shark bites have been primarily *short-term*, appearing in all 7 papers published from 1948 to 1970 and in 90.7 % of the 38 papers published in the past decade (2010–2023) (Fig. 4A). In contrast, long-term factors were first mentioned in the 1980s and now appear in 50 % of the 14 most recent publications (2019–2023).

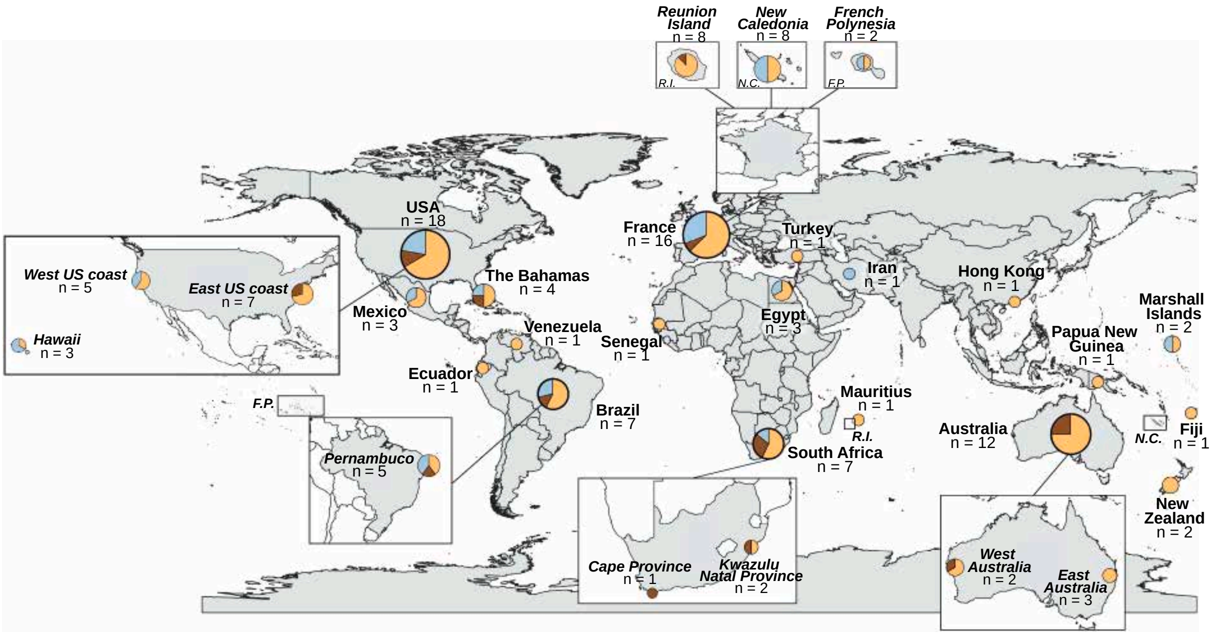


Fig. 2. Geographical distribution of studies identifying potential factors influencing shark bites. Pie charts illustrate the proportion of publications categorized by publication type (beige: research paper, brown: review, lightblue: case report). Their size represents the number of papers per country (N_{tot} = 61). Details on the regional distribution of studies for the top five countries with the highest publication counts is provided. French overseas territories have been enlarged near France for clarity, with a square associated with their initials denoting their precise location on the map. Global studies are excluded from this figure. n = number of publications. Total number sum to greater than 61 as some publications focused on more than one country.

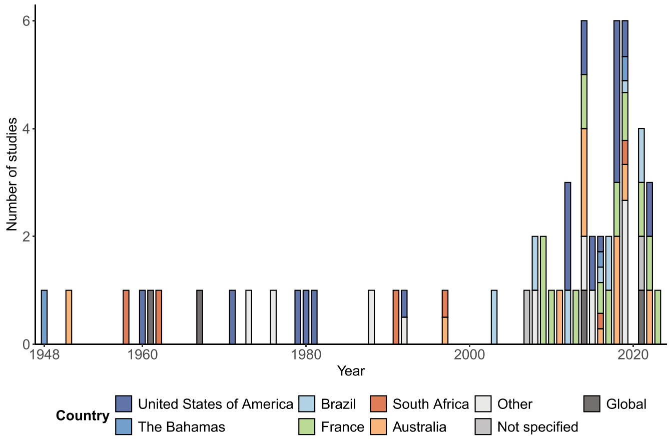


Fig. 3. Trends in number of published studies over time (1948–2023), further segregated by countries of interest. Studies conducted on a global scale are highlighted in the "Global" category. The "Other" category includes studies conducted in any country beyond the six specified hotspots - the USA, the Bahamas, Brazil, France, South Africa, and Australia. For studies covering multiple locations, each location was assigned a proportional value (*e.g.*, a study covering two locations was counted as 0.5 per location).

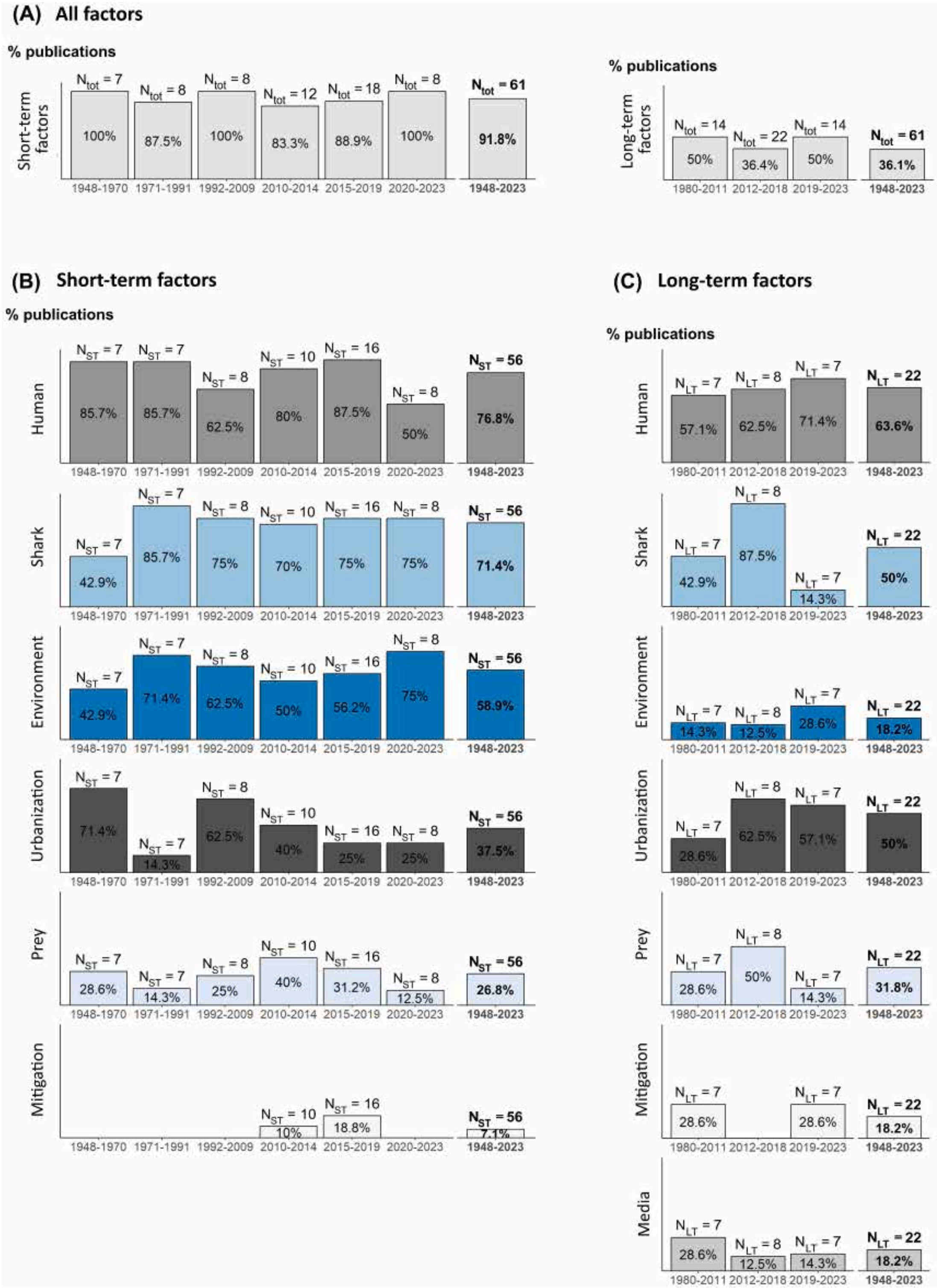
3.2. Short-term factors

Over the past 75 years, 56 publications mentioned 27 short-term factors to explain spatio-temporal variations in shark-bite number (Fig. 5 A). The short-term factors most often suggested were consistent across species (Fig. A.2) and time (Fig. 4B), implying changes in human population (n = 43 publications, 76.8 % of the $N_{ST} = 56$ publications), shark population (n = 40, 71.4 %), and environmental conditions (n = 33, 58.9 %). However, the focus on these categories shifted over time. Changes in human population were mentioned in over 80 % of short-term papers from 1948 onward, except during the periods of 1992–2009 and 2020–2023, when citations dropped to 62.5 % (5 papers out of $N_{ST\ 92\text{–}09} = 8$ publications) and 50 % (4 papers out of $N_{ST\ 20\text{–}23} = 8$ publications), respectively (Fig. 4B). Changes in shark population were cited in only 42.9 % of short-term publications from 1948 to 1970 (3 papers out of $N_{ST\ 48\text{–}70} = 7$ publications), but gained importance in later years, with citations exceeding 70 %. Changes in environmental conditions followed a similar but more variable trend, ranging from 42.9 % in 1948–1970 (3 papers out of $N_{ST\ 48\text{–}70} = 7$ publications) to 75 % in 2020–2023 (6 papers out of $N_{ST\ 20\text{–}23} = 8$ publications). Interestingly, urbanization-related factors showed a notable decline, from 71.4 % between 1948 and 1970 (5 papers out of $N_{ST\ 48\text{–}70} = 7$ publications) to 25 % between 2020 and 2023 (2 papers out of $N_{ST\ 20\text{–}23} = 8$ publications). Meanwhile, changes in prey population and mitigation measures were sporadic across all periods studied.

Changes in human population encompassed spatio-temporal variations in human density (n = 27 papers, or 48.3 % of the $N_{ST} = 56$ publications), behaviors (n = 24, 42.8 %), activities (n = 16, 28.6 %), or appearance (n = 9, 16.1 %; Fig. 5 A). All 16 studies mentioning human activities consistently indicated that sports such as spearfishing or surfing led to an increase in the number of bites. Similarly, of the 27 studies examining human density, most suggested a positive correlation with the number of shark bites (n = 24, 42.9 %). However, the influence of human behavior was more complex and largely depended on the behavior. For instance, engaging in an activity further from the immediate shoreline was consistently proposed as increasing the number of bites, while the effect of engaging in an activity at dawn or dusk on shark-bite number was inconsistent across publications. Appearance, including skin or clothes colors, was proposed to increase (n = 5, 8.9 %), decrease (n = 1, 1.8 %), or have no effect (n = 3, 5.4 %) on shark-bite number. Regarding shark population, shark density was most often cited (n = 30, or 53.6 % of the $N_{ST} = 56$ publications), followed by seasonal (n = 12, 21.4 %), and spatial (n = 7, 12.5 %) variations in shark aggressivity (Fig. 5 A). Most studies suggested that these factors increased shark-bite numbers, including the idea that areas where sharks are familiar with human presence might be at higher risk. Breeding, gestation, and birthing periods were also identified as particularly sensitive times that may increase shark aggressivity and bite incidence.

Many environmental conditions have been proposed to affect fine-scale variations in the number of shark bites (Fig. 5 A), including water turbidity (n = 14, or 24.8 % of the $N_{ST} = 56$ publications), water temperature (n = 14, 25 %), underwater topography (n = 9, 16.1 %), precipitation (n = 7, 12.5 %), moon phase (n = 6, 10.7 %), proximity to river mouth (n = 5, 8.9 %), and ocean currents (n = 4, 7.1 %). Variations in underwater topography, ocean currents, wind patterns (n = 2, 3.6 %), waves (n = 1, 1.8 %), tidal regime (n = 1, 1.8 %), proximity to river mouth, and ENSO climatic events (n = 1, 1.8 %) were all suggested to increase the number of shark bites. Conversely, water salinity (n = 2, 3.6 %) and underwater vegetation (n = 1, 1.8 %) were considered to decrease shark-bite number. All other environmental factors had at least two proposed effects (*e.g.,* increase and no effect) on the variations of shark-bite number.

A smaller number of papers cited factors associated with the urbanization of coastal habitats (n = 21, or 37.5 % of the $N_{ST} = 56$ publications), changes in prey population (n = 15, 26.8 %), or shark-bite mitigation measures (n = 4, 7.1 %; Fig. 4B). All factors related to urbanization were mostly proposed to increase the number of shark bites, except for proximity to coastal infrastructures (Fig. 5 A). Discharges from industrial, agricultural, or household sources, along with the emptying, cleaning, and disposal of fish by



(caption on next page)

Fig. 4. Trends over time (1948–2023) in the (A) type and (B–C) category of factors proposed to influence shark bites. Years were grouped so that each temporal cluster includes at least seven publications or four years. (A) Factors were classified into two types: *short-term* if they referred to fast changes, *e.g.* short spate of shark bites or changes over a few years, or *long-term* if they were proposed to explain changes in the number of shark bites over decades. N_{tot} indicates the total number of publications for the specified period. (B–C) Factors were grouped into seven categories based on whether they implied changes in: human population (*human*), shark population (*shark*), prey populations (*prey*), environmental conditions (*environment*), coastal urbanization (*urbanization*), shark-bite mitigation measures (*mitigation*), or information reporting (*media*). N_{ST} and N_{LT} indicates the number of publications mentioning short-term or long-term factors respectively. (A–C) Trailing numbers (*e.g.,* $N_{ST\ 48–70}$) indicates the corresponding temporal periods (*e.g.*, $N_{ST\ 48–70}$ = number of short-term publications from 1948–1970). Percentages were determined by dividing the number of publications referencing a specific factor type or category by the N indicated above each bar. Percentages for a single temporal period sum to greater than 100 as some publications included more than one factor type or category.

fishing boats, the dumping of food scraps by recreational boats, and shark baiting by the tourism industry, have been suggested to enhance shark presence and consequently shark bites at certain sites. In contrast, environmental degradation near coastal infrastructure would decrease the attractiveness of these sites to sharks. Prey density was often associated with an increase in shark bite number (n = 14, 25 %), while mitigation measures were exclusively seen as decreasing shark-bite number (n = 4, 7.1 %).

Of the 27 short-term factors identified, 22 were cited in at least two publications (Fig. 5 A). However, for over half of these 22 factors, the literature shows no clear consensus regarding their correlation with shark-bite numbers. Only nine were consistently suggested to either increase or decrease shark bites. Among these nine, just four — variations in underwater topography, human activity, site-dependent aggressive behavior, and river mouth proximity — were cited by five or more articles, suggesting a strong scientific consensus on these factors.

Only four publications conducted statistical analyses to test the influence of just six short-term factors on the number of shark bites (Table 1). Tested factors included shark density, mitigation measures, lunar phase, precipitation rate, temperature, and proximity to a river (Fig. 5 A; Table 1). Afonso et al. (2017) found a positive correlation between shark bites and the density of bull and tiger sharks, and a negative correlation with mitigation measures. Ryan et al. (2019) reported positive correlations linking white shark bites to temperature, precipitation, and river mouth proximity; whaler shark bites to river mouth proximity; and tiger shark bites to precipitation. Two studies assessed the impact of moon phase, yielding conflicting findings. While French et al. (2021) observed a positive correlation with lunar illumination, Ugoretz et al. (2022) found no significant correlation with any lunar phase.

3.3. *Long-term factors*

From 1948–2023, 22 publications identified 18 long-term factors to explain decadal trends in shark bites (Fig. 5B). The most frequently cited factors involved changes in human population (n = 14, 63.6 % of the N_{LT} = 22 publications), shark population (n = 11, 50 %), and habitat urbanization (n = 11, 50 %; Fig. 4C). While changes in human population have increasingly been cited over time, from 57.1 % of publications in 1980–2011 (4 papers out of $N_{LT\ 80–11}$ = 7 publications) to 71.4 % today (5 papers out of $N_{LT\ 19–23}$ = 7 publications), the focus on habitat urbanization only started to rise after 2011 (1980–2011: n = 2, 28.6 % of the $N_{LT\ 80–11}$ = 7 publications; 2012–2018: n = 5, 62.5 % of the $N_{LT\ 12–18}$ = 8 publications). Shark population dynamics showed more pronounced fluctuations in citations, with a marked decline from 2012–2018 (n = 7, 87.5 % of the $N_{LT\ 12–18}$ = 8 publications) to 2019–2023 (n = 1, 14.3 % of the $N_{LT\ 19–23}$ = 7 publications). Prey-related factors demonstrated a similar trend, representing 50 % of publications during the 2012–2018 (4 papers out of $N_{LT\ 12–18}$ = 8 publications) period, but dropping to less than 15 % in the 2019–2023 (n = 1, 14.3 % of the $N_{LT\ 19–23}$ = 7 publications) period. In contrast, changes in environmental conditions, shark mitigation measures, and media attention have only been occasionally mentioned in publications over the past 75 years.

Factors related to human population included changes in water sports popularity (n = 9, 40.9 % of the N_{LT} = 22 publications; Fig. 5B), changes in human demography and tourism (n = 8, 36.4 %), use of additional coastal areas for leisure (n = 3, 13.6 %), the development of wetsuits (n = 1, 4.5 %), and modifications of human behaviors (n = 1, 4.5 %). All factors, except the latter, were posited to increase shark bites. One article (Sprivulis, 2014) suggested that a shift away from higher-risk activities could explain the recent decrease in the number of bites in Western Australia. Regarding shark population factors, increase in shark density (n = 6, 27.3 % of the N_{LT} = 22 publications), and changes in shark distribution (n = 5, 22.7 %) were frequently cited as increasing shark bites. Habitat urbanization factors, including coastal development (n = 6, 27.3 % of the N_{LT} = 22 publications), changes in maritime traffic density (n = 2, 9.1 %), fishing of prey species (n = 2, 9.1 %), and agricultural, industrial, or household discharge rate (n = 2, 9.1 %), were generally seen as increasing shark bites by impacting habitat quality and connectivity, and consequently shark coastal distribution.

Comparatively fewer studies suggested influences from factors related to prey availability (n = 7, 31.8 % of the N_{LT} = 22 publications), environment conditions (n = 4, 18.2 %), mitigation measures (n = 4, 18.2 %), or media attention (n = 4, 18.2 %) on the long-term trends in shark bites (Fig. 4C). When cited, prey-related factors, such as prey density (n = 8, 36.3 % of the N_{LT} = 22 publications) and distribution (n = 2, 9.1 %), were predominantly suggested to increase shark bites (Fig. 5B). Only four publications (18.2 %) proposed that local shark-bite mitigation measures have successfully reduced shark bites. An equal number of studies suggested that an increase in media coverage could result in a disproportionate rise in reported shark bites. Finally, environmental conditions encompassed changes in water quality (n = 2, 9 % of the N_{LT} = 22 publications) or temperature (n = 1, 4.5 %). While increasing water temperature was considered to increase shark bites, water quality could either increase (n = 1, 4.5 %) or decrease (n = 1, 4.5 %) shark bites.

Among the 18 long-term factors identified, 14 were cited in at least two publications (Fig. 5B). Of these, 10 showed consistent

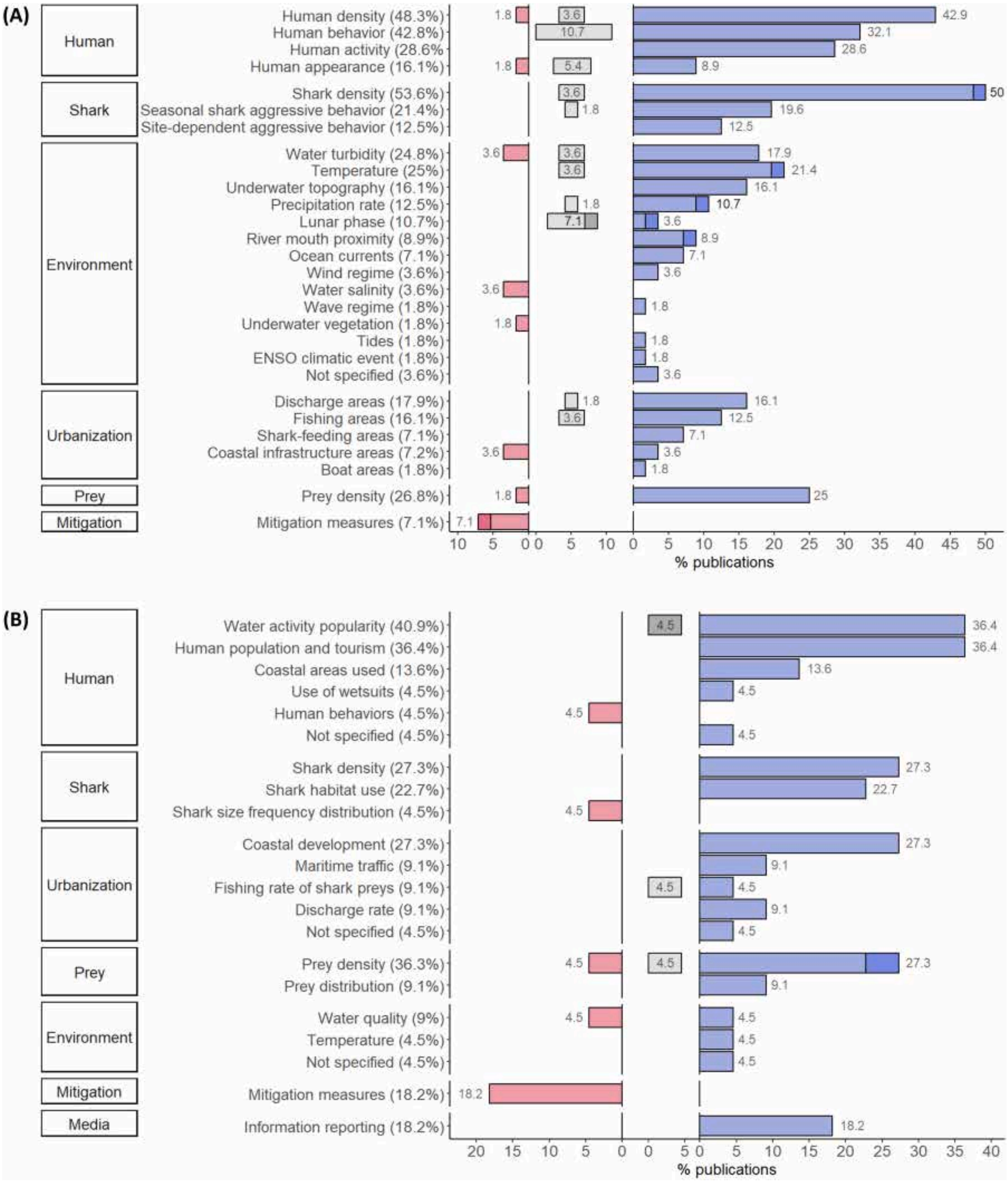


Fig. 5. (A) Proportion of the $N_{ST} = 56$ publications addressing each short-term factor. (B) Proportion of the $N_{LT} = 22$ publications addressing each long-term factor. Colors indicate the nature of the relation between the proposed factor and shark bites (blue: positive, red: negative, gray: neutral). Color intensity reflects whether the factor was statistically tested in the article (dark) or only suggested in the discussion (light). Percentages sum to greater than 100 as some publications proposed more than one factor.

correlations with shark bite numbers across the literature. Nine factors were consistently suggested to increase the number of shark bites, while one factor (the implementation of shark-bite mitigation measures) was consistently cited as decreasing shark-bite occurrence. For the remaining four long-term factors cited in at least two papers, three (water quality, water activity participation, and fishing of prey species) had two proposed effects (*e.g.,* increase and no effect), while prey density was suggested to either increase, decrease, or have no effect on the increase in shark bites over decades.

Only one publication statistically tested the effect of just two factors on the long-term variation in shark bites, which was in Western

Table 1

Overview of publications testing the impact of potential factors on shark bites. Each publication includes details on the tested factor(s), the database(s) used, the time period, the geographical area, and the species considered, the statistical method applied along with its output parameters, as well as the identified correlation between the factor and the occurrence of a bite. When relevant, the author's interpretation of the model's results is provided as a quotation. GLM = Generalized Linear Model. GAM = Generalized Additive Model.

Factor type	Reference	Period	Location	Database	Species	Factor category	Factor	Test	Relation	Significance	Citation
Long-term	Sprivulis (2014)	1974–2013	W Australia	Global shark attack file	White	Prey	Prey density	Correlation test	Positive	$R = 0.96$ *95 %CI* 0.77–0.99 $p < 0.001$	Estimated humpback whale abundance is highly correlated with total reported shark bites
								Correlation test	Positive	$R = 0.71$ *95 %CI* 0.00–0.95 $p = 0.04$	Weaker correlations were found for New Zealand fur seal population growth for total bites
						Human	Water activity popularity	Correlation test	Neutral	$R = 0.25$ *95 %CI* −0.45–0.76 $p = 0.48$	Water sport participation data was not significantly correlated with the increase in total bites over this period
Short-term	Afonso et al. (2017)	2004–2014	Metropolitan region of Recife, Brazil	State Committee for the Monitoring of Incidents with Sharks		Shark	Shark density	Pearson correlation test	Positive	$R = 0.57$ $p = 0.008$	The monthly frequencies of total number of shark bites were directly correlated with the mean monthly potentially dangerous shark abundance
								Gaussian GLM		$SE = 0.81$ $z\text{-}value = 2.36$ $p = 0.018$	Significant approximately two-fold increment in the shark-bite rate when potentially dangerous shark CPUE shifts from 0.1 to 0.5 sharks per 1000 hooks
						Mitigation	Mitigation measures	Zero-inflated poisson GAM	Negative	$SE = 0.72$ $z\text{-}value = 3.87$ $p < 0.001$	A significantly greater frequency of shark bites was predicted during the periods when the Shark Monitoring Program of Recife (SMPR) was inactive
	Ryan et al. (2019)	1915–2015	Australia	Australian shark attack file	White	Environment	Temperature	GAM	Positive	$\chi^2 = 6.83$ $p = 0.008$	The risk of attack by a white shark increased with sea surface temperature
							River mouth proximity	GAM	Positive	$\chi^2 = 20.69$ $p < 0.001$	The risk of attack by a white shark increased close to river mouths within 10 km
							Precipitation	GAM	Positive	$\chi^2 = 33.78$ $p < 0.001$	The risk of attack by a white shark peaked at a rainfall mean of ~ 100 mm
					Whaler	Environment	River mouth proximity	GAM	Positive	$\chi^2 = 15.78$ $p = 0.001$	Whaler attacks were more likely within 1 km of rivers
					Tiger	Environment	Precipitation	GAM	Positive	$\chi^2 = 8.77$ $p = 0.003$	Tiger shark attacks increased with rainfall mean
	French et al. (2021)	1970–2016	World	International shark attack file		Environment	Lunar phase	Chi-squared Goodness-of-fit test	Positive		Fewer shark attacks than expected only occurred at lower values of lunar illumination while more shark attacks than expected only occurred at higher values of lunar illumination
	Ugoretz et al. (2022)	1950–2021	California, USA	Personal research Global shark attack file		Environment	Lunar phase	Chi-squared Goodness-of-fit test	Neutral		There is no statistical difference between the documented and expected number of incidents during any moon phase

Australia (Sprivulis, 2014) (Fig. 5B; Table 1). This study, primarily focusing on white sharks, revealed a strong correlation between the rise in bites and the increase in humpback whale abundance, a weaker but positive correlation with New Zealand fur seal population growth, and no correlation with water sport participation data.

4. Discussion

Exploring the factors contributing to variations in shark bites has become a growing research area, gaining increasing attention since the mid-2000s as the number of shark bites rose globally. Most studies focused on five shark-bite hotspots, *i.e.,* initially the USA, Australia, and South Africa, later joined by Brazil and French overseas territories. Five other locations have previously been identified as hotspots, *i.e.,* Papua New Guinea, Bahamas, New Zealand, Mexico, and Fiji (Midway et al., 2019), but were under-represented in this review because studies from these regions, if any, have not discussed factors influencing the number or risk of shark bites.

Since 1948, a plethora of short-term factors have been proposed to explain regional and annual variations in shark bites, encompassing changes in human and shark population dynamics, environmental conditions, prey availability, shark-bite mitigation measures, and coastal urbanization. Factors related to human and shark population dynamics were suggested most often, potentially indicating their key role in driving shark-bite trends. However, the prevalence of these factors may also be explained by their interdependence with other factors such as environmental conditions, coastal urbanization, prey population dynamics, and shark-bite mitigation measures, which can alter human water use patterns (Gómez-Martín and Martínez-Ibarra, 2012) and/or influence the distribution and abundance of sharks (Niella et al., 2022; Payne et al., 2018; Werry et al., 2018). Shark density was the most cited short-term factor. High-risk regions were generally associated with high shark density, observed, for example, near abundant food sources (*e.g.* Ryan et al., 2019). Similarly, high-risk seasons are linked to periods of shark migration near shore, possibly in response to prey migration (*e.g.* Amin et al., 2015), reproductive cycles (*e.g.* Mourier et al., 2021), or environnemental changes (*e.g.* Afonso et al., 2017). Human density emerged as the second most cited factor and, like shark density, can account for spatial and temporal variations in shark bites. In response, several authors have delved into the interplay of human and shark presence, sparking debates about their appropriate weighting (Kock and Johnson, 2006; Lemahieu et al., 2017; Schultz, 1967). Indeed, high bite occurrences have been proposed to result from: (i) high shark presence regardless of human density; (ii) high human presence regardless of shark density; or (iii) a combination of both. Understanding the relationship between human-shark population dynamics and the risk of shark bites is further complicated by the fact that this relationship may not be linear. Human behaviors, such as engaging in water activity alone, at dusk or dawn, further from the immediate shoreline, as well as carrying catches or displaying erratic gestures, have consistently been flagged since the 1960s as behaviors increasing the risk of bites. However, there is a lack of data available to test and support these beliefs. Finally, spearfishing and board sports are frequently identified as high-risk activities. With regards to the effects of environmental conditions — the third most frequently cited short-term category — on shark bites, the top three factors mentioned are turbidity, temperature, and underwater topography. Yet, they only appear in less than 20 % of the publications.

Studies showed little agreement on the nature of the relationship between most short-term factors and shark bites. At least seven hypotheses can be proposed to elucidate these conflicting results:

- (i) The effect of a factor differs between geographic regions due to local conditions. Indeed, each location having its own dynamics might introduce local noise, potentially eliminating or even reversing the expected effect of a factor on shark bites. This hypothesis could be particularly relevant to explain conflicting responses observed across geographic regions regarding the influence of moon phase (French et al., 2021; Ugoretz et al., 2022).
- (ii) Species-dependent effects may contribute to conflicting results, with the response varying depending on the species considered. Since shark species responsible for most shark bites vary between geographic regions (Bakker et al., 2017; Lucifora et al., 2011), hypotheses (i) and (ii) are likely interconnected and could act in concert.
- (iii) Some factors can increase the risk of shark bites regardless of whether it is high or low. For example, low prey density has been proposed to lead to hungry sharks, while high prey density increases the likelihood of sharks being present and in a predatory behavior, both resulting in an increased risk of shark bites (*e.g.* Gadig and Sazima, 2003; Resko and Johnson, 2014).
- (iv) Qualitative factors, such as "human activities", may include diverse elements (*e.g.* different activities) with conflicting effects. For instance, the factor "Coastal infrastructure areas" addresses both the degradation of coastal environment through dredging, believed to reduce shark attractiveness and thereby bite risk, and the presence of piers that attract sharks, potentially increasing bite risk.
- (v) Poorly understood factor effects may generate divergent hypotheses. For instance, human density has been suggested to increase shark-bite risk, with each additional person increasing the likelihood of an interaction with sharks, or could reduce shark-bite risk, *e.g.*, extensive human noise could act as a repelling effect (Amin et al., 2015).
- (vi) The understanding of how some factors relate to the risk of shark bites has evolved with time and scientific progress, revealing that some factors previously believed to influence bite risk have been found to be negligible or irrelevant. For example, McFadden and Johnson (1971) proposed that black clothing decreases the risk of bites, while Martini and Welch (1981) suggested that orange is particularly attractive to sharks. However, recent hypotheses lean towards the idea that color has no influence on shark bites (West and Zoo, 2014), as sharks lack cone-based color vision and are likely more acutely sensitive to light, movement, and contrast (Hart et al., 2020). Conversely, some factors previously believed as unimportant are now gaining greater support within the scientific community. For example, the shared use of an area by different activities, such as fishing, cleaning fish, dumping food, swimming, and snorkeling in the same location, is increasingly recognized to increase the risk of shark bites.

(vii) Conflicting results could indicate a lack of causal relationship between the factor and shark bites.

The emergence of long-term factors to explain decadal changes in the number of shark bites occurred in the early 1980s (Miller et al., 1981). This late onset can be attributed to the relatively minor interannual variations in the number of bites before this period (ISAF, 2023). Since the 1980s, most of the suggested long-term factors fall into the human, shark, or urbanization categories. Population growth and increasing tourism, along with the growing popularity of water sports, have led to more people in the water. Advances in wetsuit technology have enabled people to access more locations and swim year-round. The emergence of new sports, such as kite surfing, has resulted in greater use of additional coastal areas. Together, these factors have not only intensified but also expanded human exposure to potential shark encounters, which may partially explain the observed rise in shark bites. In parallel, changes in shark behavior and populations — such as increases in shark density and shifts in their spatial distribution — have also been proposed. As for short-term factors, the prevalence of human and shark factors may underscore their key role in the decadal variations in shark bites or could be the result of their interconnectedness with other factors. The prominence of the "urbanization" category could be partially explained by the relatively larger number of factors it encompasses. Indeed, the "urbanization" category includes five factors, and is cited in 20 % more publications compared to the "prey" category which only includes two factors. However, both categories include one long-term factor cited in about 27 % of publications, coastal development for "urbanization" and prey density for "prey". Higher prey density can support larger shark populations (Torres et al., 2006; Wirsing et al., 2007), and sharks may stay in areas with abundant prey for longer periods (Barnett and Semmens, 2012; Heithaus et al., 2002; Lubitz et al., 2023).

In contrast to short-term factors, strong consensus exists for long-term factors, suggesting that the same factors might explain decadal trends across different geographic regions. The increase in human population and tourism, coupled with the rise of new and increasing popularity in water sports, stands out as the most frequently cited long-term factors. Both factors could have contributed to more people in the water and thus increased shark bites. Coastal development, and changes in prey or shark density are less commonly cited, but still bear importance in the literature. Coastal development, by altering habitat quality, local environmental conditions, water circulation and properties, as well as habitat connectivity (Evans, 2018; Frihy, 2001), may have exerted a substantial influence on the distribution of both shark and human populations, leading to higher bites (Burgess et al., 2010; Hazin et al., 2013, 2008). Increasing prey density, facilitated by measures like the implementation of marine protected areas or fishing policies, is proposed in several regions to explain decadal trends in shark bites (*e.g.* Western Australia: Sprivulis, 2014). However, on a global scale, further investigation on the abundance of prey species is warranted, as overfishing depletes fish stocks in many world regions (FAO, 2022; Link and Watson, 2019), yet management regulations have led to some depleted stocks recovering (Hilborn et al., 2020). Finally, the rise in shark density has often been proposed as a potential cause for the increased shark bites. However, stock assessments or trends in relative abundance of shark catch are limited to a few sites and where data exists, shark population trends are mostly estimated to be either stable or decreasing (Afonso et al., 2014; Carlson et al., 2012; Christiansen et al., 2014; Holmes et al., 2012; Reid et al., 2011; Towner et al., 2013). Noting that these studies are over a decade old. Offering an exception to this general trend, a recent study on the U.S. Atlantic coast reported increased abundance in seven coastal shark species, pointing to early signs of population recovery (Peterson et al., 2017).

Our systematic review underscores the scarcity of quantitative tests aimed at assessing the effect of potential factors on shark bites, with only five studies having conducted such analyses. Several reasons may explain this lack of statistical tests, including the sporadic and infrequent nature of shark bites (Huveneers et al., 2024), the plethora of potential factors, their interdependence, and the lack of data for many of them. Among the eight factors statistically tested, four were short-term environmental factors, namely temperature, rainfall, proximity to a river mouth, and lunar phase. Environmental factors are likely the easiest to test, given the global availability of data and time scales sufficient for substantial analyses. Afonso et al. (2017) used generalized linear and additive models to identify a positive correlation between the seasonal increase in bull and tiger shark bites in the metropolitan region of Recife (Brazil), and shark density. They also found an increase in shark bites when the Shark Monitoring Program of Recife was inactive. In Australia, Ryan et al. (2019) predicted an elevated risk of bites by white sharks under warmer sea surface temperature, higher precipitation rates, and closer proximity to a river mouth (<10 km). Whaler shark bites increased near river mouths, while tiger shark bites rose with rainfall (Ryan et al., 2019). Only the lunar phase has been the subject of two publications, with conflicting findings. French et al. (2021) suggested a potential correlation between shark bites and the moon phase at a global scale, with a greater frequency of bites occurring around the full moon. In particular, their analysis of the US West Coast revealed a statistically significant increase in bites between 51 % and 70 % lunar illumination. Conversely, Ugoretz et al. (2022) found no correlation between lunar illumination and bites in California, except at 50 % lunar illumination. These divergent findings highlight the potential complex relationship between shark bites and environmental factors, and more generally all proposed factors. Nevertheless, despite these inherent complexities, it is crucial to persist in efforts to comprehend the contributing factors to shark bites. An enhanced understanding of these factors is essential for refining risk reduction policies for humans and developing conservation plans for shark populations, particularly within the context of heightened public concern surrounding this issue. Indeed, recent studies reporting a global increase in shark bites (ISAF, 2023) and the existence of shark-bite clusters within short timeframes (Barnett et al., 2022) may offer new opportunities to investigate potential causative factors.

Statistical tests conducted by Ryan et al. (2019) revealed different environmental predictors depending on the shark species involved. This outcome is not unexpected given the variations in shark species biology and ecology, including variations in their distribution range, habitats, and feeding habits (Rigby et al., 2021, Rigby et al., 2019; Ferreira and Simpfendorfer, 2018). For instance, a coastal species that moves into shallow waters with a piscivorous diet like the bull shark (ESTUPIÑÁN-MONTAÑO et al., 2017; Trystram et al., 2017) may not be affected in the same way by coastal urbanization and overfishing as the white shark, a species extending to offshore areas and where adults primarily feed on marine mammals (Boldrocchi et al., 2017; Estrada et al., 2006; Hussey et al., 2012). With this in mind, we expected to observe differences in the proposed factors for white, bull, and tiger shark species (*i.e.,* the three most dangerous species). However, the results did not support this hypothesis, as proposed factors were consistent across each species. Several reasons could account for this discrepancy: (i) distinct factors might have been proposed for the different species, but our categorization of these factors could not reveal these differences; (ii) the same factors could be suggested, but the relationships may differ between shark species; (iii) identical factors may have been initially proposed for all species and later abandoned depending on the species; (iv) most studies deal with multiple species without differentiation, potentially masking any variations that may have emerged. In future studies, we recommend considering individual species, when possible, rather than grouping shark species together.

We noted a marked increase in publications addressing factors likely contributing to variations in shark bites since the mid-2000s. While the number of publications could have been higher before 1980, challenges in accessing older papers online hinder a comprehensive understanding of research before that period. Incorporating gray literature — such as theses, technical reports, or documents from scientific consortia and research program like the International Shark Attack File (ISAF) — into the selection process might have revealed additional hypotheses. Specifically, our study lacks evidence for at least two long-term hypotheses — the implementation of marine protected areas and the growth of shark tourism involving the use of bait to enhance shark observations in specific locations — despite their frequent mention by local communities and the public media. The absence of these two factors in scientific literature could suggest that researchers harbor reservations about their influence in explaining observed trends, but further investigations are warranted to rigorously test their impact on shark bites. However, it is crucial to acknowledge that gray literature, while potentially containing valuable information, is often less accessible than scientific publications (Banks, 2004; Corlett, 2011), limiting the possibility of a comprehensive synthesis of all existing papers. Additionally, gray literature lacks peer-review or rigorous, independent scientific review, which can pose significant challenges for conducting systematic reviews. That said, the exclusion of gray literature in our review is unlikely to have significantly impacted our overall conclusions, as many of the factors it might have introduced appear to be already well captured in the peer-reviewed literature we analyzed. For example, ISAF reports underscore several key drivers, such as (i) a positive correlation between the rising number of shark bites and the growing number of ocean users in recent decades; (ii) local variation in bites linked to underwater topography (*e.g.,* near sandbars, steep drop-offs) or water turbidity; (iii) variability based on human density, activity, behavior, or appearance; and (iv) increased number of bites near discharge or fishing zones (ISAF, 2023). These align closely with the factor categories identified in our review. This strong convergence suggests that including gray literature would likely not have changed the general structure of our findings. It could, however, have influenced the relative importance attributed to specific factors within each category.

Effectively managing shark-bite mitigation measures requires a comprehensive approach that considers the complex interactions between the environment, shark populations, and human activities. While current research lacks statistically validated findings, recurring elements identified in studies can still offer valuable guidance to local managers in setting priorities. Many studies have suggested a positive correlation between shark density and an increased risk of bites. Therefore, it is essential for managers to initiate continuous monitoring of shark populations, particularly when implementing measures that may increase shark densities. Marine protected areas (MPAs) are particularly relevant, as local communities often associate them with higher shark populations (Albano et al., 2021; Espinoza et al., 2014; Speed et al., 2018) due to increased prey abundance (Jaiteh et al., 2016) or reduced fishing pressure on sharks (Clementi et al., 2021). However, systematic evaluations of MPAs' impact on shark population remain scarce, despite ongoing debates about their effectiveness in protecting these highly mobile predators (Daly et al., 2018; Dwyer et al., 2020; Flowers et al., 2022; MacKeracher et al., 2019; Ward-Paige, 2017). Other protected areas — primarily established to sustain fishery stocks or conserve species like turtles, pinnipeds, sirenians, or seabirds, which, as important food sources, may indirectly benefit shark populations — may also attract high shark densities and require careful monitoring (Hazin et al., 2008; Meyer et al., 2009; Torres et al., 2006; Wirsing et al., 2007). If an increase in local shark density is observed in these zones, additional risk mitigation measures should be implemented. These may include public awareness campaigns, the designation of no-entry zones, swimming restrictions in high-risk areas, strategic adjustments to harbor infrastructure, and MPA network design.

Many studies have also highlighted seasonal variations in risk, particularly during shark breeding, gestation, or birthing periods. To address these sensitive times, targeted management measures can be implemented, such as: (i) increased surveillance of recreational areas using tools like acoustic listening stations, SMART lines, or drones; (ii) seasonal swimming enclosures; and (iii) public awareness campaigns to inform local populations about the heightened risk during these periods. More broadly, public awareness should be a key priority, empowering individuals to assess potential risks before entering the water. Awareness campaigns should address several critical points: (i) periods of elevated risk, including high-risk seasons (*e.g.,* shark breeding periods) and specific conditions like murky waters after heavy rainfall; (ii) risky behaviors, such as swimming alone, far from shore, or at dawn and dusk; (iii) high-risk activities, like spearfishing; (iv) high-risk zones, including areas affected by agricultural, industrial, or household waste discharge. Similar to MPAs, discharge zones are often perceived as high-risk areas, as waste can attract sharks either directly or by increasing prey abundance. Implementing systematic shark population monitoring in these zones, as well as in urbanized coastal areas with high human activity, could offer critical insights. These data would help managers better understand local shark population dynamics in these sensitive areas and refine their strategies accordingly. By integrating these considerations into targeted management plans, managers can mitigate the risk of shark bites while balancing human safety with the conservation of sharks.

5. Conclusion

Despite the limited number of publications on the subject, a plethora of factors have been proposed to influence shark bites. However, a lack of consensus on their effects persists, and few studies have statistically tested the proposed factors related to the number of shark bites. Publications consistently highlighted factors related to shark or human population dynamics, regardless of the species considered. Additionally, environmental factors have been frequently suggested to explain short-term spatio-temporal variations, while coastal urbanization has been regularly cited in the decadal increase in bites. We hope that our findings will contribute to a better understanding of the current state of research on factors influencing shark bites and will guide future studies. Specifically, and despite inherent complexities, there is a pressing need to develop new and robust approaches to limited datasets for testing causative factors. An improved understanding of these factors is essential for refining risk reduction policies for humans and developing conservation plans for shark populations, particularly in light of the heightened public concern surrounding this issue.

Ethics

Not applicable: This manuscript does not include human or animal research

CRediT authorship contribution statement

Barnett Adam: Writing – review & editing, Methodology. **Huveneers Charlie:** Writing – review & editing, Methodology. **Duval Delphine:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Vigliola Laurent:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Mangeas Morgan:** Writing – review & editing, Supervision, Methodology, Conceptualization.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2025.e03684.

Data availability

Appendix 1 (Supplementary Material) lists all articles used in this review.

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