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REVIEWS

A systematic review of sensory deterrents for bycatch mitigation of marine megafauna

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Abstract Marine megafauna are critical for marine ecosystem health and their removal can cause food webs to collapse. Methods to reduce marine megafauna mortality can result in conflict between scientists, conservationists, fishers and fisheries management due to real or perceived effects on target catch, income and food security. Sensory deterrents have been used in attempts to mitigate bycatch and retain target catch quantity and quality. Here, we completed a systematic review of 116 papers, plus 25 literature reviews published between 1991 and 2022, to investigate potential for sensory deterrents to mitigate bycatch across four marine megafauna taxonomic groups (marine mammals, sea turtles, seabirds and elasmobranchs). Lights on gillnets are the only technology so far to result in significant bycatch reductions across all four taxonomic groups. It is difficult to make generalisations about the efficacy of sensory deterrents and their ability to deliver consistent bycatch reductions. The efficacy of each method is context dependent, varying with species, fishery and environmental characteristics. Further research is recommended for field studies assessing bycatch mitigation in all sensory deterrents, including combinations of deterrents, to assess effects on target and non-target species. The associated issues of habituation, habitat exclusion and foraging around fishing gear are important, although reducing mortality of vulnerable species should remain the highest priority for conservation and preserving ecosystems that fishers depend on. Multiple complementary measures will be required to achieve consistent bycatch reduction targets in many fisheries, of which sensory deterrents could play some part if implemented appropriately.

Keywords Bycatch mitigation · Sea turtle · Elasmobranch · Seabird · Marine mammal · Sensory

Introduction

Fisheries pose direct threats to marine megafauna (here defined as marine mammals, sea turtles, seabirds and elasmobranchs) through both targeted fishing and bycatch (Lewison et al. 2004, 2014; Žydelis et al. 2009). Given the k-selection life cycle of many megafauna species (low fecundity, slow growth rate, late maturity), populations face the risk of collapse if bycatch is not managed (Dent and Clarke 2015). Marine megafauna provide vital ecosystem services, so their position in marine food webs must be safeguarded to ensure ecosystem and fishery health

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(Kiszka et al. 2015; Hammerschlag et al. 2019). The removal of apex predators can cause trophic cascades, leading to collapse or re-structuring of food webs (Daskalov 2002; Heithaus et al. 2008), threatening the livelihoods of commercial and small-scale fishers, coastal communities that depend on them and potentially having widespread conservation impacts. Given the consequences of marine megafauna mortality, bycatch mitigation is critical to preserving ecosystems and fisheries. Estimates for the annual mortality of marine megafauna in fisheries are shown in Table 1.

The impact of bycatch in commercial fisheries is known to be substantial, exacerbating the pressures on populations from climate change, habitat degradation, pollution and ocean acidification (Barbraud et al. 2012; Senko et al. 2020). Estimates for the magnitude of bycatch (Table 1) have wide ranges and likely under-estimate true values, in part due to the threat of poorly understood small-scale fisheries (SSFs) (e.g. Worm et al. 2013). It is estimated that there are over 50 million fishers in SSFs (FAO 2016), making up more than 95% of the fishers worldwide (Pauly 2006). The SSF industry contributes multiple socio-economic benefits, including food security, development of coastal communities and poverty alleviation (Béné 2006). Continued poor regulation and enforcement of policy make marine food webs vulnerable where SSFs exist (Pinnegar and Engelhard 2008). Poor management of these fisheries means that highly destructive practices, such as dynamite fishing, still occur in some regions (Katikiro and Mahenge 2016). Reliable catch data are difficult to obtain due to the presence of illegal, unregulated and unreported (IUU) catch (Gallic and Cox 2006), which can occur in all fisheries, making it difficult to assess quantity and impact of fisheries and fisheries bycatch.

All major gear types contribute to bycatch, including line fisheries, gillnets, trawls, pots/traps and seines (Lewison et al. 2004). Line fisheries are defined here as any fishery using a line and baited hooks (e.g. longlines, pole and line). Gillnets include both capture fisheries (set nets and drift nets) and bather protection (beach nets). Pots and traps are varied, including lobster pots, fish traps and pound nets. Bycatch of marine megafauna occurs either by chance entanglement in passive gear (nets and some traps), chance entanglement in active gear (purse seines and trawls), or being attracted via sensory cues, such as olfaction from prey in and around gear or bait plumes on hooks, as well as visual attractants like fish aggregating devices (FADs) used in purse seines or lights in line and net fisheries (Chumchuen et al. 2019). The associated issue of depredation (herein referred to as ‘foraging around fishing gear’, as suggested in Bearzi and Reeves (2022)) occurs where animals feed on target catch already caught in gear. Foraging around fishing gear is a common recurring issue in some fisheries (Brill et al. 2009; Hamer et al. 2012; Guinet et al. 2015; Santana-Garcon et al. 2018; Lucchetti et al. 2019). Although this paper does not focus on foraging around fishing gear, the solutions are likely congruent with bycatch reduction. Indeed, foraging around fishing gear increases bycatch risk of animals coming into contact with gear, as well as impacting fishing efficiency by damaging gear and reducing target catch (Tixier et al. 2021).

Bycatch mitigation methods are designed to reduce incidental catch of non-target species. Reductions in fishing effort, catch limits and time-area closures offer alternatives to complete cessation of activity. Other methods to address mortality include changing gear type, gear-escape options, post-capture release by the fisher and technical devices that alert or deter animals from the gear to avoid entanglement (Werner et al. 2006). Changing gear can reduce bycatch, although the perceived potential for reducing target catch can make this unpopular with fishers (Lucchetti et al.

Table 1 Marine Megafauna estimated annual mortality in fisheries and data sources. Seabird data pooled for longlines and gillnets using two sources

Megafauna Group	Annual mortality of individuals (millions)	Bycatch data period	References
Marine mammals	0.53–0.82	1990–1994	Read et al. (2006)
Sharks	63–273	2000–2010	Worm et al. (2013)
Sea Turtles	0.85–8.5	1990–2008	Wallace et al. (2010)
Seabirds	0.56–0.72	1980–2011	Anderson et al. (2011; Žydelis et al. (2013)

2019). Escape from gear can be facilitated by fisher behaviour in some cases (Basran et al. 2020), but is more common in the form of excluder devices on nets. These consist of turtle excluder devices (TEDs), seal exclusion devices (SEDs), sea lion exclusion devices (SLEDs) and devices for dolphins or other marine megafauna (Werner et al. 2006; Hamilton and Baker 2019). Weakened rope is used in some pot/trap fisheries, where the line between the trap and the surface buoy is made such that a whale can break it (Trippel et al. 2008). Similarly, hooks in longline fisheries can be attached to weaker monofilament leaders so megafauna can break them and escape (Favaro and Côté 2015). As with any interaction between marine megafauna and fishing gear, escape options can risk injury and affect post-release survival of individuals (Hamilton and Baker 2015). Post-capture release can involve no change to the gear by simply releasing all non-target catch, or altering gear to increase the chance of survival while hooked to gear and after release. For example, circle hooks rather than J hooks have reduced mortality of sea turtles on longlines (Watson et al. 2005). Gear modifications have been effective in multiple contexts, but modifications may fail, cause mortality, injury, or remain on the animal after escape (Campana et al. 2016). Each of these methods must be researched further to evaluate long-term efficacy.

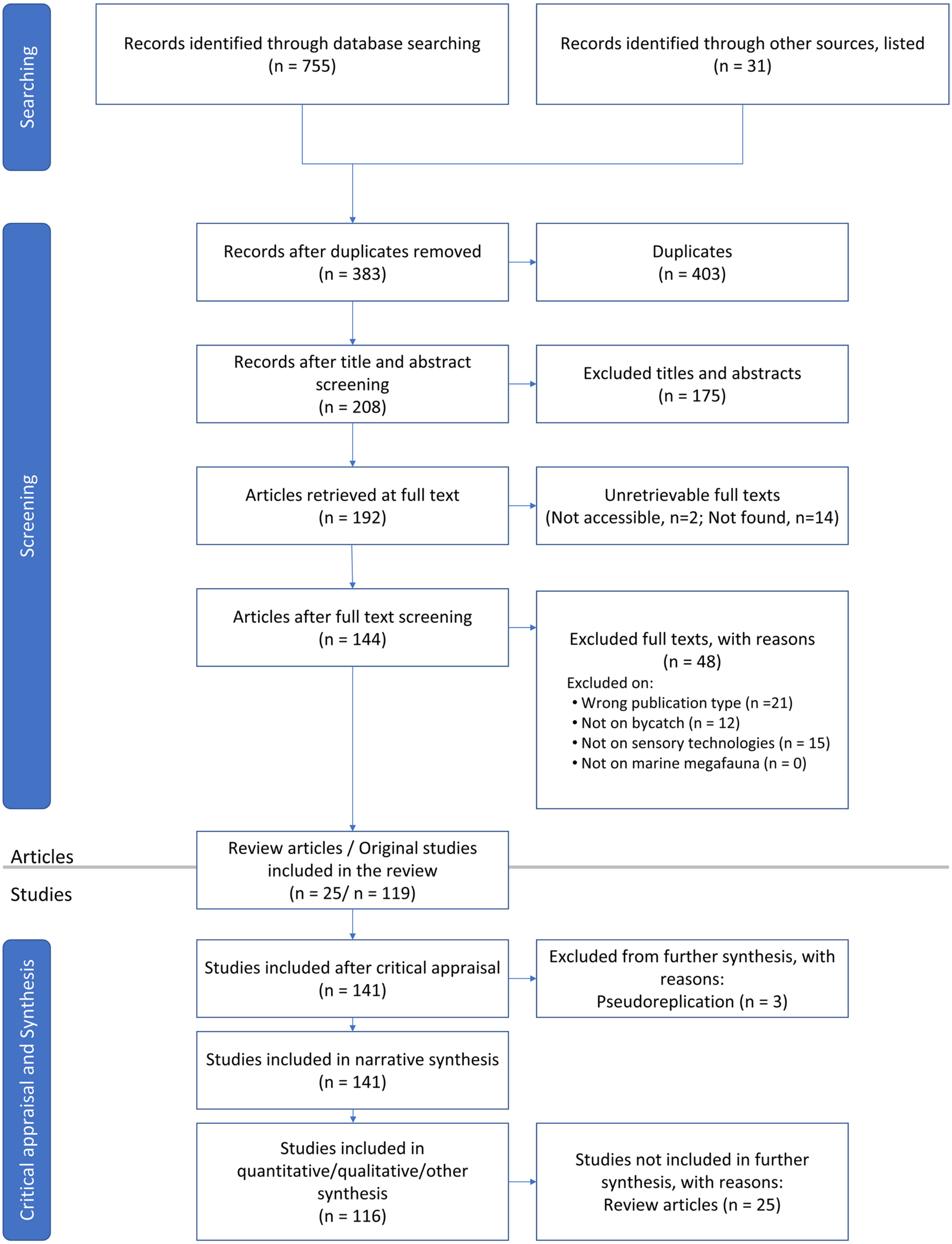
Technical strategies are intended to change the behaviour of the animal by stimulating a sensory reaction to avoid contact with gear. If successful, this renders exclusion and release unnecessary, as the animal would not interact with gear in the first place. Examples include the use of acoustic alarms (pingers), emitting sounds within the hearing range of odontocetes to alert and deter them from gear (Kraus et al. 1997), or the use of magnets to repel sharks (Robbins et al. 2011). By using technical adaptations designed to provide sensory cues to avert contact with gear (herein referred to as 'sensory deterrents'), the likelihood of entanglement or post-release mortality in non-target species may be reduced. In contrast to time-area closures, if used effectively in the right circumstances, sensory deterrents could allow fishers to continue fishing practises, receive income and provide food security for coastal communities.

Effective solutions for mitigating bycatch should (1) reduce mortality of at least one bycatch species without increasing mortality in other groups, (2) maintain target species catch quantity and quality where possible (without overfishing target catch), (3) be cost effective, (4) be viable for implementation in fisheries and (5) provide biologically relevant bycatch reductions, rather than small, but statistically significant reductions. The key challenge of reducing bycatch using sensory deterrents is that the capabilities of animals, both across and within groups, varies enormously and can overlap with target species.

By mitigating contact with gear, foraging around fishing gear may be addressed too, which reduces potential gear damage and can lead to increased target catch (Richards et al. 2018). However, animals can be highly motivated by the promise of food rewards and can be attracted by sensory cues where they are designed to deter other species, such as the 'dinner bell' effect of pingers, attracting pinnipeds to gillnets and increasing their risk of entanglement (Dawson et al. 2013). Neither escape options or post-capture release directly address foraging around fishing gear, and the risk of initial gear contact remains. This is in contrast to time-area closures or catch limits, where fishing activity is halted, so the fishers may lose out, which makes these solutions difficult to implement in many locations. The focus of this review is on bycatch mitigation using sensory deterrents, due to their potential for reducing animal contact with fishing gear, reducing bycatch and associated issues such as foraging around fishing gear.

All marine megafauna groups have the same core senses: vision, hearing, olfaction and touch. The senses are known to work in broadly the same way in all groups, with the exception of gustation (taste), which is poorly understood in marine species, so chemosensory detection is combined as olfactory for the purposes of this review (Southwood et al. 2008). Odontocetes, unlike other marine megafauna, can echolocate, using adapted tissue structures to produce and transmit click sounds (dorsal bursae complex, air sacs and melon) and lower mandibles to receive signals used in communication, navigation and foraging (Au 1993). Elasmobranchs have two additional sensory specialisations, electrosensory and mechanosensory. The electrosensory system, facilitated by the jelly-filled ampullae of Lorenzini, can detect electrical and magnetic fields, used in prey detection and navigation (Kalmijn 1982) and the mechanosensory lateral line for detecting pressure changes and vibrations in the water (Maruska 2001).

ROSES Flow Diagram for Systematic Reviews. Version 1.0



◂**Fig. 1** Flowchart detailing the literature screening process. Full details of the screening process can be found in (Haddaway et al. 2017, 2018). A report detailing the protocol for this study can be found in Online Resource 1. The outputs represent 116 studies investigating sensory bycatch mitigations in trials and 25 review papers, which are included in the narrative but excluded from the data extraction and analysis

Previous reviews on the topic of sensory technologies have mainly focused on single species or single groups of marine megafauna (e.g. Southwood et al. 2008; Friesen et al. 2017; Hamilton and Baker 2019). Others identify multi-taxa mitigation options based on one taxonomic group and then generalise to other groups, or only focus on the effects of one technology across groups (e.g. Martin and Crawford 2015; Gilman et al. 2020). In contrast, this review focusses on using sensory technologies in an attempt to avert contact and reduce mortality of multiple marine megafauna groups with fishing gear. The aim of this paper is to assess the potential of sensory deterrents for mitigating bycatch of marine megafauna in commercial and small-scale fisheries. The objectives of this study are (1) to summarise the development of sensory deterrents for reducing bycatch of marine megafauna in a systematic map, (2) to evaluate the efficacy of sensory deterrents and the potential for combining multiple technologies for maximum mitigation across taxa, and (3) to identify areas for future research in the field.

Methods

A literature search was completed using ROSES (RepOrting standards for Systematic Evidence Syntheses) protocols for systematic maps in conservation and environmental management (Haddaway et al. 2018). Scopus, WebOfScience and Proquest databases were searched up to and including 28/10/2021, then again up to and including 22/02/2022. The Title, Abstract and Keywords of each paper were searched using the string *((sense OR (sensory AND (biology OR ecology))) OR behavio*) AND (bycatch OR "incidental catch" OR "incidental capture") AND (mitigat* OR reduc*) AND ("marine mammal" OR cetacean* OR seal OR pinniped* OR elasmobranch* OR shark* OR ray* OR chondrichthy* OR seabird* OR "marine megafauna" OR turtle* OR reptile*)*. Duplicates were removed, then titles and abstracts screened, followed by a full text screening. Additional papers were sourced using unstructured citation checking. All papers that were excluded, could not be sourced, or could not be accessed were recorded in a CSV file. Authors of papers that could not be accessed were contacted via ResearchGate.

The screening process was documented using the ROSES Report (Online Resource 1) and is shown in Fig. 1. Included papers had to focus on (1) bycatch (either field study, review or lab study testing a bycatch reduction technology), (2) sensory deterrents, (3) marine megafauna (marine mammal, sea turtle, elasmobranch, seabird) and additionally (4) be peer-reviewed in academic journals. Papers were excluded if they violated any inclusion criteria. Excluded papers were generally those that discussed foraging around fishing gear, habituation and/or other behaviour around gear or detection of gear, without mentioning one of the three inclusion criteria or linking them together. The addition of extra papers from unstructured citation checking was subjective, chosen to address the aim of this review and meeting the inclusion criteria. Papers containing sufficient evidence of false results, for example due to confounding variables or pseudo-replication, were included for the narrative, but excluded from the data extraction step. Review articles were included in this study for background information, but not in the data extraction step, to avoid duplication of results reported by these publications in the synthesis. Grey literature were sourced in the search but excluded from the synthesis, due to their variable quality, however, some key grey literature reports were retained for background information due to their importance in the development of sensory deterrents.

Data extraction

Data were extracted from all included papers into a CSV file (Online Resource 2), which was imported into RStudio version 1.4.1106 for the synthesis (RStudio Team 2021; R Core Team 2022). Taxonomic information was recorded according to megafauna group (marine mammal, seabird, sea turtle, elasmobranch) to species, or the next lowest taxonomic level, and matched to the latest conservation status (IUCN 2021). The study contexts were split into three categories: field, lab and desk study. Field studies were those using sensory deterrents compared to a control to measure bycatch directly, or behaviour of animals subject to bycatch risk around gear. Lab studies were those in captive conditions measuring a behavioural change to a sensory deterrent against a control, in the context of bycatch reduction. Desk studies were those indirectly assessing bycatch mitigation potential of a sensory deterrent by either conceptual or modelling means, including the design or suggestion of novel untested mitigation options.

Gear type was recorded for each study, including concept and proof of concept, for studies based on theory and studies completed in the lab without fishing gear, respectively. Study location details included continent, ocean and country. Mitigation details were recorded in four columns: mitigation sense, mitigation class, mitigation type and technology (e.g. acoustic, acoustic deterrent device, pinger, Aquatec PICE 50-100 kHz). Potential for bycatch reduction was classed as Yes, No, Partial or Data Deficient based on study results, where Yes indicated support for the technology reducing bycatch, No indicated no support, Partial indicated some support or conflicting results and Data Deficient indicated a sample size too small to get a significant result. Significance level against controls were recorded as Yes, No, Data Deficient or Not Reported, where Yes indicated a significant result (p-value $< = 0.05$), No indicated a non-significant result, Data Deficient indicated a sample size too small and Not Reported indicated results where a significance level was not reported in the study. The basis of the results (e.g. bycatch reduction, avoidance response), any recorded effect on target catch and notes on the results were recorded, followed by basic bibliographic information and coding. Papers are identifiable in the extraction form by a Bibtex key, title, year and a unique paper number. Each paper was labelled as a Search or Addition, where Search papers were retrieved in the initial database search and Addition papers were sourced by unstructured citation checking.

Data and narrative synthesis

All papers from the data extraction step were included in the systematic mapping results by constructing graphs on study year, focal taxonomic group, fishing gear, mitigation method and a heatmap linking the number of studies for each sensory system against the marine megafauna groups to identify research gaps. The graph on study count by year was made up of the counts of individual papers. The other graphs and heatmap were made up of counts of each row entry on the data extraction sheet, representing trials, rather than the counts of individual studies (e.g. if a study was on the response of three different species to two different models of pingers, there would be six rows in the data extraction form). This means that the count of entries in the data extraction form is a proxy for the coverage of studies and that a higher number of entries for one paper compared to another means a higher representation in the study coverage in the heatmap. The systematic mapping results were used in the narrative synthesis to describe the development of sensory bycatch mitigation technologies, which include the reviews from the literature search and key grey literature (sourced separately from the search). The synthesis of the results in two Venn diagrams were completed only using the field-based studies.

Mitigation types

A summary of the types of sensory technologies are shown in Table 2, as well as the sensory systems of each megafauna group. The technologies described in Table 2 are not separated by gear or target taxonomic group, but detail all available options retrieved from the literature search. Other sensory deterrents may exist in literature outside the search for this study, so those in the table may not represent an exhaustive list. Multiple options can potentially be used in conjunction with each other, as well as combination with non-sensory bycatch mitigation, such as time-area closures or catch limits. Tactile deterrents (including the mechanosensory lateral line) are recorded in Table 2 but are excluded from the rest of the review. All surfactants detailed in the literature search fit into olfactory chemical and semiochemical deterrents. No evidence of water jets or pre-net fences were described in peer-reviewed studies beyond reviews (e.g. Jordan et al. 2013). Physical barriers either fit into visual deterrents (such as artificial kelp in physical models) or are primarily used to prevent foraging around fishing gear rather than bycatch reduction, as is the case for hook sleeves (Hamer et al. 2012). Escape options are excluded because, despite some excellent results and promise for reducing bycatch of turtles (Cox et al. 2007), they are not designed to avert contact with marine megafauna, but rather to reduce mortality

Table 2 All sensory technologies described in the peer reviewed literature in studies relating to bycatch reduction. Pooled across all taxa and gear types. Underneath see sensory modalities available to each megafauna group (indicated by an X)

	Sensory system					
	Acoustic	Olfactory	Tactile	Visual	Echolocation	Electrosensory
Mitigation Type	**Acoustic Deterrent Device (ADD):** an electronic device emitting pre-programmed sounds, including pinger or other artificial sound **Acoustic Harassment Device (AHD)**: similar to an ADD but designed to scare or harass, including loud electronic devices such as ‘seal scarers’, ‘bombs’, other explosives or air guns **Acoustic Reflection:** acoustic reflection devices (see Echolocation column) for creatures that cannot echolocate	**Semiochemical:** chemical extraction from an organism **Chemical:** manufactured or non-naturally extracted chemical **Alternative Bait Type:** bait on hooks (e.g. fish bait instead of squid) **Offal Discard Management:** Dumping waste from bait or fish while setting fishing gear	**Water Jet:** water hose or cannon deterrent **Escape Option:** physical exclusion, including turtle excluder device (TED), seal exclusion device (SED) or sea lion exclusion device (SLED) **Physical Barrier:** includes bait surround or shroud or physical model (see Visual column) **Surfactant:** Chemical deterrent reducing surface tension (see Olfactory column as repellent mechanism not fully understood)	**Lights:** LEDs in various wavelengths including UV, chemical lightsticks, strobes, vessel deck lights **Physical Model:** various structures providing a visual alert: predator cut-outs, shape models, piping, artificial kelp, looming eye buoys, high contrast panels, tori (bird scaring) lines **Gear Colour:** changes to standard gear colour including lines and nets **Bait Colour:** blue, yellow or red dye added to bait	**Acoustic Reflection Device:** an addition to gear designed to reflect biosonar, including net material alterations (barium sulfate, iron oxide, air filled tubes) and acrylic spheres	**Electropositive Metal (EPM) Alloy:** Rare earth metal alloy reacting with seawater and generating an electrical potential **Magnet:** pulsed magnetic field, permanent ferrite or rare earth magnet **Electrode Array:** pulsed electric field or microprocessor-controlled unit (MCU) **Modified Hook:** SMART (selective magnetic and repellent-treated with electropositive metal) hooks combining both EPMs and magnets
Odontocetes	X	X	X	X	X	
Other Mammals	X	X	X	X		
Elasmobranchs	X	X	X	X		X
Sea Turtles	X	X	X	X		
Seabirds	X	X	X	X		

after contact with gear is made. Exclusions and unobtainable references are listed in Online Resource 3.

Results

From the literature search 116 studies were included in the systematic map database and narrative synthesis. Additionally, 25 review articles were included in the narrative synthesis (Online Resource 4). The 116 included studies resulted in 388 entry rows (trials) on the data extraction form, of which 312 were results taken from the field that were eligible for use in the Venn diagrams, corresponding to 90 unique papers. The number of papers published each year from the literature search are shown in Fig. 2, showing the recent development of the field, the paucity of studies found before 2000 and the increase in study numbers after 2010. There were no studies sourced in the search from before 1991. The continent on which the field study papers were conducted are displayed in Fig. 3, where NA indicates that the study was done in the lab. Of the studies in North America, 25 were in the USA or Canada. In Oceania all studies were in Australia or New Zealand. There is a general lack of studies in developing nations or locations where SSFs fleets are widespread. The gear type investigated in each study are shown in Fig. 4, where 'proof of concept' or 'concept' indicates that it was a lab experiment. Gillnets and longlines dominate the gear types in the field trials, with relatively little representation from other gears. For further context, see the data extraction form (Online Resource 2).

The following sections summarise the development of sensory technologies for marine megafauna by taxonomic group. The narrative includes papers

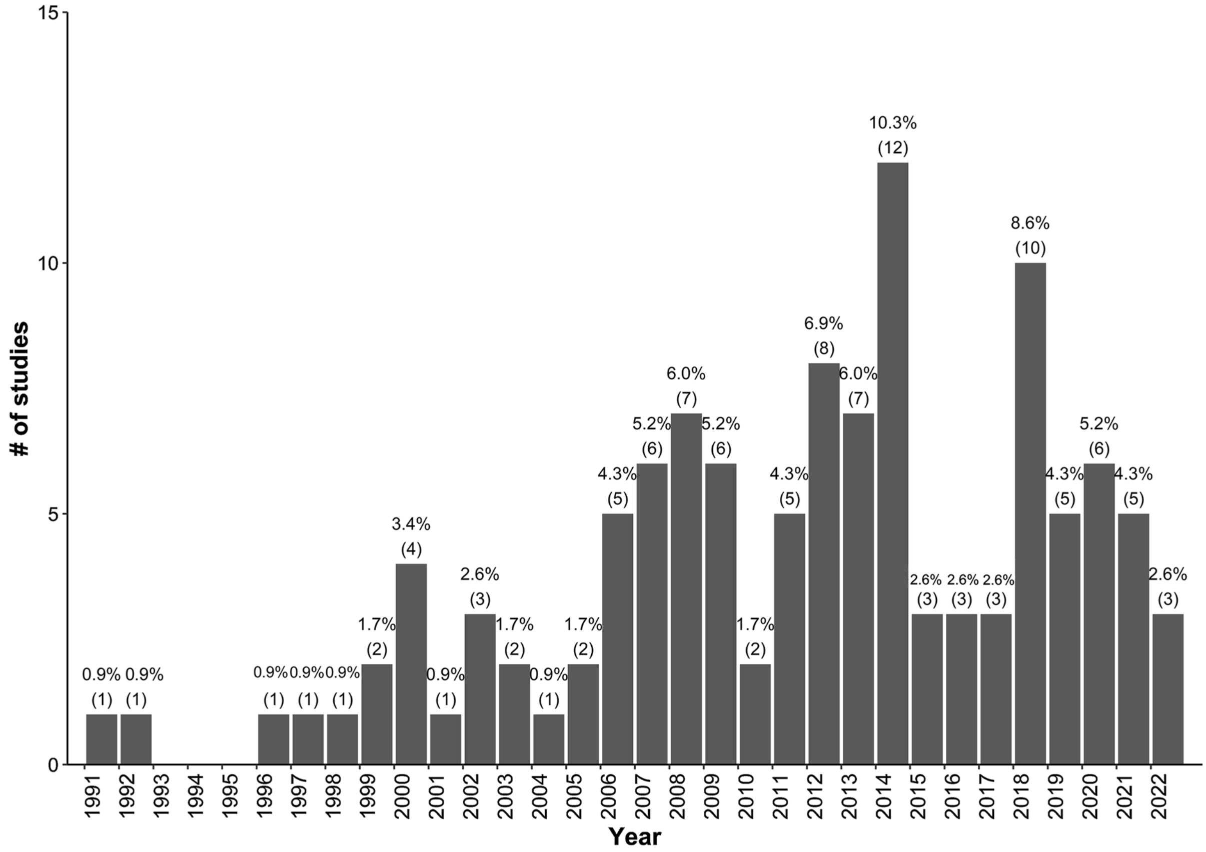


Fig. 2 Study count by year for all 116 studies included from the literature screening process, which does not include the 25 review papers. Results range from 1991 to 2022. Numbers on top of the bars in the format A(B) where A is the proportion of studies published out of all 116 studies found and B is the number of studies

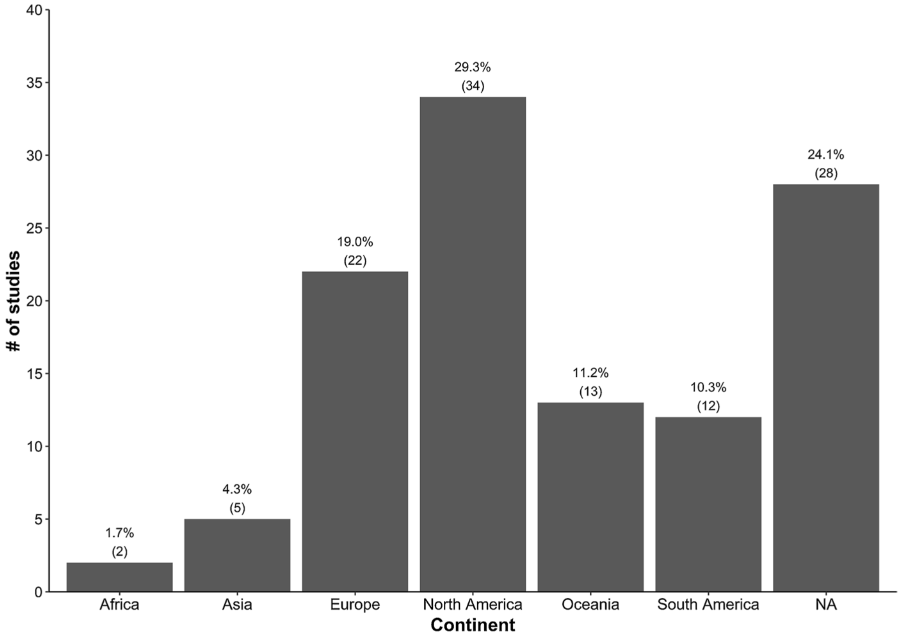


Fig. 3 Study count by continent for the 116 field studies sourced in the literature screening process. All studies completed in a lab are shown as NA and review papers are not included. Study oceans and countries are detailed in Online Resource 1. Numbers on top of the bars in the format A(B) where A is the proportion of studies published out of all 116 studies found and B is the number of studies

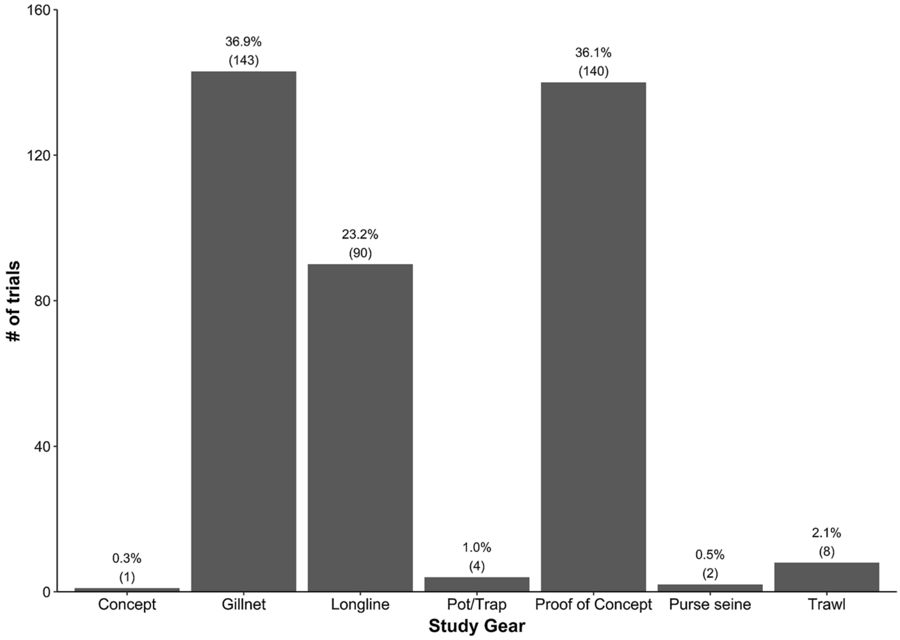


Fig. 4 Trial count by gear for the 388 total trials in the 116 studies sourced in the literature screening process. All lab studies completed are shown as 'proof of concept' or 'concept'. Review papers are not included. Details can be found in Online Resource 1. Numbers on top of the bars in the format A(B) where A is the proportion of trials published out of all 388 trials found and B is the trial count

sourced in the systematic search, highlighting some key grey literature which appeared before peer-reviewed studies in the development of technology, as well as seminal earlier work in peer-reviewed literature contributing to the development of deterrents. Comprehensive reviews on sensory technologies for each megafauna group exist. For seabirds see Gilman et al. (2005); Bull (2007); Martin and Crawford (2015); Friesen et al. (2017). For sea turtles see Echwikhi et al. (2011); Gilman et al. (2010); Southwood et al. (2008). For elasmobranchs see Cliff and Dudley (1992); O'Connell et al. (2011b); Jordan et al. (2013); O'Connell et al. (2014g); Favaro and Côté (2015); Hart and Collin (2015). For marine mammals see Dawson (1991); Dawson et al. (2013), (1998); Hamer et al. (2012); Hamilton & Baker (2019); Jefferson & Curry (1996); Read (2013); Schakner & Blumstein (2013). Mitigation of more than one taxonomic group are addressed in Cox et al. (2007); Gilman et al. (2020); Martin & Crawford (2015); Werner et al. (2006). In general, before the 1970s there was little published effort to reduce bycatch of marine megafauna, possibly because the problem was not well identified and ecological impacts were poorly understood.

Elasmobranchs

Acoustic

Acoustic shark deterrents have had little attention since initial experiments on the aversive responses of sharks to killer whale (*Orcinus orca*) calls in the 1970s (Myrberg et al. 1978). More recently, 'artificial sounds' (20 Hz–20 kHz) have been trialled in combination with strobe lights, successfully deterring small shark species (*Heterodontus portusjacksoni* and *Hemiscyllium ocellatum*) from taking baits in a lab setting (Ryan et al. 2018). However, sound alone did not deter even the small species and neither stimulus, used on its own or in combination, caused significant behavioural change in wild white sharks (*Carcharodon carcharias)*. Chapuis et al. 2019 investigated the effects of playback of two distinct sound stimuli on eight shark species, using a modified baited remote underwater video systems (BRUVS) rig. They found that the 'artificial sound' (20 Hz–10 kHz, with 95% of its energy under 1 kHz) deterred all eight species, although this was only a partial deterrent effect on white sharks. A wild killer whale call, recorded in Australia, deterred the seven reef and coastal shark species tested in Australia but not white sharks in South Africa, although the authors noted that white sharks may be sensitive to regionally-specific killer whale calls (Chapuis et al. 2019). The authors also raised concerns about the effects anthropogenic noise could have on sharks, particularly given the deterrent effect of the artificial sound on reef and coastal species. Hearing, sound use and behavioural responses to acoustic cues are little studied in elasmobranchs, so this area calls for further investigation (Mickle and Higgs 2022).

Olfactory

Elasmobranchs have highly sensitive olfactory systems which, although they vary between species, play a key role in prey detection and offer potential in commercial fisheries if a deterrent can be found that does not alter target species behaviour (Jordan et al. 2013). Early efforts were made to develop chemical shark repellent devices for military personnel during World War II. Decades of investigation produced conflicting results in semiochemicals from dead sharks (primarily ammonium acetate and copper acetate) and the apparent failure of tactile chemesthetic repellents (toxins), so research on these compounds was halted (Hart and Collin 2015). Recent developments in chemical repellents have focused more on bycatch reduction than personal protection, involving the use of semiochemicals from dead sharks ('necromones'), which caused total cessation of feeding and temporary evacuation of shark species, without affecting teleost feeding behaviour (Stroud et al. 2014). Research for elasmobranch bycatch reduction in longlines has investigated effect of bait type, rather than chemical aversion. Replacing squid with fish baits reduced bycatch in elasmobranchs (Watson et al. 2005), as they did for turtles, although studies since have found species-specific bait preferences, with mixed results for fish and squid bait (Coelho et al. 2012).

Visual

The SharkSafe barrier, which combined permanent magnets with PVC pipe or artificial kelp, was presented as an alternative to gillnets used in fisheries or for bather protection on beaches (O'Connell et al. 2014a). Even on their own, the visual stimuli triggered increased avoidance responses and decreased entrance frequencies through the barrier in large species, including white sharks, bull sharks (*Carcharhinus leucas*) and great hammerheads (*Sphyrna mokarran*) (O'Connell et al. 2014a, 2014f, 2015). The use of lights to deter sharks has had mixed success. Strobe lights reduced bait strikes by small species in lab conditions but not wild white sharks (Ryan et al. 2018). In gillnet fishery trials, Bielli et al. (2020), Mangel et al. (2018) and Virgili et al. (2018) reported that green and UV-LEDs did not reduce elasmobranch catch. However, recently green LEDs caused a significant decrease of 95% in elasmobranch catch in Peruvian gillnets, although the study used a small sample size (28 paired sets) and measured change in biomass caught rather than individual animals (Senko et al. 2022).

Electrosensory

After the introduction of beach nets to protect bathers in South African waters in the late 1960s and early 1970s, initial experiments began to develop an electrical shark barrier to prevent human-shark interactions (Smith 1974). Similar to the early chemical studies, electrical shark repellents were designed for personal use rather than bycatch mitigation in fisheries. The SharkPOD (Protective Oceanic Device) and Shark Shield Freedom7 began commercial marketing of repellents, although efficacy of these personal deterrent devices is questionable and results have been mixed (Huveneers et al. 2013, 2018).

Electrosensory bycatch mitigation research began in the 2000s by testing the effects of rare earth magnets, ferrite magnets and electropositive 'mischmetals' on elasmobranch foraging success, avoidance behaviour and bycatch levels. Rare earth metals and mischmetals exhibited mixed results from early lab and field trials (Stoner and Kaimmer 2008; Kaimmer and Stoner 2008; Brill et al. 2009; Tallack and Mandelman 2009), whereas cheaper ferrite magnets were successful in causing avoidance responses in multiple species (Rigg et al. 2009; O'Connell et al. 2010). Initial promise of neodymium-based electropositive alloys in lab experiments (Jordan et al. 2011) did not translate to field studies, where bycatch of most species remained unchanged, with the exception of significantly reduced bycatch of juvenile scalloped hammerhead sharks (*Sphyrna lewini*) (Robbins et al. 2011; Hutchinson et al. 2012; Godin et al. 2013; McCutcheon and Kajiura 2013). Jordan et al. (2011) described that the presence of conspecifics may invoke competitive feeding behaviours which override any deterrent effect of magnets and that the magnetic field may actually attract individuals in these situations. Smith and O'Connell (2014) and Siegenthaler et al. (2016) both conducted controlled lab experiments using neodymium-based rare earth magnets to successfully deter foraging attempts of three elasmobranch species, conflicting with a later lab study on sand tiger sharks (*Carcharias taurus*) that showed no effect (Polpetta et al. 2021). Field trials of rare earth magnets have resulted in mixed responses of Australian swellshark (*Cephaloscyllium laticeps*) in trap fisheries (Westlake et al. 2018) and increased bycatch of blue shark (*Prionace glauca*) in longlines (Porsmoguer et al. 2015).

Meanwhile, SMART hooks (selective magnetic and repellent-treated with electropositive metal) were developed and tested on longlines, with nine recorded elasmobranch species caught (O'Connell et al. 2014d; Grant et al. 2018). Grant et al. (2018) reported that Greenland sharks (*Somnius microcephalus*) exhibited no behavioural response to SMART hooks and that their powerful inertial suction feeding may have negated any potential deterrent effects. In O'Connell et al. (2014d), skate bycatch was reduced when species were pooled together. At the species level, only spiny dogfish (*Squalus acanthias*) catch reduced significantly (28.2%), although bycatch was still high, with 930 individuals on SMART hooks and 1296 on controls. Favaro and Côté (2015) commented that statistically significant, but not sufficiently large bycatch reductions, combined with the challenges in implementing in commercials fisheries makes electrosensory deterrents unsuitable for widespread use, suggesting that monofilament nylon leaders, or raised longlines (for demersal species) are more effective ways to reduce elasmobranch bycatch in longline fisheries.

There have been multiple trials using ferrite magnets which show potential to reduce elasmobranch mortality in place of beach nets (O'Connell et al. 2011a, 2014a, 2014e; O'Connell and He 2014). As mentioned, the development of the SharkSafe barrier, a combination of ferrite magnet and visual deterrents, triggered increased avoidance behaviours of several large shark species targeted by beach nets, including white, bull, lemon (*Negaprion brevirostris*) and great hammerhead sharks (O'Connell et al. 2014c, 2014a, 2014f, 2015). O'Connell and He (2014) report that efficacy of these barriers may not extend to rays and small shark species in nets, although alterations in barrier spacing may resolve this. However, the use of ferrite magnets could reduce bycatch of small shark species in trap fisheries, with an increase in target catch rates (Richards et al. 2018).

Recent developments involve use of pulsing electrical and magnetic signals to illicit aversive responses and reduce bait consumption (Howard et al. 2018; Polpetta et al. 2021). Howard et al. (2018) presented positive results in deterring feeding in sandbar sharks (*Carcharhinus plumbeus*) using electric fields from an electrode array, but bimodal bait consumption in groups of spiny dogfish, with either 0% or 100% of baits being taken during trials. Pulsed electrical or magnetic fields have triggered some aversive behaviour in captive largetooth sawfish (*Pristis pristis*) and sand tiger sharks respectively, although these subtle responses found in controlled conditions may not be sufficient to prevent capture in active fisheries (Abrantes et al. 2021; Polpetta et al. 2021).

Inconsistent results investigating magnetic deterrents across species and in various contexts can be due to multiple factors, including conspecific or heterospecific density, individual satiation, water visibility, salinity and the species tested (O'Connell et al. 2014g). Hutchinson et al. (2012) and Porsmoguer et al. (2015) argued that the limitations and cost of magnetic repellents make it challenging to establish generalisations about their efficacy, and therefore, they are currently unsuitable for implementation as bycatch reduction technologies. There is a consensus that further research in this area should be encouraged due to the unique sensory capabilities and potential for bycatch reduction of elasmobranchs found across multiple studies (e.g. Tallack and Mandelman 2009; Jordan et al. 2013; O'Connell et al. 2014g; Hart and Collin 2015; Polpetta et al. 2021), however in the meantime, it is necessary to pursue alternative bycatch mitigation options until electrosensory repellents are proven to be consistently effective in a variety of contexts (Favaro and Côté 2015).

Seabirds

Acoustic

Pingers were tested alongside visual deterrents after initial trials of pingers with marine mammals. Melvin et al. (1999) found that bycatch of common murres (*Uria aalge*) was reduced by 50% with the introduction of pingers (1.5 kHz), although there was no such reduction in bycatch of rhinoceros auklets (*Cerorhinca monocerata*).

Olfactory

Cherel et al. (1996) found that strategic offal discard was effective at deterring procellariiform birds from attempting to take bait or alighting on longlines. In factory stern trawlers where, unlike longlines, there is no olfactory or visual attraction from bait, offal discharge has caused increased contact rates with gear and consequent mortality (Sullivan et al. 2006; Kuepfer et al. 2022). As well as gear differences, discarding offal may have species-specific effects, by reinforcing the behaviour of birds attending vessels (Weimerskirch et al. 2000).

Pierre and Norden (2006), found that shark liver oil was successful at deterring flesh-footed shearwaters (*Ardenna carneipes*) and other seabird species (pooled) from diving behind vessels. In Norden and Pierre (2007), four chemicals were tested on procellariiform seabird assemblages in New Zealand. None of the chemicals had any significant effect on the behaviour of species in the family *Diomedea*, or on giant and cape petrels (*Macronectes giganteus, Macronectes halli, Daption capense*). However, 'fisher oil' (directly extracted from school shark, *Galeorhinus galeus*, livers) significantly reduced numbers of birds gathering behind vessels and number of dives in flesh-footed shearwaters (Norden and Pierre 2007). Fewer flesh-footed shearwaters and black petrels (*Procellaria parkinsoni*) were present behind vessels using fisher oil and commercial shark liver oil. Two commercial fish oils (Alaskan pollock and Peruvian anchovy) had the same effect in flesh-footed shearwaters only. These results highlighted the species-specific differences in deterrents, with repellent effects found on the burrow-nesting procellariiformes but not those with different life histories and ecology within the same order. Incidentally, this supports the indication that these chemicals work as olfactory deterrents rather than tactile chemesthesis (Norden and Pierre 2007). Species-specific differences in reaction to olfactory and visual stimuli are discussed in Friesen et al. (2017), who suggested multi-modal signals, by using multiple sensory cues, would have the greatest efficacy and broadest species coverage to mitigate seabird fishery interactions.

Visual

Cherel et al. (1996) commented that seabird bycatch was reduced when deck lights on longlining vessels were switched off during night sets, although not whether this was statistically significant. Night setting is believed to reduce bycatch because fewer birds are active at night or cannot locate baited hooks purely from olfactory cues alone (Cherel et al. 1996; Bull 2007). Seabird scaring lines (herein referred to as tori lines), for use in longline fisheries, first appeared in grey literature reports in the early 1990s (Bull 2007). Løkkeborg (1998) reported consistent significant reductions in seabird bycatch and interactions with Norwegian longline vessels using tori lines. Continued research provided further positive evidence (Lokkeborg and Robertson 2002), although weather conditions, line quality and setting height (unique for each vessel) all affected performance (Brothers et al. 1999).

Meanwhile, in drift gillnet fisheries, Melvin et al. (1999) found that bycatch of common murres was reduced by 40–45% when the upper 20–50 meshes were replaced with mesh made of white twine, as a visual alert. Bycatch of rhinoceros auklets was significantly reduced (42%) when the upper 50 meshes were replaced with mesh made of white twine, with no significant change in bycatch by changing the upper 20 meshes only. Trippel et al. (2003) found significant bycatch reductions of great shearwaters (*Ardenna gravis*) using barium sulfate nets coloured blue, with 94 caught in 121 control nets and 11 in 72 test nets, although the authors note that this effect could be due to increased net stiffness. Blue-dyed bait trials successfully mitigated albatross interactions in swordfish and tuna longline fisheries (Gilman et al. 2005), although dyed bait may not be as effective as side-setting and underwater chutes, which attempt to prevent any contact with bait (Gilman et al. 2007a). Cocking et al. (2008) found that both blue-dyed fish and squid baits reduced strikes of birds in the family *Procellariidae* in Australian longlines, although the effect of blue-dyed fish diminished with time. It should be noted that the paired trial observations in this study may be non-independent due to the presentation of both blue and unaltered bait simultaneously, rather than each bait type being presented one at a time. Bait type may also mitigate procellariform bycatch too, although results have been conflicting, with some species preferring squid (Gonzalez et al. 2012), while others prefer fish (Li et al. 2012).

Deterrent lasers, such as the SeaBird Saver, appear in grey literature (van Dam et al. 2014), but in no peer-reviewed studies. These devices may repel seabirds in the short term, but long-term efficacy is not known (Pierre 2018) and the impact of lasers on bird eye health should be investigated before further implementation of this technology.

Research on tori lines continued with investigations of diversified methods, line and streamer designs in seabird bycatch reduction. Light streamer designs had no significant effect on bycatch of two albatross species in Japanese longlines, compared to traditional designs (Sato et al. 2012). However, Domingo et al. (2017) found that bycatch of six albatross and petrel species was not significantly different between tori line use and controls, although when pooled across all species, procellariiform bycatch was significantly reduced.

Recent visual deterrent investigations on gillnets have considered the use of lights, high contrast panels and gear colour on avoidance behaviour and bycatch (Hanamseth et al. 2018; Mangel et al. 2018; Field et al. 2019). Hanamseth et al. (2018) reported orange gillnets increased aversive reactions of little penguins (*Eudyptula minor*) compared to green and clear line, although these were in controlled lab conditions and did not measure effects on target catch. Studies on lights have described species-specific responses. Bycatch of long-tailed ducks (*Clangula hyemalis*) increased with the use of white LEDs in Baltic gillnets, while there was no significant difference in bycatch of velvet scoters (*Melanitta fusca*) and no significant difference in bycatch for either species with green LEDs (Field et al. 2019). Field et al. (2019) also showed that high contrast panels, as suggested in Martin and Crawford (2015), caused no significant change in duck bycatch compared with controls without panels. Further evidence of the effect of lights on ducks was presented in Cantlay et al. (2020), who found that long-tailed ducks were attracted by a white flashing LED, with no effect of three different wavelengths of light in lab trials. In contrast to the ineffectiveness of LEDs on ducks, Mangel et al. (2018) reported that Guanay cormorant (now *Leucocarbo bougainvilliorum*) bycatch was significantly reduced by 85.1% by using green LEDs in Peruvian gillnets. In the same area, Bielli et al. (2020) reported an 84% reduction in seabird bycatch using green LEDs, although statistical significance was not reported. Looming eye buoys (rotating panels with eye spots, attached to a buoy) are a promising development in deterring seabirds, with significant reductions of long-tailed duck abundance within 50 m of the modified buoys compared to controls (Rouxel et al. 2021).

In this study, habituation trials were confounded by the seasonal presence of migrating ducks, so further research was suggested to investigate the long-term deterrent capabilities of looming eye buoys (Rouxel et al. 2021).

Marine mammals

Acoustic

Sensory technologies designed to deter marine mammals emerged in the late 1970s and 1980s with the introduction of acoustic reflectors and pingers in gillnets (Dawson 1991). Pinger studies began with research on Dall's porpoise (*Phocoenoides dalli*) bycatch in Japanese gillnets and entanglement of humpback whales (*Megaptera novaeangliae*) in Canadian cod traps (Lien et al. 1992; Hatakeyama et al. 1994). The efficacy of pingers was initially difficult to assess due to variable study designs, reporting standards and marginal results (Dawson 1994; Dawson et al. 1998). Jefferson and Curry (1996) argued that despite promising results with pingers, small, but significant, bycatch reductions may be insufficient to address bycatch problems and consistent reductions would need to be achieved using independent observers before implementation in fisheries. Kraus et al. (1997) presented the first well-designed study in peer-reviewed literature, providing empirical evidence that bycatch of harbour porpoise (*Phocoena phocoena*) was significantly reduced by introducing 10 kHz pingers to gillnets in the Gulf of Maine.

Field studies continued to present significant bycatch reductions in harbour porpoises, using pingers in various frequency ranges from 10 to 160 kHz (Trippel et al. 1999; Gearin et al. 2000; Newborough et al. 2000). These were backed up by behavioural studies displaying harbour porpoise avoidance responses, however, no avoidance behaviour was witnessed in striped dolphin (*Stenella coeruleoalba*) in captive trials (Kastelein et al. 2000, 2001, 2006; Teilmann et al. 2006). Results from studies on other marine species were more variable. Pingers were determined to have a 'dinner-bell' effect on some species of pinniped, including harbour seal (*Phoca vitulina*) and South American sea lion (*Otaria flavescens*), both of which were attracted to or attacked nets significantly more when pingers were active (Melvin et al. 1999; Bordino et al. 2002). Other non-echolocating mammals, such as dugongs (*Dugong dugon*), exhibited no behavioural change when close to 4 or 10 kHz pingers (Hodgson et al. 2007), highlighting that bycatch technologies should not be implemented in fisheries before thorough testing on bycatch species. Cox et al. (2004) reported no avoidance response from common bottlenose dolphins (*Tursiops truncatus*) around gillnets equipped with pingers, except reduced entry into a 100 m buffer around nets when the alarms were active. The results from Kastelein et al. (2006) and Cox et al. (2004) provided evidence that not all odontocetes avoid pingers, perhaps explained by behavioural flexibility in these species (Dawson et al. 2013). In contrast, Barlow and Cameron (2003) conducted a study on gillnets on the USA Pacific coast, where there were significant reductions in bycatch of odontocetes and pinnipeds (pooled across species—eight odontocetes and two pinnipeds), which were led by significant bycatch reductions of 85.1% and 68.9% in common dolphin and California sea lion respectively. Similar success was demonstrated with the Franciscana dolphin (*Pontoporia blainvillei*), where implementation of 10 kHz pingers achieved a significant 85.7% bycatch reduction in Argentinian gillnets (Bordino et al. 2002).

Some pinger studies investigating the behavioural responses of small odontocete cetaceans have been subject to pseudo-replication, leading to inflated sample sizes and potentially false results (Dawson and Lusseau 2005, 2013). Culik et al. (2001) and Stone et al. (1997) found that active pingers significantly increased surfacing distances in harbour porpoise and Hector's dolphin (*Cephalorhynchus hectori*) respectively. Monteiro-Neto et al. (2004) described significant reductions in surfacing activity of Tucuxi (*Sotalia fluvatilis*) in quadrants close to active pingers, compared to trials using inactive pingers. However, the surfacing positions used in these three studies do not take into account individual animals or groups, so are not statistically independent (Dawson and Lusseau 2005) and are therefore excluded from the data extraction step in this review.

Species-specific reactions to pingers continued to be demonstrated, with Carretta et al. (2008) reporting significant reductions in beaked whale bycatch using 10–12 kHz pingers in gillnets (pooled across species). Bottlenose dolphin interaction with gillnets reduced with deployments of Aquatec pingers (5–160 kHz) in field trials (Brotons et al. 2008). Further captive pingers trials on three pinniped species and three odontocete species displayed at least partial aversion in each (Bowles and Anderson 2012), although it is important to consider that these trials in captive animals may not translate to real world scenarios. However, net interaction in three species was observed, including foraging attempts of harbour seals and California sea lions around gear, as well as agonistic behaviour towards gillnets by Commerson's dolphins (*Cephalorhynchus commersonii*) (Bowles and Anderson 2012). Studies on harbour porpoises continued to produce positive significant results, either by directly measuring bycatch of individuals (Gönener and Bilgin 2009), or increased avoidance behaviour (Carlström et al. 2009), each using 10–12 kHz pingers. Trials of an alternative 40–120 kHz acoustic alarm significantly reduced harbour porpoise bycatch in Danish gillnet fisheries (Larsen and Eigaard 2014). Another alternative design, the Porpoise Alarm (PAL, 133 kHz), imitating wild porpoise calls, triggered increased surfacing distance of harbour porpoises compared to controls by 19–30 m, although with commercial pingers the surfacing distance was increased by at least 321 m (Culik et al. 2015). Carretta and Barlow (2011) continued work in the same California fishery as Barlow and Cameron (2003), finding bycatch reductions of common dolphin and northern elephant seal (*Mirounga angustirostris*), but increases in bycatch of California sea lion. The increases in sea lion catch were attributed to behavioural changes during an El Niño year, reduction in fishing fleet size and a potential 'dinner-bell' effect.

Hamer et al. (2012) suggested a toolbox of solutions may be needed to reduce bycatch, on a case-by-case basis for each fishery including technical mitigation options, fisher behaviour and management strategies, rather than a single technical gear modification, such as pingers, which may be ineffective at deterring some species. This approach was successful in the Gulf of Maine fishery, where a Take Reduction Plan paired time-area closures with pingers and caused drastic reductions of porpoise bycatch from 1990 to 1999, to below target levels (Read 2013). However, harbour porpoise bycatch in this region has fluctuated since 1999, with annual bycatch exceeding potential biological removal (PBR) since 2008 (Orphanides 2012; Dawson et al. 2013). Harbour porpoise bycatch has dropped below PBR since 2017 (e.g. NOAA 2021), however, this case study highlights the importance of continued engagement with fishers and management authorities.

Research into Australian shark nets, gill nets, traps and trawls tested pinger efficacy on a number of mammal species (Erbe and McPherson 2012; Soto et al. 2013; Harcourt et al. 2014; Pirotta et al. 2016; Santana-Garcon et al. 2018). Erbe and McPherson (2012) calculated that humpback whales, dugongs and dolphin species should be able to detect both 3 kHz and 10 kHz pingers from at least 40 m and 110 m respectively, although detection of nets may not be sufficient to repel these animals. Indeed, pingers (2–5 kHz) were ineffective at triggering avoidance responses of humpback whales during behavioural experiments (Harcourt et al. 2014; Pirotta et al. 2016), bottlenose dolphins from trawls (Santana-Garcon et al. 2018) and only minor behavioural responses in both Australian snubfin dolphin (*Orcaella heinsohni*) and Indo-Pacific humpback dolphin (*Sousa chinensis*) (Soto et al. 2013). Meanwhile, studies on small odontocetes continued to display either positive results for potential bycatch reduction (Mangel et al. 2013; Clay et al. 2019; Kindt-Larsen et al. 2019), or inconclusive results (Bilgin and Kose 2018). Despite potential bycatch reductions of small odontocetes, pingers could cause habitat exclusion (Carlström et al. 2002). Agent-based modelling has revealed that combinations with time-area closures could solve this for harbour porpoise populations and allow access to key foraging grounds (van Beest et al. 2017).

Acoustic harassment devices were found to be ineffective when humpback whale behaviour was unaffected by a 'seal scarer' in an Icelandic purse seine fishery (Basran et al. 2020). In contrast, the authors reported that in two separate incidents, two humpback whales were encircled by the purse seine gear, but escaped through a 100 m opening in the net while standard pingers were active (Basran et al. 2020). However, this combination of pingers and fisher behaviour (by leaving the net open to allow escape) would need verification in controlled trials to be confirmed as an effective and viable bycatch mitigation option for purse seines. Reviewing bycatch mitigation options for marine mammals, Hamilton and Baker (2019) concluded that pingers would be effective at deterring some species, but further research is required to address a range of taxonomic groups and fisheries. 'Seal safe' banana pingers (50–120 kHz) increase avoidance responses in vulnerable Franciscana dolphins, although this effect is fairly small, with 19.4% reductions in surfacing frequency close to the pinger and 15% at 100 m (Paitach et al. 2022). Significant reductions of bycatch and increased avoidance behaviour in harbour porpoises continue, adding to the evidence base that pingers are effective for at least some small odontocetes in gillnet fisheries globally (Chladek et al. 2020; Omeyer et al. 2020; Königson et al. 2021).

Olfactory

No marine mammal olfactory studies using primary data were sourced in the peer-reviewed literature. Discard management is discussed in Bonizzoni et al. (2022), referencing grey literature, as a potential to reduce bycatch of both seabirds and marine mammals in Australian trawl fisheries.

Visual

Preliminary observations showed that cape fur seals (*Arctocephalus pusillus*) displayed little reaction to the artificial kelp SharkSafe barrier (O'Connell et al. 2014b), benefiting the case for removing entangling beach nets as these barriers may repel sharks but not impact non-target marine mammals, although further research is required to verify this. Recent developments in sensory technologies have indicated that visual deterrents may be effective at reducing marine mammal bycatch. Green LEDs resulted in a 70.8% and 66.7% reduction in small cetacean catch per unit effort (CPUE) in Peruvian surface driftnets and bottom set nets respectively (Bielli et al. 2020).

Echolocation reflection

Early acoustic reflector research had contrasting results on dolphins and porpoises. Neither nickel bead chain or plastic tubing net attachments resulted in significant differences in dolphin bycatch (Hembree and Harwood 1987). Au and Jones (1991) investigated net detection distances of bottlenose dolphin and harbour porpoise, with three alternative designs each resulting in theoretically greater detection distances in both species. Development of acoustically reflective gillnets continued with the introduction of barium sulfate fibres. Trippel et al. (2003) reported significant reductions of harbour porpoise bycatch in barium sulfate nets, however, it was not clear whether this was due to greater acoustic reflectivity or the greater net stiffness. Koschinski et al. (2006) reported reduced acoustic activity of harbour porpoises close to barium sulfate gillnets and suggested pairing these nets with acoustic tones, in an attempt to encourage use of biosonar and aversive responses. Both Larsen et al. (2007) and Trippel et al. (2008) found significantly reduced bycatch of harbour porpoises using stiff nets, but that the iron oxide nets in Larsen et al. (2007) also reduced target catch quantity. Mooney et al. (2007) tested barium sulfate and iron oxide nets in lab conditions to assess theoretical detection distances of harbour porpoise and bottlenose dolphin. They deduced that barium sulfate increases detection distances at a 0^{o} degree angle of incidence (horizontal to the sea surface and perpendicular to the net) for both species. However, detection distances for porpoises may be within 5 m, and potentially only just above this distance for bottlenose dolphins, putting both species at risk of bycatch when travelling quickly near nets. Stiffness of all nets was found to reduce when soaked in seawater (Mooney et al. 2007). Neither stiff nylon nets, nor barium sulfate nets reduced bycatch of La plata dolphin in field trials (Bordino et al. 2013).

A longline echolocation disruptor (1-250 kHz) was tested on a trained false killer whale (*Pseudorca crassidens*), resulting in an initial reduction in target location success, but with improved accuracy as the experiment progressed (Mooney et al. 2009). However, performance of a trained captive animal does not reflect real world fishing gear interactions with marine megafauna and the disruptor was not tested on wild animals. Acoustic reflection has been revisited with the addition of acrylic spheres to gillnets, which improve on net material additions by theoretically allowing net detection at any angle of approach (Kratzer et al. 2020). Promising pilot studies using this technology highlight the need for testing in large scale trials to make a judgement on efficacy in commercial fisheries (Kratzer et al. 2021).

Sea turtles

Acoustic

No sea turtle acoustic studies were sourced in the peer-reviewed literature.

Olfactory

Technologies targeting olfaction appear in grey literature (Swimmer and Brill 2006) and peer-reviewed studies in the 2000s, with investigations into reducing bycatch on longlines (Southwood et al. 2008). Watson et al. (2005) investigated olfactory stimuli for bycatch prevention by testing the effect of alternative bait types. By replacing squid bait with mackerel bait, bycatch of both loggerhead (*Caretta caretta*) and leatherback (*Dermochelys coriacea*) turtles were significantly reduced. Watson et al. (2005) combined the effects of bait type with non-sensory bycatch mitigation, finding further reductions in bycatch by using circle hooks. Replacing squid with fish bait has continued to exhibit bycatch reductions in all tested turtle species (Gilman et al. 2007b; Coelho et al. 2012). Effects of coloured baits have produced mixed results, often not translating to field studies. Replacing squid bait with fish has shown potential for reducing sea turtle bycatch on longlines, and is still being investigated (Echwikhi et al. 2011). Fish baits rather than squid are reported to be more effective at reducing bycatch, although there is potential to reduce target catch in teleost fishes using this method (Gilman et al. 2020).

Visual

Swimmer et al. (2005) tested altered squid bait colours on sea turtles in lab and field trials. In the lab, both loggerhead and Kemp's Ridley turtles (*Lepidochelys kempii*) chose significantly more control bait than bait dyed blue. Interestingly, loggerheads also chose to strike control bait above red dyed bait, but Kemp's Ridley turtles chose red bait above controls significantly more frequently. However, in field trials using blue dyed squid on Costa Rican longlines, bycatch was not reduced in either species (Swimmer et al. 2005).

After initial studies on bait types, Southwood et al. (2008) described the similarities between turtle and target species reactions to olfactory cues, but noted key differences in visual capabilities. Crognale et al. (2008) explored visual differences between leatherback turtles and targeted swordfish in a theoretical study to find a longline deterrent. Differences in species biology mean green (*Chelonia* mydas) and loggerhead turtles have different visual capabilities to leatherbacks and swordfish, which both have similar spectral sensitivities. They concluded that light flickering at a rate of > 16 Hz would be difficult to detect for the leatherbacks but viewed as flickering by swordfish (Crognale et al. 2008). Visual deterrents on gillnets developed with trials of green chemical lightsticks, green LEDs and predator models (shark cut-outs) in Mexico (Wang et al. 2010). All methods reduced bycatch of green turtles by at least 40%, although shark cut-outs also significantly reduced target catch. Wang et al. (2013) followed up the original study by trialling UV-LEDs in the same fishery, reporting a significant 39.7% reduction in green turtle bycatch and no effect on target catch, similar to previous results using lights. The authors also note that the efficacy of net illumination is dependent on the circumstances of use, commenting that lights may be ineffective when used in the day. Combinations of gear visibility from lights, UV-absorbent plastic and physical predator models have been suggested as effective bycatch mitigation options in gillnets (Gilman et al. 2010).

Research on visual deterrents continued in lab trials, where Piovano et al. (2013) investigated yellow, red and blue-dyed bait on loggerhead turtle behaviour. There was no clear overall preference for bait colour, with individuals choosing different colours to strike first and tending to repeatedly strike the same colour in subsequent trials, leading to the conclusion that bait colour would be ineffective at reducing bycatch in loggerheads (Piovano et al. 2013). Bostwick et al. (2014) found that 3D shark models and 3D sphere models had the potential to repel loggerhead turtles from striking at bait. Four and two out of six avoidance behaviours significantly increased for the shark and sphere model respectively, compared to control conditions. However, there is no record of a sphere model being tested in fisheries trials.

Recently, research efforts have been focused on reducing sea turtle bycatch in gillnets using lights. Virgili et al. (2018) found that UV-LEDs significantly reduced loggerhead turtle catch in an Italian gillnet fishery, without reducing target catch quantity, also commenting that LEDs provide better light penetration through water than chemical lightsticks. Both Ortiz et al. (2016) and Bielli et al. (2020) came to similar conclusions investigating green LEDs in Peruvian gillnets, finding significant 63.9% reductions in green turtle and significant 74.4% reductions in all turtle species bycatch, respectively.

Multi-species sensory deterrent efficacy and study gaps

A summary of the efficacy of sensory technologies from the data extraction process is shown in Fig. 5. Any technology with at least one significant result in favour of bycatch reduction is displayed in Diagram A. Any technology that would not be effective for reducing bycatch (indicated by non-significant or significant negative results in at least one study) is represented in Diagram B. In cases where there are conflicting results within or between studies, technologies appear in both diagrams.

A heatmap displaying the number of trials found in the literature search relating to each sensory deterrent category and taxonomic group is shown in Fig. 6. As some studies tested more than one method and included multiple megafauna species, the total number of trials in the table exceed the number of studies found in the literature. The heatmap represents counts of the number of trials, but not whether these trials were successful. Reviews are not included to avoid duplication of findings.

Discussion

General principles in bycatch reduction

From a conservation perspective, time-area closures are an ideal and simple solution for reducing anthropogenic mortality of marine megafauna, if implemented and regulations are properly enforced.

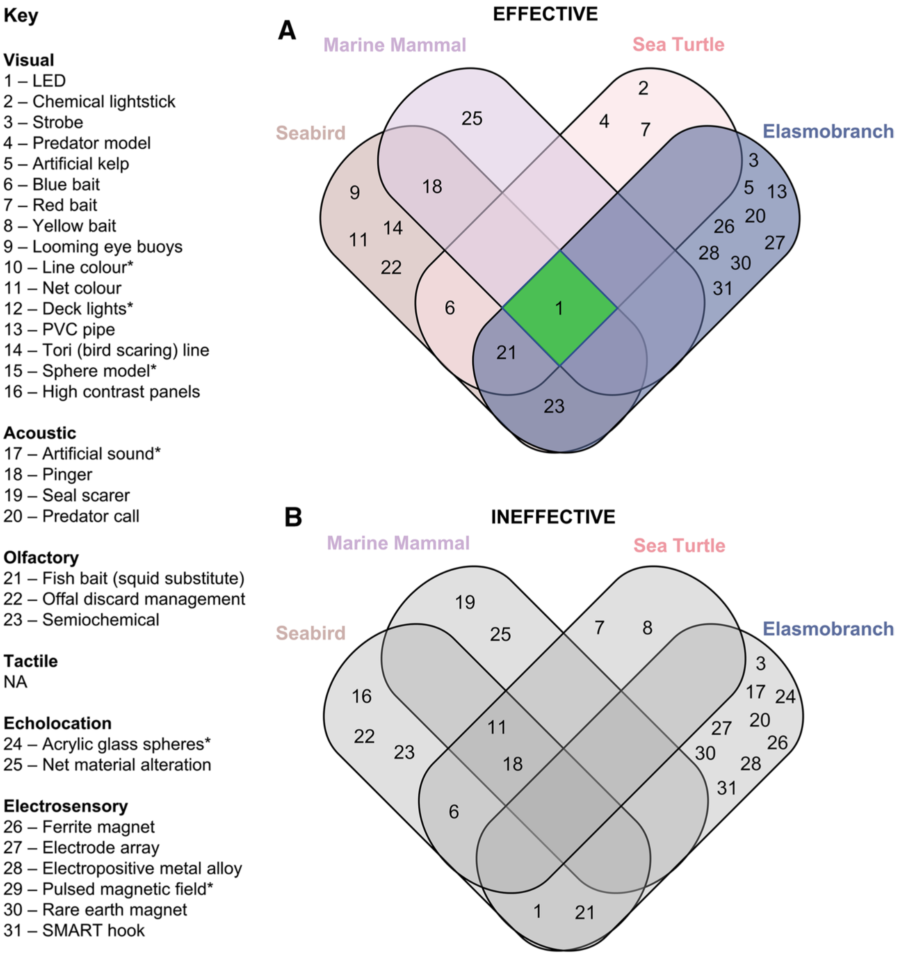


Fig. 5 Effective and ineffective sensory deterrent Venn diagrams. (A) Technologies that have been shown to work on groups of marine megafauna in at least one study with statistically significant results. (B) Technologies that have been shown to have no significant effect, or a negative effect on marine megafauna groups. Some technologies appear in both diagrams. Asterisks (*) note technologies with partial efficacy, positive mitigation potential with no significant result, or where significance is not reported

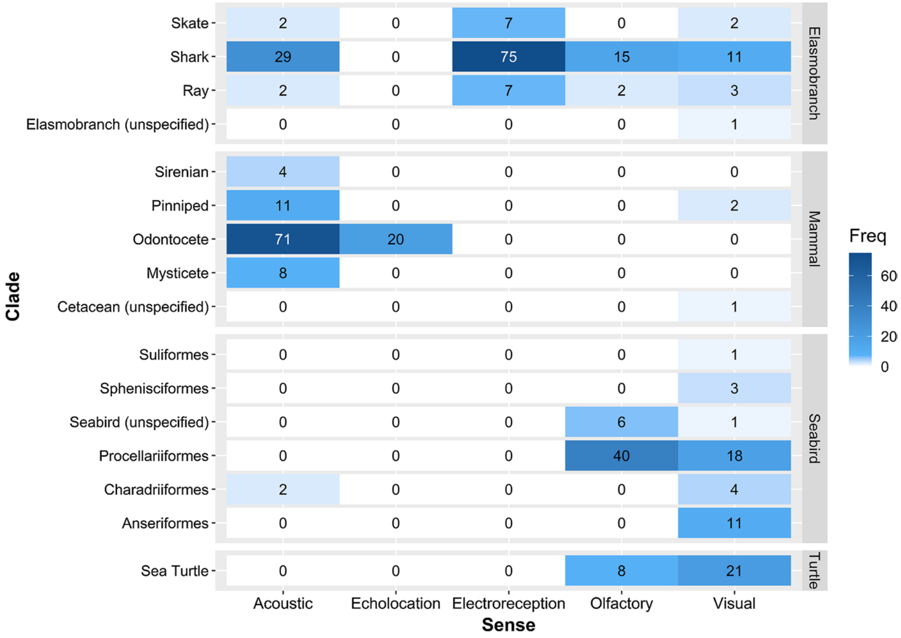


Fig. 6 Heatmap showing the number of trials of each sensory deterrent system against the clade on which it was tested. Number of trials (388 in total) exceeds the number of studies (116) due to multiple technologies or species being tested in each study

Changing gear may be a viable alternative in some situations, to reduce overlap with vulnerable populations. Where closures or gear changes are not currently possible (e.g. due to community dependence or lack of political support), bycatch reduction programmes must address bycatch of vulnerable marine megafauna to safeguard marine ecosystems, while attempting to maintain target catch quantity and quality. In such situations, sensory technologies may offer solutions, potentially enabling fisheries to continue operating while reducing bycatch, ideally in combination with other measures, such as periodical closures and catch limits. The efficacy of these technologies is dependent on the characteristics of the fishery and species composition in the area, meaning that management must be done on a context dependent basis (Jordan et al. 2013). Where only one marine megafauna group is present, there would be no need to address bycatch in all groups, but rather have a bespoke management programme based on that species group, as long as the programme does not cause attraction or increase entanglement risk of other potential bycatch species. Species and fishery-specific factors must be taken into account and technologies carefully tested in well-designed studies before wide-scale implementation in any fishery setting. It is not sufficient to infer that the results of one study with one gear type in one location will generalise and be applicable to other species, locations and gear. The nature of sensory deterrents is that results conflict, so proper well-designed trials are critical to success.

It is necessary to include a quantitative goal in bycatch reduction plans, ensuring that bycatch meets reductions required by the population biology of the species and demonstrating continued efficacy through time (Dawson et al. 2013). Sufficient statistical power is critical for assessing quantitative goals, to ensure that bycatch levels do not exceed set mortality limits, such as PBR (Dawson et al. 1998). Prior power analyses are useful for designing experiments to avoid inconclusive results due to insufficient sample size, leading to accepting potentially false null hypotheses of no effect of treatment (Type II error). However, only 6% (7) of the 116 studies in this review reported a prior power analysis (see Online Resource 2 for further detail). Further, statistical significance tests are important to assess outcomes of experiments such as mitigation trials. However, biologically relevant effect sizes are more important for conservation, rather than small, but significant, bycatch reductions. We encourage the use of resources which support the creation of bycatch reduction plans with quantitative bycatch reduction goals, monitoring and evaluation (FAO 2020; Rogan et al. 2021). Compliance and ongoing efficacy of bycatch reduction technologies relies on affordable costs and effective bycatch monitoring and reduction programmes (Virgili et al. 2018; Bielli et al. 2020). Where technologies are unaffordable or logistically difficult to implement, compliance will likely be reduced. To support reductions through time, technologies should be re-usable where possible to save on replacement costs and waste (Wang et al. 2010).

Bycatch reduction requires close collaboration between fishing communities, scientists, fisheries management and environmental organisations. For programmes to work consistently through time, fisher and vessel behaviour must be in line with management plans (Roberson and Wilcox 2022) and multiple measures are likely necessary to achieve sustained success (O'Keefe et al. 2014). Where management programmes or technologies are implemented inconsistently or fail, bycatch levels may increase (Palka et al. 2008; Carretta and Barlow 2011). The dangers of poorly designed bycatch reduction programmes are that if they fail to reduce bycatch sufficiently, then advocacy from the fishing community is unlikely and subsequent adherence to policy may be poor in any current or future programmes (Palka et al. 2008). Cox et al. (2007) highlighted that collaboration, monitoring and compliance are critical and must have the support of the fishing community to be effective. Compliance may be achievable only through mandating the use of bycatch reduction technologies (Dawson et al. 2013) and combining sensory deterrents with additional measures to achieve success (Field et al. 2019). Observers may be effective at ensuring compliance on individual vessels, but observer coverage of entire fleets is often impractical, particularly in SSFs, where fisher buy-in is crucial. Remote electronic monitoring may offer an alternative with further improvements in automated analysis (Bartholomew et al. 2018), but until this technology matures, fishery-independent observations will be necessary to measure bycatch in trials (Jefferson and Curry 1996). In SSFs all animals may be seen as having value as food, or for sale, and therefore there may be no concept of bycatch. In these situations the value of foraging around fishing gear and gear damage reduction could be leveraged, alongside legislation and enforcement measures, to encourage buy-in from the fishing community and achieve effective reductions in marine megafauna mortality. Quantifying the impacts and characteristics of bycatch in both commercial and SSFs is key to understanding the challenges and the potential solutions.

Habituation and habitat exclusion are important factors when using sensory technologies. Habituation to sensory deterrents has been recorded in empirical studies (Amano et al. 2017), and where it is not observed, this is perhaps due to the long time periods over which it could occur and difficulties in detecting it during short field studies which focus on immediate results (Königson et al. 2021). Habitat exclusion has been found in studies and derived in models when investigating some technologies, although evidence of the effects on populations are not clear (van Beest et al. 2017). Habituation may lead to increased bycatch or foraging attempts around fishing gear, and habitat exclusion could have impacts on population size, or act as barriers to key foraging grounds (Carlström et al. 2002), so both should be taken seriously and investigated in trials. Some papers argue that habituation could be beneficial because it may cause reduced, but still effective, avoidance distances (Teilmann et al. 2006; Omeyer et al. 2020). It is argued that these avoidance distances could reduce habitat exclusion while maintaining bycatch reductions (Kindt-Larsen et al. 2019). However, habituation would likely undermine the use of a technology eventually, and any short-term benefits of mild habituation may disappear quickly. This would result in wasted money spent on technologies, the original bycatch problem would return and the trust of the fisheries would be damaged. Modulation of sensory cues and combinations of mitigation options could alleviate potential habituation and habitat exclusion (Teilmann et al. 2006). Using technologies only in months of high bycatch could potentially reduce habituation effects (Amano et al. 2017), although effects of seasonal use would need to be tested before implementation and additional bycatch mitigation strategies would likely be required. Significant habituation and habitat exclusion may limit the ability of technologies to provide consistent bycatch reductions (O'Connell et al. 2015).

Bycatch and foraging around fishing gear are connected issues. Successful sensory technologies have the advantage of reducing initial contact between gear and marine megafauna, which therefore reduces the likelihood of foraging attempts around gear. However, it is important to note that the incentive of food reward may overcome deterrent stimuli during foraging attempts around fishing gear (Cantlay et al. 2020). Decreased bycatch and foraging around fishing gear have the benefit of sustaining levels of target catch, whilst reducing megafauna mortality and gear damage. Other mitigation types do not have the same benefits, for example, escape devices may still allow animal-gear contact in trawl nets. However, for some taxa and gear types, prevention of interactions and bycatch may not be possible. For these situations, or where fishery closure, movement of activity or gear changes are not possible, escape devices may be required to address bycatch and foraging around fishing gear (Hamilton and Baker 2019; Lucchetti et al. 2019).

Sensory deterrents for bycatch mitigation across multiple taxonomic groups

LEDs are the only technology so far to produce significant positive results for bycatch reduction in all four marine megafauna groups (Fig. 5A). Green LEDs (500 nm) have empirically shown bycatch reductions across all groups in gillnet trials off the Pacific coasts of central and South America (Mangel et al. 2018; Bielli et al. 2020; Senko et al. 2022). These relatively recent findings are promising, although some important exceptions should be considered. Differences in vision between leatherback, green and loggerhead turtles highlight that results could be species-specific and may not necessarily generalise within, or across, megafauna groups (Crognale et al. 2008). It appears that sea duck (family *Anatidae*) behaviour is not affected by lights, and ducks can even be attracted to light sources in the case of flashing white LEDs (Cantlay et al. 2020). It should also be noted that elasmobranch catch has either not changed significantly, or actually increased in some studies using green LEDs (Mangel et al. 2018; Virgili et al. 2018) and significant bycatch reductions were found in a study using a small sample size and measuring biomass reduction, rather than bycatch reduction of individual animals (Senko et al. 2022). Water turbidity was not reported in any of these studies and could potentially reduce efficacy of LED lights. In addition, the ecological impact of illuminating marine environments at night may cause different problems. Therefore, caution should be taken before assuming that green LEDs will reduce bycatch in gillnets for all marine megafauna species.

Sixteen sensory deterrents appear in both Fig. 5A and B, highlighting the variability of responses in different species and in different contexts. The six technologies appearing only in Fig. 5A (chemical light stick, predator model, artificial kelp, looming eye buoys, PVC pipe, tori lines) also require further assessment before concluding their effectiveness, as they are relatively little studied. The exception to this is perhaps tori lines, which have encouraging results (Løkkeborg 1998; Lokkeborg and Robertson 2002).

Bait alterations have been effective on multiple megafauna groups in longlines. Blue bait has potential to reduce interactions with both seabirds and turtles (Swimmer et al. 2005; Cocking et al. 2008), while changing squid bait for fish bait can reduce seabird, elasmobranch and sea turtle bycatch (Watson et al. 2005; Gonzalez et al. 2012; Gilman et al. 2020). Fish bait in place of squid has promise for marine mammal fishery interactions too (Garrison 2007), although will need testing in bycatch reduction trials, rather than assessing only foraging around fishing gear. Decreases in target catch and species-specific reactions of sharks and birds require attention, so catch composition of the fishery needs to be considered when changing bait type (Coelho et al. 2012; Li et al. 2012). Semiochemicals, such as shark liver oil and shark necromones have promise in repelling elasmobranchs and some seabirds, although this is species-specific (Pierre and Norden 2006; Norden and Pierre 2007; Stroud et al. 2014). Pingers have a strong track record for reducing bycatch in some odontocete cetaceans, especially neophobic species such as harbour porpoises (Dawson et al. 2013) and potentially some seabirds too (Melvin et al. 1999). However, significant bycatch reductions using pingers have not been found for elasmobranchs (Mangel et al. 2013).

More technologies have been trialled with success for one taxonomic group rather than multiple, generally due to species-specific biology, such as electrosensory systems in elasmobranchs (Jordan et al. 2013), echolocation in odontocetes (Trippel et al. 2008), or visual cues above the water for seabirds (Rouxel et al. 2021). Where multiple groups are caught, it may be appropriate to use multiple technologies in combination. Combinations of sensory deterrents can be effective across multiple groups, such as pingers reducing common murre and harbour porpoise bycatch (Kraus et al. 1997; Melvin et al. 1999). Alternatively combinations of non-sensory mitigation options with sensory deterrent may work. If areas are characterised by transient migrating populations and some permanent populations of different species, time-area closures when migrations pass through may be paired with sensory deterrents for the resident species or group. In cases where bycatch still occurs, post-release or escape mechanisms may be critical. For example, circle hooks combined with blue fish bait could support turtle post-release survival (Echwikhi et al. 2011).

A number of gaps in technologies tested in the literature are displayed in Fig. 6. The gaps (represented by zeros) in echolocation and electrosensory options should be ignored, because only odontocetes can echolocate and elasmobranchs have specialised electrosensory systems. There is a lack of research on olfactory deterrents for marine mammals as they would likely be ineffective for odontocetes (Schakner and Blumstein 2013). Recent findings suggest that offal discard management may reduce interactions and bycatch of odontocetes in trawls (Bonizzoni et al. 2022). These discards are unlikely to be detected by odontocetes using olfaction. Offal discard management was grouped within olfactory deterrents for the purposes of this study, although in reality the sensory deterrents in this review may be detected by different species using different sensory mechanisms.

Acoustic studies have mostly used pingers, with studies usually focusing on mammals, but other groups are also represented in bycatch. Four papers are exceptions to the pinger trials in the acoustic section. Basran et al. (2020) reported on seal scarers as an unsuccessful pinger alternative. Ryan et al. (2018) and Chapuis et al. (2019) investigated ‘artificial sounds’ and orca calls on sharks, and Kratzer et al. (2021) reported on bycatch of sharks in acoustically reflective gillnets in a study on marine mammals. Incidentally, the 29 acoustic trials on sharks came from only nine papers. Culik et al. (2015) and Chladek et al. (2020) used synthetic porpoise calls, rather than conventional pingers, to deter wild porpoises. However, for the purposes of this review, these Porpoise Alarm devices were grouped with pingers for the data extraction and analysis, because they emit an acoustic signal in the hearing range of odontocetes, but not other megafauna species. Seabird and sea turtle sensory deterrents are most frequently focused on visual and olfactory cues. Olfactory studies revealed that bait type can influence both turtle and elasmobranch bycatch levels (Gilman et al. 2020) and semiochemicals such as dead sharks (or shark ‘necromones’) have the potential to reduce gear interactions with both elasmobranchs and seabirds (Norden and Pierre 2007). Visual deterrents have the broadest range of tested technologies, with LEDs the only technology so far tested (and found successful) in trials across all taxonomic groups (Bielli et al. 2020).

Few papers explicitly test the effects of technologies on multiple taxonomic groups (e.g. Bielli et al. 2020). However, many records on the effects of technologies focusing on single groups also record data on other taxa. For example, the effects of pingers and visible upper sections of gillnets on sharks and mammals in the Melvin et al. (1999) study on seabirds and the effects of pingers on sharks in the Barlow and Cameron (2003) study on marine mammals. Attempts by Martin and Crawford (2015) to generalise seabird bycatch mitigation technologies by designing high contrast panel attachments for gillnets were not successful when tested in field trials (Field et al. 2019), but the principles of attempting to reduce bycatch across multiple taxa should be encouraged. Recently studies are beginning to include cross-species mitigation options while attempting to retain target catch quantity and quality. For example, Bielli et al. (2020) found that lights can reduce bycatch in mammals, turtles and seabirds and Gilman et al. (2020) conducting a meta-analysis, concluded that changing bait from squid to fish reduces risk of blue shark and marine turtle bycatch, as also found in Watson et al. (2005).

Limitations of this review

A systematic search was used with the intention of providing reproducible methods and retrieving a representative sample of literature, rather than exhaustively sourcing all works related to the study aim. Other excellent databases exist for sourcing related papers (such as BMIS 2022), as well as other scholarly databases and comprehensive technical reports. This review is limited to the search terms and unstructured citation checking process described in the methods, but should offer a representative view of the field. Selection of grey literature for the narrative section is subject to bias. There are undoubtedly important grey literature reports and peer-reviewed academic papers that will have been missed from this search and therefore from the systematic map and the narrative synthesis. Inclusion criteria contains subjectivity when interpreting papers and this should be considered if repeating the search. Publication bias may present the peer-reviewed literature only with results deemed to be interesting enough for publication. Studies which test mitigation options that do not produce significant results are unlikely to be published. We recommend that anyone using this paper to find information relating to specific species should conduct further searches to ensure all relevant information is sourced.

Published results are often quantitative (e.g. level of bycatch reduction), making meta-analysis a tempting synthesis method. However, this method may be impractical for now, due to the variability in study design and reporting, which inhibits comparisons across studies on multiple mitigation types and species. Vote counting is not a solution to this problem, due to the variability in results. It was therefore decided to present the results in a Venn diagram with a minimum of one paper in support or against of a technology, alongside a narrative synthesis to summarise the previous research. For a more comprehensive understanding, we recommended reading the summary of results in Online Resource 2 and the referenced papers. Meta-analysis for each species or across groups would be useful future research, as long as reporting standards of field studies are consistent and list relevant confounding factors.

Recommendations for future research

A small number of well-studied sensory bycatch mitigation options were identified, such as pingers for harbour porpoises and magnetic deterrents for elasmobranchs (e.g. Chladek et al. 2020; Richards et al. 2018). However, there are few studies actually measuring bycatch reductions in the field, with many undertaken as proof of concept, by measuring a behavioural response rather than bycatch quantity. Even in field studies, there is often variability in results between regions, taxa and fisheries, meaning that additional research for promising mitigation options would be valuable.

General recommendations include reporting standards, study design, locations, study context and unintended effects on animals. Studies should detail key information that would support comparison (Cox et al. 2007). This includes reporting every species caught in the trials, if bycatch of each species (or pooled taxonomic group) was significantly increased, decreased or unaffected compared to controls (e.g. Carretta and Barlow 2011). Consistent metrics should be reported, using number of individuals caught per unit effort (e.g. km net x hours or number of hauls) and normalised for abundance, where possible, rather than biomass (Gilman et al. 2005). Gear type, study location, technology used and technical specifications (e.g. 500 nm lights, C8 barium ferrite magnet or 10–12 kHz pinger) should be described in detail, including failure rates of the technology throughout the trials (e.g. Carretta and Barlow 2011). Sample and effect sizes should be listed, as well as an interpretation of the evidence for bycatch reduction using the technology. Trials should be designed to achieve appropriate statistical power to assess the significance of results (Dawson et al. 1998), so pilot studies are recommended. Where possible, studies should be completed in the field, measuring actual bycatch quantities reported in CPUE, rather than measuring behaviour. However, experimental trials may involve substantial mortality of animals, so the vulnerability of each species affected by field trials must be considered. Modelling or behavioural responses may provide alternative or complementary metrics, particularly where bycatch trials are impractical or unethical (e.g. due to the presence of critically endangered species) (Jordan et al. 2013). Behavioural experiments must consider and mitigate pseudo-replication in study design (Dawson and Lusseau 2005, 2013). New technologies could stimulate research of behaviour around gear in active fishery settings rather than in labs, such as the use of autonomous underwater vehicles equipped with video cameras (Poisson et al. 2021) or cameras deployed on fishing gear (Mitchell et al. 2019). Studies should attempt to measure and comment on initial observations, and if possible on the long-term effects, of the technology on habituation (Jefferson and Curry 1996) and habitat exclusion (Larsen and Eigaard 2014). Investigating new locations is encouraged (Fig. 3), particularly in understudied regions where SSFs are present, such as in Asia, Africa and South America.

We encourage further research combining sensory deterrents to achieve bycatch reduction across taxonomic groups. Effective low-cost technologies that are easy to implement are likely to achieve the highest advocacy and compliance from the fishing industry. There is a further need for long-term trials in areas where CPUE of threatened species is low and efficacy of bycatch mitigation methods may take a long time to demonstrate. Combinations of deterrents should be used in commercial fishing trials to assess potential for large-scale bycatch reductions across species groups, for example combining LEDs and pingers on gillnets, which would test the efficacy of cost-effective lights with relatively established acoustic deterrents. Trials that combine technologies must consider that it may be difficult to identify which technologies cause bycatch reductions, where they occur, and technologies may interfere with each other. Despite limitations and poor performance in longline trials to date (Favaro and Côté 2015), we also encourage continued research on electrosensory deterrents for elasmobranchs. The unique sensory capabilities of elasmobranchs present opportunities for selective bycatch mitigation, particularly use of ferrite magnets in place of beach nets (e.g. O'Connell et al. 2014e, 2014a) and the recent development of electrode arrays and pulsed magnetic fields (Howard et al. 2018; Polpetta et al. 2021). Combinations of sensory and non-sensory mitigation options should be trialled too. For details of non-sensory options, see e.g. Werner et al. (2006). It is important to stress that we do not support implementation of these technologies in fisheries where they have not been proved effective consistently over multiple years. As of yet, there are no technologies described in this review that are generalisable to all circumstances, or can be used as the sole solution to bycatch problems. Even in cases where technologies are successful, they must be accompanied by additional measures to ensure continued success (Dawson et al. 2013; Read 2013).

We recommend further research of all sensory deterrents where there is mortality but no direct fishery application. The use of LED lights on gillnets should be investigated further, including the effects of water turbidity on results, and the ecological impacts of illuminating marine environments with LED lights. The use of cheap cut-out predator models in front of power station intakes or leaders for pound nets should be investigated for reducing sea turtle mortality (Wang et al. 2010) and further research into magnetic repellents in place of beach nets to reduce mortality across all groups, whilst still deterring potentially dangerous sharks from swimmers. Reduction of mortality here does not depend on maintaining a level of target catch as it does in fisheries, and the removal of beach nets would prevent the completely wasteful mortality of a wide variety of creatures. We hypothesise that there would be no significant increase in swimmer mortality if beach nets are removed without replacement, which would be the cheapest option, although scientific trials of this are open to potential ethical issues, community and political backlash.

Conclusion

Sensory deterrents have provided different results in a variety of contexts based on marine megafauna species composition, target catch biology, gear type, location and environmental conditions. Results do not always translate between lab and field studies. Avoidance behaviour does not always lead to permanent bycatch mitigation solutions, so directly measuring bycatch reduction in field trials is recommended. Effective non-sensory bycatch mitigation options exist, so combinations of technologies and management actions will be required to reduce bycatch in most areas. Lights on gillnets appears to be a particularly promising area for future research, as well as some electrosensory deterrents for elasmobranchs and the established acoustic deterrents for neophobic odontocetes. However, technical adaptations are insufficient to tackle bycatch on their own in most cases. Combinations of sensory deterrents should not be implemented without first proving consistently effective in field trials. Therefore, it is vital that complementary measures including time-area closures, quotas and modification of fisher behaviour should be considered in bycatch reduction programmes, alongside technical adaptations.

Advocacy and collaboration with the fishing community is critical to success. By leveraging fisher knowledge, bycatch may be reduced whilst maintaining target catch quantity and quality to support community income and food security. Sensory technologies have the potential to play some part in safeguarding marine megafauna populations and marine ecosystems, whilst preserving socioeconomic interests. The separate but associated issue of overfishing target catch is extremely important and must be addressed to prevent the collapse of entire ecosystems. However, by eliminating megafauna bycatch, the interests of science, conservation, management and the fishing community may be satisfied by conserving apex predators and keystone species to maintain balanced marine food webs. Sensory deterrents are not perfect, and their success is dependent on the characteristics of the fisheries and species present. But, along with complementary measures, there are promising avenues for future research to reduce bycatch across multiple taxonomic groups.

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