UNIVERSIDAD SAN FRANCISCO DE QUITO USFQ

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Do new techniques in longline fisheries significantly reduce bycatch rates? A review of global efforts to mitigate bycatch.

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RESUMEN

La pesquería de palangre es uno de los artes de pesca más utilizados para la captura de varias especies de atún y picudo e incluso de tiburón en las pesquerías que lo permiten. La captura incidental es uno de los mayores problemas a los que se enfrenta la pesca con palangre, ya que incluye la captura de especies vulnerables como aves marinas, tortugas marinas, tiburones y mamíferos marinos. Estas especies son atraídas por los anzuelos cebados de la pesquería y quedan heridas, atrapadas o muchas veces llegan a morir. La baja tasa de supervivencia después de ser liberadas de los anzuelos contribuye a la pérdida de biodiversidad marina. Esta Revisión Sistemática tuvo como objetivo principal el determinar si hay evidencia de que el uso de nuevas técnicas en la pesca del palangre ha logrado reducir significativamente las tasas de pesca incidental. La búsqueda se hizo tomando en cuenta el período 2000 a febrero del 2021, momento en el cual se empezó la búsqueda. Se obtuvo un total de 36 artículos para ser analizados. Casi la mitad de estudios presentaron resultados significativos reduciendo la captura incidental (17 artículos) y la mayor parte de estos (47%) reportaron reducciones en porcentajes o en números de captura. Las técnicas utilizadas se clasificaron en siete categorías: anzuelos circulares, estrategias submarinas, magnetos, líneas espantapájaros, cambios en líderes/redes, cambios en los cebos y repelentes/atrayentes. La técnica de anzuelos circulares fue la que mostró más resultados significativos al reducir la captura incidental. Mientras que el uso de magnetos requiere de más estudios para ser aprobado en las pesquerías de palangre. Se identificaron vacíos de información para ciertos grupos de especies vulnerables, como los mamíferos marinos. Finalmente, esta revisión es una línea base para evaluar qué técnicas serían las más efectivas de aplicar en Ecuador para mitigar la captura incidental en la pesquería de palangre.

Palabras clave: Palangre, espinel, captura incidental, reducción significativa, técnicas, nuevos dispositivos.

ABSTRACT

Longline fishery is one of the most common fisheries for the capture of various species of tunas, billfish and even of sharks in some fisheries. Bycatch is one of the biggest problems that longline fishing faces, as it involves the capture of vulnerable species like seabirds, sea turtles, sharks and marine mammals. These species are attracted by the baited hooks of the fishery and get injured or trapped and in many cases they die. The low survival rate after being released from the hooks contributes to marine biodiversity loss. The main objective of this Systematic Review was to determine if there is evidence that the use of new techniques in longline fisheries has significantly reduced bycatch rates. The search included studies from 2000 to February 2021, when the search was carried out. A total of 36 articles were obtained and analyzed. Almost half of the studies showed significant results reducing bycatch (17 articles) and most of these (47%) reported reductions in percentages or numbers of catches. In addition, the techniques were classified into seven categories: circle hooks, underwater strategies, magnets, tori-lines, changes in leaders/nets, changes in baits, and deterrents/attractants. The circle hook technique was the one that showed the most significant results at reducing bycatch. Meanwhile, the use of magnets requires more studies in order to be approved in longline fisheries. Information gaps were also identified for certain groups of vulnerable species, such as marine mammals. Finally, this review serves as a baseline to evaluate which techniques will be the most effective to apply in Ecuador to mitigate bycatch longline fishing.

Key words: Longline fishery, bycatch, significant reduction, techniques, new devices.

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INTRODUCTION

Fisheries are an important component of food security as a source of animal protein, and of human livelihoods as an income for billions of people that depend on this activity (Alfaro-Shigueto et al., 2010; Boerder et al., 2019). Longline fishery is one of the most common types of fisheries in the open ocean. It consists of a main line that hangs from floating buoys and that displays a series of connected baited hooks. The main line can have up to 4,000 hooks that are installed by hand on the surface; they drift before descending to depths of 25–175 m (shallow longlines) or up to 400 m (deep longlines), depending on the target species (Robertson et al., 2018; Ward et al., 2008). This type of fishery has a minimum negative impact on habitats and a low energy consumption of fossil fuels per unit of landed catch (Ingólfsson et al., 2017). However, longline fishing is of major concern in both tropical and temperate regions of the world (Ward et al., 2008), because in addition to target species, it catches non-target species, which include both incidental or bycatch species; the former can be retained for commercial use, but bycatch is usually discarded (Beverly et al., 2009).

Around the 40.4% of world’s catches is considered bycatch, with an annual estimation of 38.5 million tonnes (Davies et al., 2009; Jordan et al., 2013). There are three main reasons for discarding non-target species: 1) species are not marketable, 2) the size of the species caught is below those targeted, and 3) they are protected species (Ingólfsson et al., 2017; Patrick & Benaka, 2013). Fishermen discard species with no commercial value because they do not want to lose available hooks for target species. Individuals are discarded in poor health conditions and with a low probability of survival (Piovano et al., 2010). This contributes to overexploitation and it is one of the largest drivers of marine biodiversity loss in the world (Suuronen & Gilman, 2020). Bycatch species with higher risk of becoming endangered are K-selected species, or endemic species with restricted home ranges (Gilman, 2011).

Most longline fisheries worldwide have as target species large predatory fishes like billfish, several tuna species (*Thunnus* spp.), swordfish (*Xiphias gladius*) and even sharks (Beverly et al., 2009; Sales et al., 2010). Notwithstanding, longline fishing sometimes is treated as a non-selective fishery both for species and for their sizes (Gamblin et al., 2007). Few studies have focused on improving the species size selection with longline fishing, and it has been found that bait size is considered the most important gear component that influences selectivity (Ingólfsson et al., 2017). Increasing species selectivity in a multispecies fisheries would grant access to healthy fish stocks if the capture of over-exploited species can be reduced (Pol et al., 2008).

In longline fishing many marine species are incidentally hurt, caught or killed by the hooks in the gear (Domingo et al., 2012). Some of the most vulnerable species are seabirds, sea turtles, rays, sharks and marine mammals (Sales et al., 2010; Suuronen & Gilman, 2020). Most notably, populations of elasmobranchs and sea turtles have had drastic declines because of longline fishing (Swimmer et al., 2011). Sea turtles, for example, are at higher risk, because they spent most of the time near the surface, in the upper 100 m of the water column, which is where most of the longline fishing occurs. In addition, the overlap of fishing grounds with sea turtle migratory routes is another important factor that increases their mortality (Andraka et al., 2013; Beverly et al., 2009).

On the other hand, longline fishing impacts the structure of marine ecosystems and food webs, including a reduction of genetic diversity of many species (Suuronen & Gilman, 2020). In addition, cascading ecological changes is causing food webs modifications because of bycatch of marine megafauna (e.g. seabirds, sea turtles, marine mammals, sharks) (Lewison et al., 2004). For example, the decline of top predators like sharks increases the number of prey (e.g. seals). Then, some fish species that are food for seals, decrease, which in turn provokes an increment of phytoplankton, and a decrease of zooplankton (Gangwish, 2016). Bycatch can also disturb the normal flow of nutrients, as it could trigger anoxia, and can cause negative impacts on the benthos by accumulations of biomass on surface waters (Hall et al., 2000). Finally, high bycatch rates can also have negative socioeconomic implications for fishing communities. Bycatch of non-target species and of juveniles of target species can have negative consequences on species recruitment and population growth leading to overexploitation, which in turn affects future catches and economic profits. As a consequence, it provokes conflicts between fisheries, as they compete for depleted resources, which jeopardizes long-term resources and services for humans (Gilman, 2011).

Scientists' concern is increasing about the impact of longline fisheries. Thus, for many decades the development and application of species-selective and size-selective fishing gear and techniques have been a challenge for fishery technologists. Without changes to improve these fisheries, the number of fish discards will increase and their mortality as well (Ingólfsson et al., 2017). A responsible management does not only have to be effective at regulating target species, it should also focus on bycatch and overlooked mortalities (Gilman, 2011). It depends on the longline industry to react more forcefully to economic incentives and disincentives for more effective and viable mitigation methods (Gilman et al., 2003). Over the years many mitigation measures, such as new techniques and devices, changes in gear arrangements, and, the development in fishing strategies have been incorporated (Domingo et al., 2012). Field and laboratory experiments have been tested using chemical, acoustical, and visual deterrents to determine cost-effective approaches to prevent bycatches (Bostwick et al., 2014). However, there is no consensus if these initiatives have been effective, because the techniques have to be tested in each fishery evaluating bycatch reduction in order to be approved (Coelho et al., 2015; Curran & Bigelow, 2011; Fernandez-Carvalho et al., 2015). To fill this gap, the present study aimed to determine, through a systematic review, if there is evidence that the use of new techniques in longline fisheries has significantly reduced bycatch rates.

OBJECTIVES

General: Compile relevant literature on the methods, strategies or new techniques that have been applied to longline fisheries to reduce bycatch.

Specifics:

- Compare the results obtained in the studies of the different techniques applied to reduce bycatch.
- Verify if the studies show a significant difference in the rate of bycatch before and after using new techniques or devices.
- Identify global patterns of studies reducing bycatch rates.
- Discuss the most common techniques applied in the studies to reduce bycatch.

METHODS

Databases

The present work was carried out through a systematic review of existing scientific literature from three databases: Scopus, ScienceDirect, and Bycatch.org. However, some articles from the Google Scholar search engine that were not found in the Systematic Search were added to complement the information.

Scopus and ScienceDirect databases were selected because the university (USFQ) allows students to create an account, which enables access to different uses of the databases. In addition, they compile articles on different topics, from various journals, and most of them are open access. Finally, Bycatch.org (https://www.bycatch.org/) is a Consortium that supports collaborative scientific research and industrial fishing, allowing effective solutions to reduce by-catch of endangered species (Consortium for Wildlife Bycatch Reduction, 2014); this database made it possible to obtain articles that are open access and closely related to the subject of this study.

Systematic Search

The search protocol was established based on the research question: “Is there evidence that the use of new techniques in longline fisheries has significantly reduced bycatch rates? Six criteria were considered for selecting the articles: (1) articles that focused on the consequences of longline fisheries; (2) articles that contained data or evidence of changes in bycatch rates; (3) articles that were based on the field or were experimental studies (no reviews, no manuals, no reports or books); (4) articles mentioning at least one technology or method to improve the longline fishery; (5) studies that were carried out since 2000; and (6) articles that were open access and in English.

In mid-January of 2021 searches were undertaken with topic-related terms and Boolean operators in Scopus and ScienceDirect. Four main aspects were taken into consideration: Fishery, Problem, Intervention, and Study type, and the search terms were: “longline fishery”, “bycatch”, “mitigate bycatch”, "new techniques”, and, “bycatch reduction devices”. Synonyms of these were used and combined to achieve more results (Table 1). Bycatch.org database search was made with the different filters provided by its search engine: by selecting the type of fishing gear with lines or hooks, and by only including field studies of longline fisheries related to bycatch. Furthermore, this search included all the types of reduction techniques and all species that are usually caught incidentally.

The search using the terms and combinations in the three search engines retrieved 278 articles: 93 in Scopus, 45 in ScienceDirect, and 140 in Bycatch.org. After this, a five-level PRISMA was made (Fig. 1). This flowchart allowed visualizing the number of articles included/excluded in the systematic review. The first level included the total of articles found on each database, without any exclusion criteria. The second level discarded duplicates, non-open access, and articles that were not related to the topic just by reading the title. In the third level some articles were excluded because of not fulfilling the inclusion criteria described above; this was done by reading the Abstracts. Finally, the two last levels included the articles that were completely read, and the ones that were used for the analysis.

Manual Search

Nine articles from Google Scholar that were relevant to the research and that were not obtained in the Systematic Search were also included in the analyses. These articles were found within the references of the articles of the other databases.

Comparing the techniques to reduce bycatch rates

Studies were classified according to the bycatch reduction techniques applied. Then, to compare the results and to identify trends, the following components were extracted from each study: type of technique, target and bycatch species, significant/non-significant results obtained, region, and the correspondent citation (Table 2).

To score the studies as showing a significant ("Yes") result in reducing bycatch with the techniques applied, they had to explicitly mention in their results a significant statistic (e.g. a p-value or a reduction in %) and/or the phrase "significant bycatch reduction" of the non-target species in the study. If a study did not present one of these two criteria, it was considered a "No" study, i.e. to show a lack of evidence for significantly reducing bycatch rates of non-target species (Table 2).

RESULTS AND DISCUSSION

After having identified 278 papers with the Systematic Search, 251 did not fulfill the study inclusion criteria, remaining 27 articles to analyze, plus nine additional articles found manually, yielding a total of 36 articles. The articles mentioned several ways to reduce bycatch in fisheries, for example by banning fishing in certain areas or seasons, modifying gear, using bycatch reduction devices, creating incentives for fishermen, and modifying practices or fishing methods (Patrick & Benaka, 2013). Nevertheless, measures like fishing quotas or protected species banned to fishing do not assure that incidentally caught individuals are returned alive to the ocean (Afonso et al., 2011). The implementation and development of more specific mitigation techniques have been carried out in just a few of all studies, which were the ones included in the analyses and are described in the next sections.

Results Reducing Bycatch Rates

In this review, seven categories of bycatch reduction techniques were identified across the 36 articles (Table 2): circle hooks (13 articles), underwater strategies (6 articles), magnets (6 articles), tori-lines (4 articles), net sleeves and leaders (3 articles), changes in baits (2 articles), and deterrents and attractors (2 articles).

Of the total of 36 articles, 17 reported significant results of reducing bycatch in longline fisheries, while 15 did not. A third result was added as some articles found significant results for some species and not for others; four articles fall within this category named “Some groups” (Fig. 2). Two articles within this category (Pacheco et al. & Swimmer et al., 2011) presented a significant reduction of bycatch for sea turtles using circle hooks, but for some shark species (e.g. crocodile shark) and rays they obtained insignificant results. The two other studies using magnets presented significant results reducing bycatch only for scalloped hammerhead pups (Hutchinson et al., 2012), but not for juvenile/adult scalloped hammerhead sharks, and by using barium-ferrite permanent magnets for elasmobranchs (O'Connell et al., 2011).

On the other hand, three subcategories were identified for those studies that reported significant results: 1) studies that reported significant statistics (29%), 2) studies that reported a percentage or a number in reducing bycatch rates (47%), and 3) studies (24%) that reported the word “significant” in their results (Fig. 2). Each study with its evidence is summarized in Table A.

Global efforts in bycatch reduction techniques

The number of studies varied among different regions of the world oceans (Figs. 3&4). The Western Atlantic and the Eastern Pacific were the regions with the highest number of studies in this review (50%, 18 articles). On the contrary, the three regions with the lowest numbers were the Mediterranean Sea (14%, 5 articles), the Eastern Atlantic (11%, 4 articles), and the Indian Ocean (8%, 3 articles).

In terms of the techniques applied to reduce bycatch, in four of the six global regions circle hooks was the technique mostly reported, while, changes in baits were only reported in two regions and presented a low percentage (11%) in both, even though these regions (Western Atlantic and Eastern Pacific) were the ones with more articles (Fig.4).

Discussion of the most common techniques applied in the studies

Circle hooks was the technique of most articles, and also the one with the majority of studies presenting significant results (7-9 articles). Underwater strategies presented the same portion of significant and non-significant results in the studies. Magnets, on the other hand, showed a higher number of studies with significant results, however only for certain groups of species. Finally, only two techniques (circle hooks and magnets) reported studies in which only certain species presented a significant reduction in bycatch (Fig. 5).

Circle Hooks

This technique is one of the less expensive to cut down incidental fishing mortality (Afonso et al., 2011). The shape of circle hooks is circular or oval depending on the fishery (Curran & Bigelow, 2011). This gear modification consists in adjustments in the terminal tackle from a traditional J-style hook. Its difference with circle hooks is the alignment of the point with the shank. Circle hooks have a point aligned perpendicular to the shank, while J-style hooks have the point parallel to the shank (Afonso et al., 2011; Cooke & Suski, 2004). Circle hooks reduce deep hooking that affects internal organs, causing the death of the caught fish (Özgül et al., 2015; S. Piovano et al., 2009). A reason to the decrease in deep hooking is the width of the hook that acts as a barrier for its entire ingestion. Smaller-mouthed species, such as dolphinfish and pelagic stingrays, tend to get less captured (Curran & Bigelow, 2011; Swimmer et al., 2011). Swimmer et al. (2011), inserted a wire as an appendage into their circle hooks, which added a physical barrier that prevented ingestion, as it extended the width dimension of the hook. This superficial hooking could be explained because circle hooks tend to move over soft tissue and swivel as the eye of the hook quits from the mouth, lodging in the jaw. This provokes lower mortality rates during haulback, increasing the probability of species post-release survival (Pacheco et al., 2011).

Of all techniques identified in this review, particular attention in longline fishing has been given to circle hooks. Nine of 13 articles demonstrated significant results, which suggests that the majority of studies using circle hooks significantly reduced mortality rates (Afonso et al., 2011; Andraka et al., 2013; Coelho et al., 2015; Curran & Bigelow, 2011; Fernandez-Carvalho et al., 2015; E. Gilman et al., 2007; Özgül et al., 2015; Pacheco et al., 2011; S. Piovano et al., 2009; Piovano et al., 2010, 2012; Sales et al., 2010; Swimmer et al., 2011). They are specifically employed to reduce the bycatch of sea turtles (e.g., leatherback, loggerhead, green sea turtle) and sharks (e.g., blue, oceanic whitetip, silky). For example, Swimmer at al. (2011) found that 52% less ($p<0.0001$) sea turtles were caught with circle hooks as opposed to J-style hooks. It was also observed that lower bycatch rates of non-target species actually increased the catch of target species when using circle hooks. For example, Özgül et al. (2015) found both an increase in catches rates and of the size of the swordfish *Xiphias gladius*, when using circle hooks instead of J-style hooks. Similarly, higher catch rates of the bigeye tuna have been documented using circle hooks, although the reasons are not well understood (Pacheco et al., 2011).

Contrary to these results, some studies have not found differences in catches of target species with circle hooks (as opposed to J-style), or have found inconsistent patterns. For example, the number, length and total weight of target species (e.g. swordfish and bigeye tuna) were similar with both hooks styles in Curran & Bigelow, (2011) and in Piovano et al. (2009), while Swimmer et al. (2011) found a 30% reduction of target species catches when using circle hooks. Furthermore, Sales et al. (2010) found an increase of tuna and blue sharks (legal fishing) catches, but also a 14.2% decrease the number of swordfish caught. Similarly, Andraka et al. (2013) reported a significant increase of blue and silky shark catching rates in Costa Rica and in Ecuador with circle hooks. This meant a benefit for fisheries because these species are allowed for fishing in Costa Rica and commercialized in Ecuador (if incidentally caught), but at the same time these are vulnerable species (Rigby et al., 2017, 2019). It seems thus that in many studies not all target species or bycatch species present similar patterns in the application of this technique (Gilman et al., 2007), it is thus important to consider several aspects before implementing it.

Underwater Strategies

The underwater setting of the longline gear is one of the strategies that showed significant results in mitigating bycatch. This method consists in deploying the gear at deeper depths (Cambiè et al., 2013). Generally, these changes on gear deployment to eliminate shallow hooks have to take into consideration the vertical distribution of hooks and the patterns of species distribution (Beverly et al., 2009). To improve this technique, devices like underwater setting chutes and underwater bait setting capsules have been developed for longline fishing.

Underwater setting chutes consist of large metal chutes attached to the stern. These devices allow deploying the baited hooks underwater. A machine sets the main line, then the baited hooks are dispatched through the underwater setting chute (Gilman et al., 2003). On the other hand, underwater bait setting capsules consist of a tool that originated from the New Zealand longline fisheries. This machine, which is computer and hydraulically operated, sets baited hooks individually underwater (Robertson et al., 2018) and below the dive depths of albatrosses and petrels. The principal components of this underwater tool are: a winch assembly (containing two hydraulic motors), a track assembly (a stainless steel track and the head unit of the track), a bait capsule, a capsule docking cart (the base of the capsule is a saucer-shaped spring loaded trap door), and two control units (the systems interface unit and the mode selection unit) (Robertson et al., 2014).

Three of six studies (Fig. 5) using underwater strategies reported significant results in reducing bycatch for many species of sea turtles, seabirds, and sharks (Beverly et al., 2009; Cambiè et al., 2013; E. Gilman et al., 2003; Pham et al., 2014; Robertson et al., 2014, 2018). The group that benefited the most with deeper longlining were the sea turtles, because baited hooks were removed from their foraging ranges (Beverly et al., 2009). The implementation of this technique significantly reduced their bycatch of up to 40% in surface waters (Cambiè et al., 2013). Similarly, chutes decreased seabird contacts with fishing gear up to 95% compared with the traditional gear (Gilman et al., 2003).

Regarding how the catches of target species have been influenced with this technique, positive reactions have been reported. For example, swordfish catches were not affected, because swordfish have vertical movements through the water column. Furthermore, the size of their catches increased, because larger individuals tend to swim at deeper depths. Thus, the number of juveniles caught decreased, which may also prevent overfishing (Cambiè et al., 2013).

The availability of hooks in deeper waters provoked increases in catches of deeper species such as bigeye tuna (Beverly et al. 2009), as well fisheries efficiency gains between 7.5% and 29.6% when using seabird mitigation methods, which grants an economic incentive to use them (Gilman et al., 2003). Furthermore, in some fisheries the number of non-target species with commercial value such as marlin species, dolphinfish, and wahoo has decreased, although this has been viewed as an economic disadvantage by the fisheries sector (Beverly et al., 2009). Finally, deep longline fishing is a great alternative to trawl fisheries, as they avoid habitat destruction of benthic communities.

Magnets

Permanent magnets have been used to have a repellent effect for sharks. This aftermath occurs because elasmobranchs use their electro sensory system through the ampullae of Lorenzini to recognize movements of their prey (Porsmoguer et al., 2015). The ampullary organs identify low frequency bioelectric fields provided by preys in a narrow range (Godin et al., 2013). Generally, ampullary organs in sharks involve hundreds of receptor cells that are located in the head. Nonetheless, receptors are also found in pectoral fins of skates and rays (Collin & Whitehead, 2004). These metals or magnets do not have an effect on teleost species because they lack Lorenzini ampullae. Thus, the catch of target fish species such as billfish or tunas should not be altered (Godin et al., 2013; Hutchinson et al., 2012; O'Connell et al., 2014).

The magnets create a heavy electrical stimulus overwhelming the elasmobranchs' electro sensory system, which drives them away from baits, and modifies their swimming and feeding behaviors (Godin et al., 2013; O'Connell et al., 2011; Porsmoguer et al., 2015). These magnets can be made of different elements such as praseodymium, lanthanide metals, rare earth magnets, neodymium-iron-boron or barium-ferrite, and their shape is like a cylinder (O'Connell et al., 2011).

Three of six studies (Fig. 5) using magnets exhibited significant results reducing non-target species bycatch (Hutchinson et al., 2012; O'Connell et al., 2011, 2014), with one of them showing significant results only if using barium-ferrite magnets (O'Connell et al., 2011), and another showing a significant bycatch reduction of the Spiny Dogfish (*Squalus acanthias*) when using SMART hooks that are semi-circle hooks with attached magnets (O'Connell et al. 2014). On the contrary, some studies demonstrated an attractor effect for sharks. For example, Porsmoguer et al. (2015) registered higher CPUEs (Catch Per Unit Effort) for blue sharks (*Prionace glauca*) using hooks with magnets. Furthermore, they also noticed that the hooks were still magnetized after their extraction, and that field experiments yielded different results from laboratory studies (Porsmoguer et al., 2015). The same species (e.g. *Squalus acanthias*) using the same electromagnetic element (Nd2Fe14B and Neodymium (Nd) metal) showed a deterrent effect in lab trials (Jordan et al., 2011 in Porsmoguer et al. 2015) but no in field experiments (O'Connell et al., 2011 in Porsmoguer et al. 2015).

As mentioned above, magnets do not affect catches of teleost species, but Godin et al. (2013) found a significant reduction of swordfish catches (48% less individuals), which provided evidence of hooks treated with Nd/Pr having a negative effect. Thus, it is important to take into account the behavior, the habitat conditions, species sizes and maturity, and other aspects that could affect catches and the conservation status of target and bycatch species while using magnets (O'Connell et al., 2011). Similarly, Hutchinson et al. (2012), found that hammerhead shark pups were more sensitive to hooks treated with lanthanide metals making them more susceptible to bycatch than other species. Nevertheless, there is evidence of learned behaviors, which allows individuals becoming increasingly tolerant to the momentary irritation of the magnetic fields. Because of this, magnets and electropositive metals will show weak effects on the feeding behavior of sharks, demonstrating no significant effects on reducing bait predation (Robbins et al., 2011).

Tori-lines and Weighted Branch Lines

These techniques are commonly used to mitigate seabird bycatch in longline fishing. Some studies describe these methods as cost effective, because they reduce seabird catches, decrease bait loses, and do not need meaningful changes in fishing gear or vessels. Thus, fisheries do not have economic losses while protecting seabirds (Sato et al., 2012, 2013). Tori-lines are known also as bird-scaring lines that scare away birds from the zones where baits are reachable. There are two types of tori-lines depending on the streamers: one with long streamers and another with light or short streamers (Melvin et al., 2014; Sato et al., 2012). Most bird-scaring lines are composed of a line with many streamers that prevent seabird attacks on baited hooks until the lines submerge. However, there also exists the possibility of including two tori-lines together, called paired tori-lines (Sato et al., 2013). These bird-scaring lines are generally attached on the upper deck to port and starboard of the stern (Melvin et al., 2014).

There is a complementary technique to bird-scaring lines, which consists in weighting branch lines. This method is designed with a weighted section that has to be inserted into the monofilament area of the branch line at a certain distance from the hook (Melvin et al., 2013, 2014). This weighted branch line enables baited hooks to sink more rapidly, reaching depths below the foraging areas of seabirds (Melvin et al., 2014).

Half of the studies (two of four) employing tori-lines presented significant results reducing bycatch (Fig. 5). Having said that, Sato et al. (2012) mentioned that tori-lines do not prevent the mortality of seabirds, but its implementation displaced seabirds further away from the vessels. Furthermore, in this study researchers found that paired tori-lines had a significant effect in reducing seabirds' aggregations compared to the use of single tori-lines (Sato et al. 2013). However the authors could not conclude if the effect of paired tori lines were statistically significant at reducing bycatch because sample sizes were too small (Sato et al., 2013).

The two tori-lines studies displaying significant results mitigating bycatch had in common the use of weights in branch lines for a faster sink. Also, they found a higher mortality of seabirds during the daylight hours of the longline fishing (Melvin et al., 2013, 2014). The combination of mitigation measures such as nighttime setting, weighted branch lines and bird-scaring lines, resulted in zero seabirds per 1000 hooks in Melvin et al. (2014). For both studies, the catches of target species were not negatively affected implementing these measures. Thus, implementing all these measures at the same time will raise positive effects reducing seabird bycatches.

Net Sleeves and Leaders

Net sleeves were developed to mitigate the problem of killer whales and other toothed whale interactions with longline fisheries. Moreno et al. (2008) used a technique that consisted in setting a buoyant net sleeve (cachalotera in Spanish) on the vertical hook lines. This net slides up and down the line, so when a fish is captured the sleeve can slide down the line protecting the hook and the fish. Rabearisoa et al. (2012) have used net sleeves of two types: the spider and the sock. The difference between them is that the spider has legs of 1200 mm long, and the sock covers the fish totally to protect them against predators. In the first study (Moreno et al., 2008), the percentage of catch damaged or predated by killer whales was twice less applying this new technique. Furthermore, they noticed that after approximately one week marine mammals disappeared from chasing boats in order to predate on hooked fish. However, they did not mention a significant reduction of bycatch of sperm and killer whales.

In addition, modifications in the main and branch lines have also been made. Replacing wire leaders with nylon have demonstrated lower catches for sharks and species like the snake mackerel, because they have sharp teeth and are able to cut off the lines and scape from the leaders (Ward et al., 2008).

Within this category only one study (Fig. 5) using nylon leaders (Ward et al., 2008) recorded significantly less catches of non-target species (e.g. sharks and snake mackerel); almost 50% less. On the other hand, catches of the bigeye tuna of the south-western Pacific region increased using nylon leaders; it is hypothesized that they avoid bait attached to wire leaders (Ward et al., 2008).

Regarding target species, a higher CPUE was noticed than the previous four years (Moreno et al., 2008). Thus, these techniques clearly do not affect target catches and will not represent an economic loss for the fishery of the Southeastern Pacific. Furthermore, the two types of net sleeves manipulated in Rabearisoa et al. (2012) did not show a reduction of the caches of target species (e.g. swordfish and tunas) in the South-west Indian Ocean. In this study swordfish were less protected than tunas because of their bill, with the device getting stuck on the top of their heads (Rabearisoa et al., 2012). To correctly apply this technique new trials should make changes in the length of net sleeves in order to maximize its success for all species.

Changes in Baits

Significant changes in baits consist on modifying bait color, using manufactured baits, and using different bait species. Longline fisheries, such as the Hawaiian swordfish fishery, has used fish instead of squid, which reduced bycatch rates of sharks (Gilman et al., 2007). Similarly, and in order to deter turtles from feeding from hooks, Swimmer et al. (2005) used squid baits that were soaked with 1% solution of blue food coloring. Finally, commercially manufactured baits have also been developed. Pol et al. (2008) established the bait called Norbait, which is composed of a gelling agent and Atlantic mackerel and it resembles a sausage. Definitely, bait type has a great influence on species selectivity in longline fishing, being the key aspect of this activity (Løkkeborg et al., 2014; Pol et al., 2008).

Only one study using changes in baits presented significant reductions of bycatch species (Fig. 5). Commercial manufactured bait (Norbait) significantly reduced the catch of the Atlantic cod, a non-target species from Northwest Atlantic, but this technique did not completely eliminate the capture of this species (Pol et al., 2008). On the other hand, the use blue-dyed bait documented in this review (Swimmer et al., 2005) did not reduce bycatch of sea turtles in Eastern Tropical Pacific (ETP). However, these results came from a trial done in the field. The same experiments were run in lab conditions, which yielded significant results; thus, it is necessary to carry out more experiments applying dyed baits in the field (Swimmer et al., 2005).

Deterrents and Attractors

The purpose of these methods is to prevent bycatch before endangered or non-target species take the bait and get caught. Afonso et al. (2021) used egg-shaped light attractors in the terminal part of the branch lines of baited hooks. To prove the efficacy in the fishery they selected three colors with different wavelengths: green (525nm), blue (465nm), and white light, because marine species are able to identify different wavelengths. These color-specific lights are cheap and easy to implement to mitigate bycatch in longline fishing (Afonso et al., 2021).

On the other hand, fish oil biogenic deterrents are a technique used to specifically mitigate seabird bycatches. Pierre & Norden (2006) used oil extracted from shark's livers that came from the shark trade. This oil is dripped continuously from a plastic container at the stern of the vessel (Pierre & Norden, 2006). This biogenic technique was developed to decrease the number of seabirds chasing longline vessels, without having negative effects in their welfare.

Two studies were identified using this technique (Figure 5). Both studies reported significant results reducing bycatch. Alfonso et al. (2021) found that different colors attract specific species: green lights attracted all species, which actually increased the total catch and did not reduce the bycatch. White and blue lights attracted less species, such as sea turtles and blue sharks, respectively. On the other hand, Pierre & Norden (2006) found no negative effects on target species, and their technique (fish oil) significantly diminished the amount of seabirds following vessels and the number of dives seabirds executed behind them (Pierre & Norden, 2006). Thus, both techniques bring positive effects at reducing bycatch, but they operate for specific non-target species.

RECOMMENDATIONS

Of the 36 studies presented in this review some limitations and recommendations have been identified. The recommendations presented in this section will help stakeholders to adopt or improve the mitigation measures for the longline fisheries around the world oceans.

Circle Hooks

A limitation of using circle hooks is that in certain cases the catches of target-species will be maintained but not increase, which would be perceived as a disincentive for the fishing industry because of the investment in circle hooks (Swimmer et al., 2011). Nevertheless, circle hooks implementation is economic and quickly to establish (Afonso et al., 2011). Another incentive for fishermen is that they will save time because fewer species would need to be discarded. In addition, the use of circle hooks would increase the safety of the crew, by avoiding interactions with species such as stingrays. Another benefit is that circle hooks reduce bait competition, because many species have smaller mouths and circle hooks are wide (Afonso et al., 2011; Curran & Bigelow, 2011; Fernandez-Carvalho et al., 2015; Piovano et al., 2010). Therefore, there are both disincentives and incentives to adopt this mitigation technique in longline fishing.

Many studies have suggested doing more research on measures to reduce post-release bycatch mortalities. Even though species catches with circle hooks may not die from explicit injuries, they may suffer of physiological stress induced by the capture (Afonso et al., 2011; Andraka et al., 2013; Özgül et al., 2015; Sales et al., 2010). In addition to the shape of the hooks, future experiments should consider other attributes, such as hook size, bait type, fishing depths, time of setting, and soaking time. For example, Andraka et al. (2013) in Costa Rica found no significant reduction in catch rates of sea turtles using 16/0 circle hooks sizes comparing to J-style hooks. Unlike this, 18/0 circle hooks presented a significant reduction (75% less captures) in comparison with J-style hooks. Furthermore, it is important to consider that many species such as sea turtles present different catching rates among seasons and oceans (Coelho et al., 2015).

Underwater Strategies

The operations fleets using underwater setting capsules to reduce seabirds bycatch are meant to be used in coastal areas. Thus, trials in high seas should be tested before applying them in longline fisheries (Robertson et al., 2014). A limitation of applying these underwater techniques is that small size vessels are not able to use this gear, because they could not reach the required distances to fishing in greater depths. Thus, for future studies it will be useful to experiment at different depths to benefit all fisheries, in order to reduce seabird mortality (Cambiè et al., 2013; Robertson et al., 2018).

Magnets

Species maturity and size are important characteristics to take into consideration when using magnets. Moreover, repellent effects of magnets do not apply for all species of sharks. Hutchinson et al. (2012) suggested putting more effort in research linking neuroanatomy and foraging ecology of sharks. This would also contribute in the development of new techniques and species deterrents (Hutchinson et al., 2012; O'Connell et al., 2011; Porsmoguer et al., 2015). Furthermore, two studies recommended considering the level of hunger of shark species that could influence the repellent effects. Also, high densities of local species (e.g. blue sharks) might raise competition and aggressiveness, limiting the effects of electropositive metals. Also, species and region where the trials occur could affect the desire results. Choosing the right place to apply this technique is important, because electropositive metals are not so effective in pelagic zones as in coastal regions (Godin et al., 2013; O'Connell et al., 2014).

Tori-lines

When applying tori-lines all the studies agreed to take into consideration the moon phase, lighting, season, and latitude of fishing, as all these factors can affect the night setting of the techniques (Melvin et al., 2013, 2014; Sato et al., 2012, 2013). Furthermore, considering that heavy materials display complex movements, it is necessary to analyze the effectiveness of the streamers motion (Sato et al., 2012). This would avoid entanglements of tori-lines streamers, that could affect seabirds and pose a hazard for crew members.

Net Sleeves and Leaders

The application of net sleeves and leader modifications have to take into account the relatively high costs. Nonetheless, the increased catchability of target species (e.g. bigeye tuna), and the long lasting life of net sleeves could compensate the costs, incrementing the long term financial returns (Moreno et al., 2008; Rabearisoa et al., 2012; Ward et al., 2008).

Changes in Baits

Regarding to bait modifications, more physiological studies of color vision of various species are needed. Experiments have to focus on species chemosensory capabilities to obtain greater results at reducing bycatch (Pol et al., 2008; Swimmer et al., 2005). Moreover, it is necessary a better understanding of the effects of light lures and lunar illumination on the behavioral response of pelagic species. These kinds of techniques have to be carefully assessed, because they might bring environmental impacts to marine wildlife and also to humans, due to their highly toxic contents (Afonso et al., 2021; Pierre & Norden, 2006).

In General

- Future studies should consider filming non-target species' behaviors and interactions with the baits while applying the new techniques. This will serve to clarify if feeding strategies are related to size and shape of the hooks (Pacheco et al., 2011; Robbins et al., 2011).

- Products of fisheries applying new techniques (e.g. relatively large circle hooks, instead of J-hooks) should be labeled, in order to provide consumers an incentive in buying those products
- Another future consideration is fleet communication. This has to be implemented because sharing the position of a non-target species to the rest of the fleet would allow real time prevention of bycatch hotspots (Gilman et al., 2007).
- All studies revealed that one of the most difficult considerations is to maintain good relationships and an open communication with stakeholders in order to improve the implementation of bycatch reduction devices (Piovano et al., 2012). If all stakeholders have an active participation in research, more effective and practical solutions to reduce bycatch in longline fishing will be possible. Similarly, the involvement of the fisheries sector is crucial. It was striking that in this review only one study presented a complete trial that involved fishermen. Piovano et al. (2012) considered three steps for collecting data. The first one involved fishermen in talks about sea turtle conservation and the use of circle hooks. Then, fishermen candidates were selected based on their longline fishing experience, so they could test the new methodology in their vessels with their commercial fishing gear. Finally, fishermen were interviewed to record opinions about the use of circle hooks in their fisheries. Results of interviews demonstrated that 56% of fishermen would incorporate this bycatch reduction technique if it did not generate a decrease in target species capture. Nevertheless, the majority of fishermen requested for economic incentives (Piovano et al., 2012). Thus, it is important to involve the government when implementing these techniques.

- It is important to consider that all studies of this review only considered the mortality of bycatch species during hauling. Only one study estimated the post release mortality of blue sharks using archival satellite pop-up tags (Campana et al., 2009). Campana et al. (2009) displayed a post-release mortality of 19% for blue sharks; they established a strong link between the post release mortality and the hook type used for longline fishing. Applying satellite tags would corroborate if the techniques (e.g. circle hooks and nylon leaders) would contribute to post release survival of bycatch species after handling practices.

CONCLUSIONS

After analyzing the 36 articles included in this review, the general and specific objectives were fulfilled. It was found that there is evidence in studies reporting significant reduction in bycatch using new techniques in longline fishing. First, circle hooks, underwater strategies, and deterrents/attractors were recognized as the most efficient techniques in terms of ecological, economic, and social aspects. On the contrary, magnets are the least recommended technique before more behavior/foraging ecology and neuroanatomy studies are carried out. Furthermore, it was identified that the application of biogenic oils was the less documented technique, and the one that mostly needed to be further researched because of its positive results at reducing bycatch.

One limitation of this review was the relative low number of studies included. It is thus recommended to use more databases to obtain more results. Furthermore, a meta-analysis should be done; this could yield more confidence to prove if the mitigation techniques are efficient in reducing bycatch or not. An example of a meta-analysis (focused on seabirds) is reported in Avery et al. (2017), where they even found an increase of target species catches, while reducing seabirds' bycatch. Moreover, doing a meta-analysis focused on different regions of the ocean will contribute in identifying which techniques are better for each region and even for each fishery.

It is also important to remark that this review focused more in the techniques giving short-term results that had as a principal objective to reduce bycatch of species that are not marketable or are of concern. It included the majority of techniques that have been developed to mitigate the bycatch of most common species in all regions of the world, while others have focused more on the techniques to reduce bycatch of specific species, for example of seabirds, one of the groups mostly studied (Avery et al., 2017; Løkkeborg, 2011). On the contrary, the less studied group in longline fishing was marine mammals. Although, efforts are well known for other fisheries (e.g. gillnets), the number of studies of this group were few and focused more on killer whales interacting with target species. Thus, more research of techniques to reduce marine mammals bycatch in longline fishing is needed.

Finally, since 1994 artisanal fisheries in Ecuador started to operate in wooden "mother ships" with the purpose of intensifying fishing effort, expanding their fishing range until reaching the Galápagos Archipelago, and implementing more hand-lines and longline fishing (Alava et al., 2019). This review serves as a first step to evaluate the techniques that could be the mostly effective to apply in Ecuador in order to mitigate bycatch, and more importantly if stakeholders want to reincorporate this fishery in the Galápagos Marine Reserve.

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TABLES

Table 1. Combinations of the search terms used in two of the databases.

Database	Search query
Science Direct	(longline OR "longline fishery") AND (bycatch OR "bycatch rate" OR "incidental catch" OR "artisanal fishery") AND ("mitigate bycatch" OR "reduce bycatch") AND ("more efficient" OR "bycatch reduction devices")
Scopus	(TITLE-ABS-KEY ((longlin* OR "longline fishery" OR longlining OR "longline fishing" OR "artisanal fishery")) AND TITLE-ABS-KEY ((bycatch* OR "bycatch rate" OR "incidental catch" OR by-catch*)) AND TITLE-ABS-KEY ((improve OR "more efficient" OR "new techniques" OR enhance OR develop OR "bycatch reduction devices")))

Table 2. Summary of the main bycatch reduction techniques of the chosen studies.

Technique	Principal target species	Principal bycatch species	Significant Results reducing bycatch	Region	References
Circle Hooks	Tunas, swordfish, billfishes	Sharks, skates, rays	No	Western equatorial Atlantic	Afonso et al., 2011
	Swordfish	Sharks, rays	No	Mediterranean Sea	Özgül et al., 2015
	Dolphinfish, tunas, billfishes, sharks	Sea turtles	Yes/No	Eastern tropical Pacific (ETP)	Swimmer et al., 2011
	Swordfish, bigeye tuna yellowfin tuna	Sea turtles, rays, sharks	Yes/No	Western equatorial Atlantic	Pacheco et al., 2011
	Swordfish	Loggerhead sea turtles	Yes	Mediterranean Sea	Piovano et al., 2009
	Tunas, blue sharks, swordfish, dolphinfish	Sea turtles	Yes	South-western Atlantic	Sales et al., 2010
	Bigeye and yellowfin tuna, swordfish, dolphinfish	Blue shark, pelagic stingray	Yes	Central Pacific	Curran & Bigelow, 2011
	Swordfish	Sea turtles	No	Mediterranean Sea	Piovano et al., 2012
	Swordfish	Pelagic stingray	Yes	Mediterranean Sea	Piovano at al., 2010
	Tunas, billfishes, wahoo, swordfish	Sea turtles	Yes	Eastern Pacific	Andraka et al., 2013
	Swordfish, Bluefin tuna	Sea turtles	Yes	Tropical Northeast Atlantic	Coelho et al., 2015
	Swordfish, bigeye and Bluefin tuna	Sea turtles	No	Tropical Northeast Atlantic	Fernandez-Carvalho et al., 2015
	Swordfish, tuna,	Sea turtles,	Yes	Central Pacific	Gilman et al.,

Underwater strategies	wahoo, opah	sharks			2007
	Swordfish, dolphinfish, Atlantic Bluefin tuna	Sea turtles	Yes	Mediterranean Sea	Cambiè et al., 2013
	Bigeye and yellowfin tuna, albacore, swordfish, billfish	Longnose lancetfish, snake mackerel, stingray, sharks	No	Central Pacific	Beverly et al., 2009
	Tunas, swordfish	Seabirds	Yes	Central Pacific	Gilman et al., 2003
	Yellowfin and albacore tuna, swordfish	Seabirds	Yes	South-western Atlantic	Robertson et al., 2018
	Cod and haddock	Seabird, deep-sea sharks	No	Northeastern Atlantic	Pham et al., 2014
	Tuna, billfish	Seabirds	No	South-western Pacific	Robertson et al., 2014
Magnets	Swordfish, shortfin mako, tunas	Blue shark	No	Northeastern Atlantic	Porsmoguer et al., 2015
	Tuna, marlin, snapper	Sharks, skates, rays	Yes/No	Northwest Atlantic	O'Connell et al., 2011
	Swordfish	Blue sharks	No	Northwest Atlantic	Godin et al., 2013
	Tunas, billfishes, dolphinfish	Sharks	Yes/No	Pacific (three regions)	Hutchinson et al., 2012
	Yellowtail kingfish	Galapagos sharks	No	South-western Pacific	Robbins et al., 2011
	Haddock, Atlantic halibut and cod	Spiny dogfish, elasmobranchs	Yes	Northwest Atlantic	O’Connell et al., 2014
Tori-lines	Tunas	Seabirds	No	North-western Pacific	Sato et al., 2012
	Bigeye, yellowfin and albacore tunas, billfishes	Seabirds	Yes	Indian	Melvin et al., 2014
	Tunas, swordfish	Seabirds	No	North-western Pacific	Sato et al., 2013
	Bigeye and yellowfin tuna, albacore, swordfish	Seabirds	Yes	Indian	Melvin et al., 2013
Net Sleeves and leaders	Bigeye tuna, yellowfin tuna, swordfish	Sharks, snake mackerel	Yes	South-western Pacific	Ward et al., 2008
	Austral hake	Killer whales, marine mammals	No	Southeastern Pacific	Moreno et al., 2008
	Tunas, swordfish	Toothed whales	No	South-West Indian	Rabearisoa et al., 2012
Changes in Baits	Mahi mahi, tunas	Sea turtles	No	Eastern Tropical Pacific (ETP)	Swimmer et al., 2005
	Haddock	Atlantic cod	Yes	Northwest Atlantic	Pol et al., 2008
Deterrents and Attractors	Swordfish, yellowfin and bigeye tuna, albacore	Blue shark, sea turtle, marlins, elasmobranchs	Yes	Western equatorial Atlantic	Afonso et al., 2021
	Snapper	Seabirds	Yes	South-western Pacific	Pierre & Norden, 2006

FIGURES

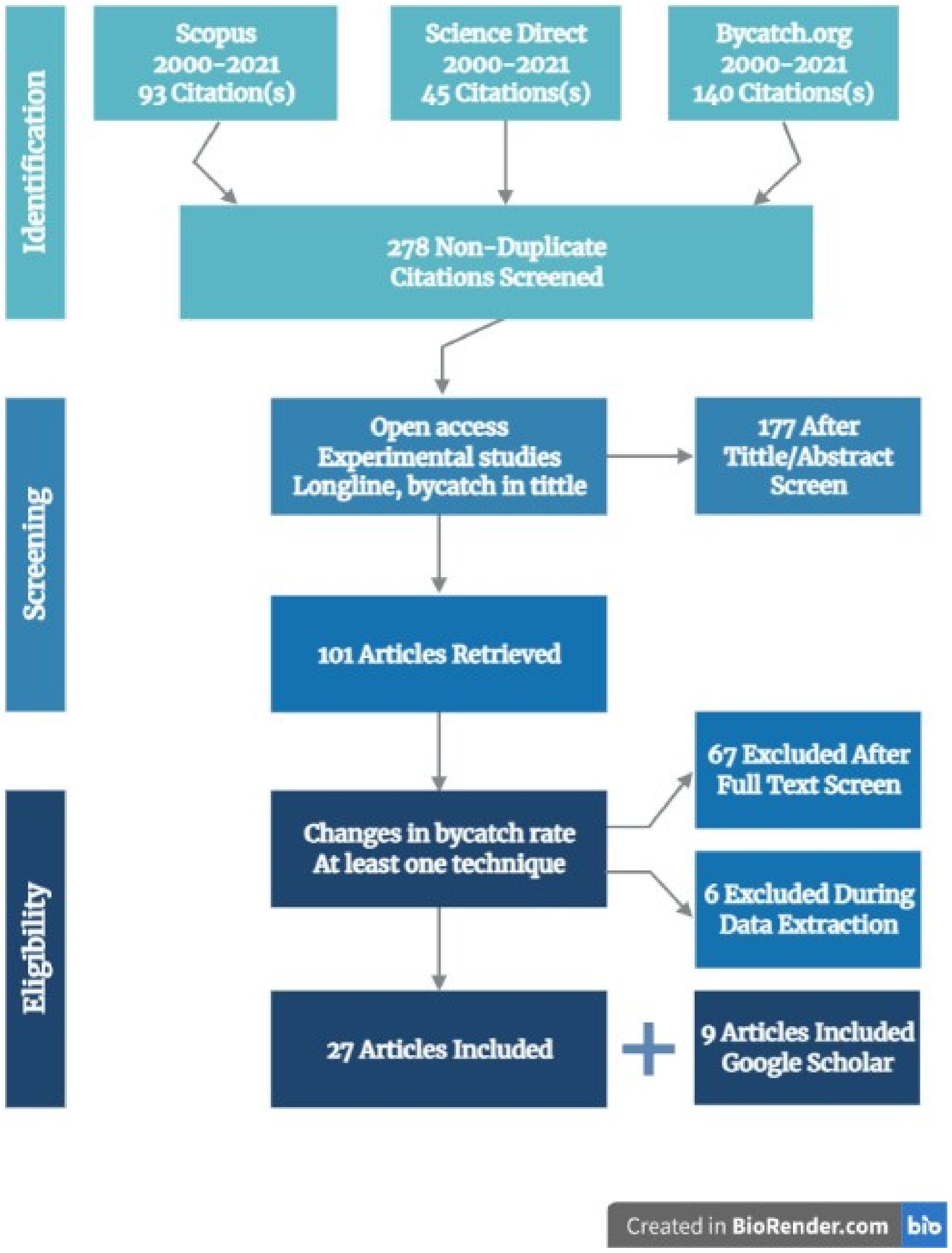

Figure 1. PRISMA Flow diagram with inclusion/exclusion criteria for selecting the studies.

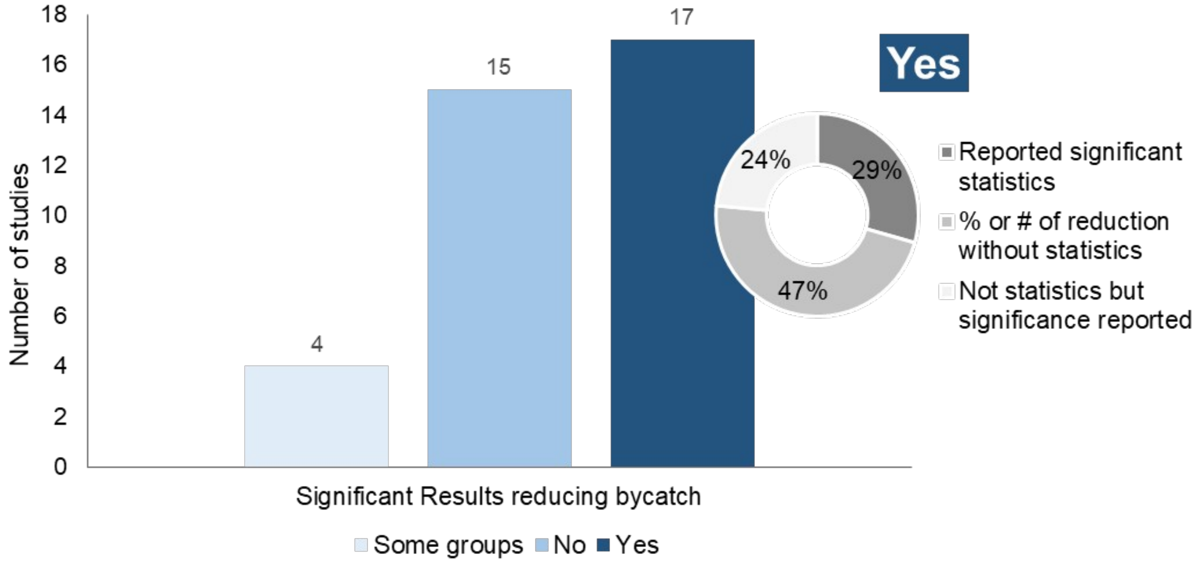

Figure 2. Number of studies with significant (dark blue) and no-significant results (light blue) and significance for some group of organisms (very light blue).

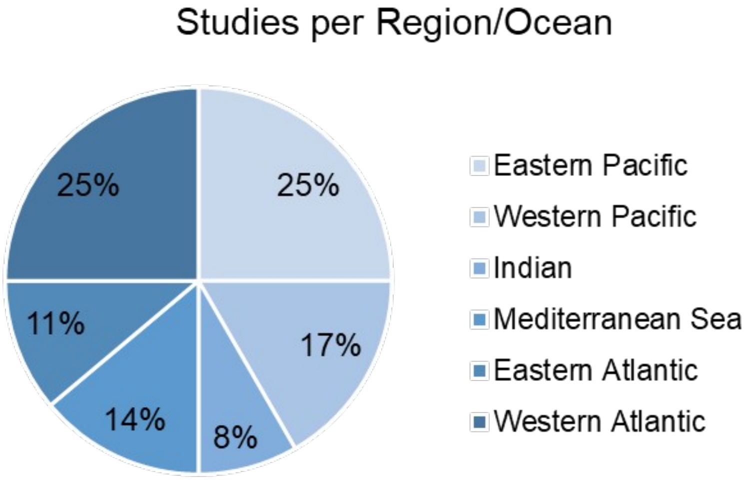

Figure 3. Percentage of bycatch reduction techniques studies per region/ocean.

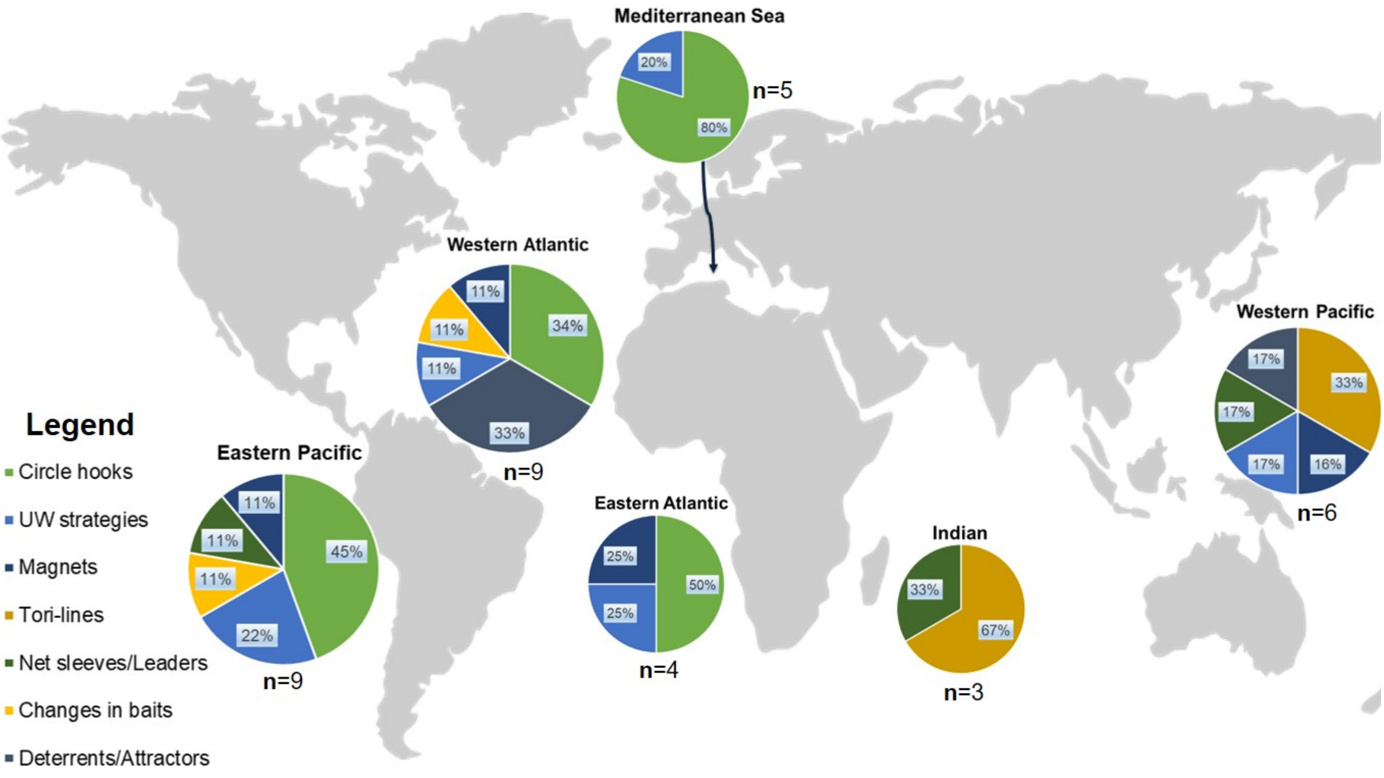

Figure 4. Percentage of the different techniques used across the six regions of the studies.

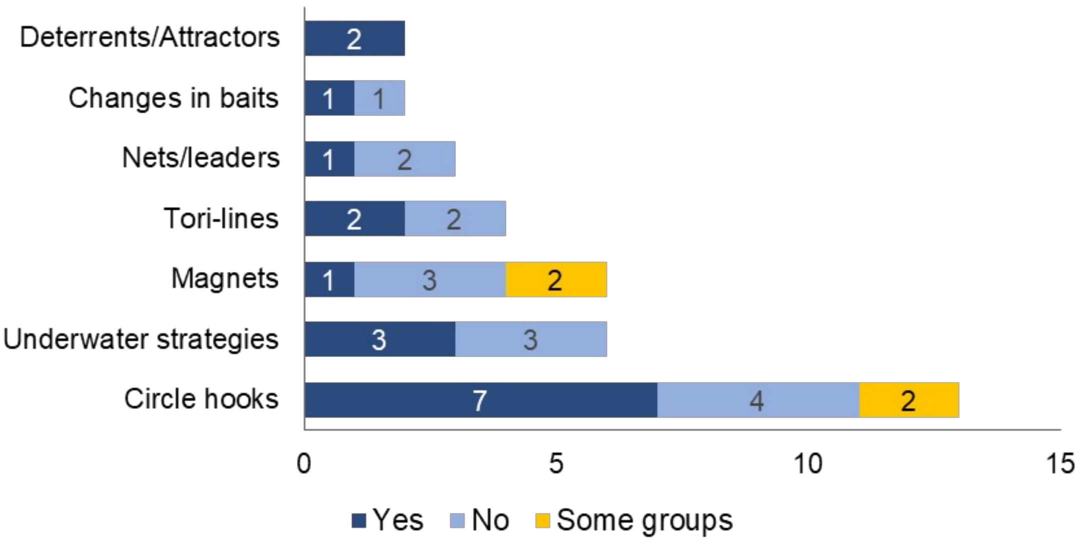

Figure 5. Number of studies with specific techniques to reduce bycatch, and the number of studies presenting significant and no-significant results for each technique.

APPENDIX

Table A. Analyses of the significances of the chosen studies.

Technique	Principal target species	Principal bycatch species	Reported significant statistics	% or # of reduction without statistics	Not statistics but significance reported	Why not significant results	Significant Results reducing bycatch	Region	References
Circle Hooks	Tunas, swordfish, billfishes	Sharks	Night shark: t = 4.011, P = 0.002; Blue shark: t = 3.652, P = 0.001; Silky shark t = 2.461, P = 0.013; Oceanic whitetip: t = 1.249, P = 0.031	CPUE scalloped hammerhead shark's = 0.77, JH = 2.05, did not mention if its significant or not		Compared to J-style hooks, circle hooks significantly increased catch rates of blue, night, silky, and oceanic whitetip sharks in pelagic sets operating	No	Western equatorial Atlantic	Afonso et al., 2011
Circle Hooks	Swordfish	Sharks, rays		Total number of catch: circle hooks = 1, J-style hooks = 5		Had lower but no significant reduction	No	Mediterranean Sea	Özgül et al., 2015
Circle Hooks	Dolphinfish, tunas, billfishes, sharks	Sea turtles, rays, sharks	Sea turtles: p < 0.0001, 52% less; Sharks: marginal significant differences t = 1.96, p = 0.0550; Rays: nearly equal between hook types (t = -0.52, p = 0.6041)			Only for rays were no significant results	Yes and No	Eastern tropical Pacific (ETP)	Swimmer et al., 2011
Circle Hooks	Swordfish, bigeye tuna yellowfin tuna	Sea turtles, rays, sharks		Sea turtles: circle hooks = 11, J-style hooks = 19; Pelagic stingray: circle hooks=20, J-style hooks = 155; Manta		Increase more than twice (significant) for crocodile shark	Yes and No	Western equatorial Atlantic	Pacheco et al., 2011

				Ray: circle hooks = 1, J-style hooks = 6				
Circle Hooks	Swordfish	Loggerhead sea turtles		Loggerhead CPUEs circle hooks = 0.409, J-style hooks = 1.371 (Circle hooks captured 23%, J hooks captured 77%)		Yes	Mediterranean Sea	Piovano et al., 2009
Circle Hooks	Tunas, blue sharks, swordfish, dolphinfish	Sea turtles		Loggerhead: circle hooks = 0.727 turtles per 1000 (41-62% reduction of sea turtles with circle hooks), J-style hooks = 1.605 turtles per 1000 hooks; Leatherbacks: circle hooks = 0.096 per 1000, J-style hooks = 0.274 turtles per 1000 hooks		Yes	South-western Atlantic	Sales et al., 2010
Circle Hooks	Bigeye and yellowfin tuna, swordfish, dolphinfish	Blue shark, pelagic stingray	Blue shark: p = 0.0391 (~17.1% reduction in blue shark catchability with circle hooks); P. stingray: p = 0.0114 (63.2% circle to J-style hooks)			Yes	Central Pacific	Curran & Bigelow, 2011
Circle Hooks	Swordfish	Sea turtles		Loggerhead: circle hooks = 2 turtles(18%), J-style hooks = 9 turtles (82%)		No	Mediterranean Sea	Piovano et al., 2012
Circle Hooks	Swordfish	Pelagic stingray	P. stingray: CPUE of circle hooks per set was	Pelagic stingray: circle hooks = 45, J-style = 177 hooks		Yes	Mediterranean Sea	Piovano at al., 2010

			significantly lower than that recorded for large J-style hooks (Wilcoxon Signed Rank test: $Z = 4.419$, $p < 0.001$)						
Circle Hooks	Tunas, billfishes, wahoo, swordfish	Sea turtles	Ecuador: $p < 0.001$, 50% less turtles; Panama: $p < 0.001$, ~50%; Costa Rica (Circle hook 18/0): $p < 0.001$, ~75% less turtles				Yes	Eastern Pacific	Andraka et al., 2013
Circle Hooks	Swordfish, Bluefin tuna	Sea turtles		Leatherback: 55% less; Hardshell turtles: 59% decrease changing from J-style to circle hooks with 95% confidence			Yes	Tropical Northeast Atlantic	Coelho et al., 2015
Circle Hooks	Swordfish, bigeye and Bluefin tuna	Elasmobranchs	Elasmobranchs: $p = 0.34$ no significance between hooks			Oceanic whitetip show higher catches when offset circle hooks $p = 0.04$	No	Tropical Northeast Atlantic	Fernandez-Carvalho et al., 2015
Circle Hooks	Swordfish, tuna, wahoo, opah	Sea turtles, sharks		Sea turtle: significantly declined by 89.1%; Sharks: significantly decreased by 36%			Yes	Central Pacific	Gilman et al., 2007
Underwater strategies	Swordfish,	Sea turtles		Loggerhead: catches decreased from around 40%–1% in mid-water longline sets			Yes	Mediterranean Sea	Cambiè et al., 2013
Underwater strategies	Bigeye and yellowfin tuna, albacore, swordfish,	Pelagic stingray, sharks		Blue Shark: Shallow = 218 individuals, deeper = 227; Pelagic stingray 14 individuals for both	Catch rates of sharks (blue and shortfin mako) and pelagic		No	Central Pacific	Beverly et al., 2009

	billfish			techniques	stingrays indicated no differences between the two set types				
Underwater strategies	Tunas, swordfish	Seabirds		Chute was 98% effective at reducing albatross contacts with fishing gear near baited hooks	The chute eliminated seabird capture; no birds were observed to be caught during setting with the chute. No albatrosses hauled aboard during chute treatment replicates		Yes	Central Pacific	Gilman et al., 2003
Underwater strategies	Yellowfin and albacore tuna, swordfish	Seabirds		4 m underwater reduced seabird mortality by 87%. In 2010: a combined total of 252 birds were observed in the risk zone when baits were set at the surface and 101 birds when baits were set underwater, giving a reduction of 59.9%. In 2012: 185 birds for surface setting and no birds for underwater setting (10m depth), a reduction of 100%			Yes	South-western Atlantic	Robertson et al., 2018
Underwater strategies	Cod and haddock	Seabird, deep-sea sharks				Analyses suggested that cumulative	No	Northeastern Atlantic	Pham et al., 2014

						fishing effort in a particular area did not have a significant effect on bycatch			
Underwater strategies	Tuna, billfish	Seabirds			Underwater setter is a novel technology designed to prevent this form of mortality without the need for other seabird deterrent devices and practices	Only explain how works the device and make predictions of seabird bycatch reduction	No	South-western Pacific	Robertson et al., 2014
Magnets	Swordfish, shortfin mako, tunas	Blue shark		Individuals caught by hooks equipped with magnets = 94, individuals caught by hooks w/o magnets = 75	Catch rate per unit of effort (CPUE) were higher for hooks with magnets than for hooks without magnets	Present an attractive effect	No	Northeastern Atlantic	Porsmoguer et al., 2015
Magnets	Tuna, marlin, snapper	Sharks, skates, rays	Total capture between magnetic and control treatments was no significant (χ 2 = 0.533, P = 0.4652); Elasmobranch catch with the use of barium-ferrite permanent magnets was significantly less than the catch				Yes and No	Northwest Atlantic	O'Connell et al., 2011

			w/o magnets (χ 2 = 4.235, P = 0.0396)						
Magnets	Swordfish	Blue sharks			Electropositive metals do not have any significant deterrent effect on sharks bycatch species		No	Northwest Atlantic	Godin et al., 2013
Magnets	Tunas, billfishes, dolphinfish	Sharks	Scalloped hammerhead pups: mean CPUE was significantly less, (p = 0.01) on the hooks equipped with metal compared to the control; Sharks (juvenile, adult) combined did not show any significant changes in catch rates (p = 0.58, n = 45)	Scalloped hammerhead pups: Nd/Pr metal = 18, control hook = 42 sharks		Diverse feeding strategies and sensory modalities used by shark species for detecting and attacking prey cause different responses towards magnets	Yes and No	Pacific (three regions)	Hutchinson et al., 2012
Magnets	Yellowtail kingfish	Galapagos sharks			The magnet and electropositive metal devices tested elicited only a weak effect on shark feeding behavior	Depredation rates were highly dependent on the total number of sharks present at the time of the experiment. Deterrents have high potential for reducing shark bycatch for species that occur in lower	No	South-western Pacific	Robbins et al., 2011

						densities			
Magnets	Haddock, Atlantic halibut and cod	Spiny dogfish (*Squalus acanthias*)	Spiny dogfish: capture was significantly reduced on the SMART hooks (paired t-test; t ¼ 3.0446, d.f. ¼ 15, p ¼ 0.0087)				Yes	Northwest Atlantic	O'Connell et al., 2014
Tori-lines	Tunas	Seabirds		Total number of Laysan albatross caught was two, three and four, and the bycatch number was estimated at 0.011, 0.017 and 0.022 birds/1000 hooks for the light streamer tori-line, the hybrid streamer tori-line and the modified light streamer tori-line trials, respectively		Statistical tests were not conducted because the sample sizes were too small to test for any effect	No	North-western Pacific	Sato et al., 2012
Tori-lines	Bigeye, yellowfin and albacore tunas, billfishes	Seabirds			Two bird-scaring lines with aerial extents of 100 m forced attacks by diving seabirds to the area beyond 100 m astern of the vessel, and that weighting branch lines significantly reduced diving bird attacks		Yes	Indian	Melvin et al., 2014
Tori-lines	Tunas,	Seabirds	The total number of			Statistical tests were	No	North-western	Sato et al.,

	swordfish		bycatch was nine (eight Laysan albatrosses and one gull spp.) and bycatch rates were estimated at 0.11 for ST and 0.06 for PT per 1000 hooks			not conducted because the sample sizes were too small to test for any effect		Pacific	2013
Tori-lines	Bigeye and yellowfin tuna, albacore, swordfish	Seabirds			Regressions of seabird catch rates on primary and secondary were both statistically significant		Yes	Indian	Melvin et al., 2013
Net Sleeves and leaders	Bigeye tuna, yellowfin tuna, swordfish	Sharks, snake mackerel		Sharks: wire = 103 individuals; nylon = 44 individuals	The catch rate of all bycatch species combined on nylon was almost half that on wire. For many species, including blue marlin (*Makaira nigricans*), snake mackerel (*Gempylus serpens*), and sharks, wire leader catch rates were higher than nylon catch rates		Yes	South-western Pacific	Ward et al., 2008
Net Sleeves and leaders	Austral hake	Killer whales, marine mammals			The presence of groups of sperm and killer whales was similar in	Difference in percentage of catch damage was two-fold less with the	No	Southeastern Pacific	Moreno et al., 2008

					terms of abundance in trials without net sleeves and with net sleeves	use of the new system. Netting sleeves represent a significant advance in efforts to reduce the number of fish lost to toothed whales as the depredation rate fell to a maximum of 0.36%			
Net Sleeves and leaders	Tunas, swordfish	Toothed whales	No significant difference between shark and whale depredation rates for sets equipped or not with socks (H = 0.12, p = 0.73)			Shark damage was common but affects fewer fish on the line whereas toothed whale depredation is sporadic but affects almost the whole catch	No	South-West Indian	Rabearisoa et al., 2012
Changes in Baits	Mahi mahi, tunas	Sea turtles		Turtle catch rates were similar for sets made with both blue and untreated bait (8.4 and 8.1 individuals per 1000 hooks, respectively)		Dyeing bait does not appear to have potential as an effective mitigation measure to reduce sea turtle bycatch in experimental trials	No	Eastern tropical Pacific (ETP)	Swimmer et al., 2005
Changes in Baits	Haddock	Atlantic cod			The median values for Atlantic cod captures significantly among the three bait types, with overall catches with Norbait© significantly lower than herring		Yes	Northwest Atlantic	Pol et al., 2008

					and clam baits				
Deterrents and Attractors	Swordfish, yellowfin and bigeye tuna, albacore	Blue shark, sea turtle			Blue sharks: caught significant less with blue attractors; Sea turtles: less caught with blue and white		Yes	Western equatorial Atlantic	Afonso et al., 2021
Deterrents and Attractors	Snapper	Seabirds	The number of flesh-footed shearwaters and the total number of seabirds of all species behind the vessel decreased significantly over time through the tests $p = 0.009$		The effect of shark liver oil versus seawater treatment was statistically significant for flesh-footed shearwaters and all seabirds		Yes	South-western Pacific	Pierre & Norden, 2006