Title

Effects of fishery bycatch-mitigation measures on marine vulnerable fauna and target catch

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Abstract

Reducing fisheries bycatches of vulnerable species is critical to marine biodiversity conservation and sustainable fisheries development. While various preventive technical measures have been implemented, their overall effects are poorly understood. Here, we employed a meta-analysis approach to quantify the effects of 42 technical measures on the target catch and the bycatch of seabirds, elasmobranchs, marine mammals, and sea turtles. We showed that these measures generally reduced the bycatch while having no statistically significant effect on the target catch. Sensory-based measures generally outperformed physical-based ones in reducing the bycatch. Mitigation measures that worked well for multiple fishing gears or taxa, while useful, were very rare. Most of the adoptions by regional fisheries management organizations (59%) were supported by our findings, though many others are yet to be robustly evaluated. Our study encourages the innovation and adoption of technical measures and provides crucial insights for policymaking and further research in sustainable bycatch management.

Main text

Introduction

The worldwide bycatch of marine endangered, threatened, and protected species (ETP species, hereafter) stands as one of the greatest challenges to sustainable fisheries development [1,2]. To date, fishing activities widely occur across the global ocean and produce 44% of the world's total fisheries and aquaculture production for human consumption [3,4]. These activities have not only led to the overexploitation of half of all commercially harvested fish and invertebrate stocks [3,5], but have also threatened many non-target ETP species or marine megafauna, especially seabirds, elasmobranchs, marine mammals, and sea turtles (SEMS, hereafter) [1,2]. Among the SEMS, elasmobranchs are not only bycatch species, but have also been exploited as target species in some regions [6]. During fishing operations, SEMS may interact with fishing gear, either intentionally (e.g., feeding on bait or fish captured on hooks) or unintentionally (e.g., low detectability of fishing nets) [7]. Incidentally, these species are entangled or hooked, resulting in drowning, severe injuries (e.g., gut-hooking, cuts, gashes, and barotrauma), and physiological stress underwater and on board [8,9]. Studies have estimated that fishing activities killed more than half a million marine mammals and at least 400,000 seabirds in a year [10,11]. The decline of SEMS is of global concern, because of their critical role in maintaining marine ecosystems, their cultural value to humans, and their low population growth rates [12-14]. For fishermen, the interactions with SEMS may be undesirable due to the induced losses, including loss of bait and captured fish, damage to fishing gear, and extra time to handle the bycatch [7]. Therefore, managing SEMS bycatch is important for both biodiversity conservation and the long-term socio-ecological sustainability [15].

Developing mitigation measures that can effectively reduce SEMS bycatch is therefore crucial [7,16]. Various preventive measures have been developed and can be broadly classified into two categories: operational and technical measures [7,9]. The former includes (i) static and dynamic closure to specific fishing gears, (ii) avoiding areas or periods with high risk of encounter of SEMS, and (iii) retaining offal during active fishing to reduce feeding opportunities for SEMS [7,16]. The technical measures mainly refer to gear innovations and modifications or bait changes and can be broadly categorized depending on the mitigation mechanisms, namely, the physical- and sensory-based measures (Fig. 1)

[17]. The physical measures aim to prevent SEMS from entering fishing nets (e.g., grids in trap fisheries), reduce contact rates by sinking gears faster (e.g., lead weighting in longlines), and reduce hooking rates by modifying hooks (e.g., circle hooks) [7,16,18,19]. And, the sensory approaches aim to reduce feeding attraction to SEMS (e.g., mackerel baits for sea turtles), deter SEMS species away (e.g., acoustic harassment devices), and avoid net entanglement by increasing the detectability by SEMS species (e.g., beam chain for cetaceans with echolocation) [7,16,18,19].

The outcome of some measures can be mutually beneficial for the SEMS and the target catch since their mechanism might be to reduce the contact between fishing gears and SEMS [20]. Meanwhile, the outcome of some measures can only be unilaterally beneficial for the SEMS because the target fish may perceive the stimuli of the measures in a similar way to the SEMS [17,21]. For example, the change of natural baits to artificial baits can simultaneously reduce both bycatch and target catch [22]. Therefore, evaluating the effects of mitigation measures on both the bycatch and the target catch is essential for further cost-efficiency analysis. On the other hand, the reliability of the estimated effects of a mitigation measure derived from a single experiment is often limited by spatiotemporal coverage and data availability [7,16,18]. Therefore, evaluating the overall effects based on accumulated studies from multiple sites and experiments can provide stronger inferences to guide policymaking, e.g., the conservation and management measures in regional fisheries management organizations (RFMOs, hereafter) [23]. The RFMOs are key actors in international fisheries management and have mandates to adopt mitigation measures to manage the target stock and the SEMS bycatch in their Convention Areas [24-26]. However, previous studies that synthesized the evidence on mitigation measures have either relied largely on qualitative methods or had limited scope in terms of fishing gears, SEMS groups, and geographical regions. Additionally, only few studies have examined the SEMS bycatch and the target catch simultaneously [7,16,18-20,27-29].

In this study, we focused on technical measures for reducing SEMS bycatch and aimed to address three hierarchical questions based on the publicly available data. First, how do technical measures affect the SEMS bycatch and target catch in general (or "functional effectiveness"). Second, to what extent do the overall effects of measures differ within each of the four subgroups (i.e., fishing sectors, fishing gears, SEMS groups, and mitigation mechanisms). Third, how a specific measure for a specific fishing gear and SEMS group affects bycatch and target catch (e.g., the use of circle hooks to reduce the hooking rate of sea turtles in longlines). Two fishing sectors were considered: artisanal and commercial. The former refers to non-industrial fisheries, and any small-scale fisheries described as artisanal, while the latter includes industrial and semi-industrial fisheries, and any small-scale fisheries not described as artisanal [7,30]. We defined the fishing gear according to the Food and Agriculture Organization (FAO, hereafter), e.g., hook-and-line, gillnet, trawl, and trap [31]. Furthermore, we compared the adoption status of technical measures (i.e., as recommended or required by RFMOs) to those that had been evaluated in this study.

To address these questions, we collected publicly accessible studies meeting our inclusion criteria for meta-analysis, following a systematic review protocol (see details in "Methods" section and Extended Data Fig. 1) [32]. This allowed us to identify potential research directions for addressing these questions. From the included studies, we calculated unitless effect sizes (i.e., *g* metric) of mitigation measures on the SEMS bycatch and target catch for each experimental comparison based on the reported data (e.g., sample size, mean, and its variance). Based on these individual effect sizes, we estimated the overall effect sizes for measures across all studies or subgroup studies using mixed-effect models [33]. If an overall effect size was positive (or negative) and statistically significant, we assumed that the considered measure increased (or decreased) either SEMS bycatch or target catch. To ensure the robustness of the estimations, we used a bias-corrected 'trim-fill' recalculation [34] when the effect of publication bias was statistically significant for an observed significant overall effect size. If the directions of the bias-corrected effect sizes were inconsistent with the original ones, we relied on the bias-corrected effect sizes to interpret the results. Since the data on SEMS bycatch were often incomplete for calculating effect size for standard meta-analysis, we calculated a simple change ratio (the difference between bycatch in treatment and control divided by bycatch in the control) as a complementary effect size measure for the SEMS bycatch. Our results provided evidence of the overall effects of the most diverse sets of technical mitigation measures, with global implications for advancing ocean sustainability.

Results

Overall effects of technical measures

In total, 42 technical measures (Fig. 1a, b and see detailed descriptions in Supplementary Table 1) were tested in 121 case studies (listed in Supplementary Information). Technical measures generally reduced SEMS bycatch while they did not have an overall significant effect on target catch. The estimated overall effect size (g metrics) of measures for the SEMS bycatch across all included studies was -0.35 (Fig. 1c; n = 150, 95% confidence interval: -0.46 to -0.23; trim-fill bias-adjusted: -0.31, -0.40 to -0.22). The results were generally consistent with those of the change ratio (n = 276, -0.40, -0.48 to -0.32). The overall effect size of measures for the target catch across all included studies was 0.09 (Fig. 1c; n = 167, 95% confidence interval: -0.01 to 0.20).

Effects of technical measures within each of the subgroups

For the fishing sector subgroups, most of the included studies (93%) were conducted in commercial sectors (Supplementary Table 2), for which technical measures generally reduced the SEMS bycatch (Fig. 2; n = 149, -0.36, -0.47 to -0.24; trim-fill bias-adjusted: -0.31, -0.40 to -0.22). Meanwhile, measures generally did not significantly affect the target catch in both commercial and artisanal fisheries (Fig. 2). For fishing gear subgroups, most included studies were conducted in hook-and-line (64%, primarily longlines and only one study for handlines) and gillnet (24%) (Supplementary Table 2). Technical measures generally reduced the SEMS bycatch in hook-and-line (Fig. 2; n = 126, -0.34, -0.46 to -0.21; trim and fill: -0.30, -0.40 to -0.19) while their effects in gillnet were affected by publication bias (Fig. 2; n = 21, -0.34, -0.62 to -0.07; trim and fill: -0.08, -0.27 to 0.10) (Fig. 2). Meanwhile, technical measures generally did not affect the target catch (Fig. 2). For SEMS subgroups, most of the included studies were for elasmobranchs (40%), followed by sea turtles (31%), cetaceans (21%), and seabirds (21%) (Supplementary Table 2). We found that measures generally reduced the bycatch of seabirds (Fig. 2; n = 23, -0.75, -1.03 to -0.48; trim-fill adjusted-bias: -0.45, -0.69 to -0.22), elasmobranchs (Fig. 2; n = 75, -0.27, -0.42 to -0.12; trim-fill: -0.26, -0.42 to -0.11), and sea turtles (Fig. 2; n = 46, -0.27, -0.46 to -0.07; trim-fill: -0.15, -0.23 to -0.06) but did not affect the target catch. The examined measures, however, did not have a significant effect on the bycatch of cetaceans or pinnipeds, but increased the target catch when used to exclude the pinnipeds (Fig. 2; n = 19; 0.29, 0.01 to 0.57). For broad mitigation mechanisms, both sensory-based measures (Fig. 2; n = 72, -0.50, -0.65 to -0.36; trim and fill: -0.38, -0.51 to -0.26) and physical-based measures (Fig. 2; n = 78, -0.19, -0.33 to -0.05; trim and fill: -0.18, -0.30 to -0.05) were effective in reducing

SEMS bycatch. The effect of sensory-based measures was generally higher than that of physical-based measures ($P < 0.01$), particularly for the elasmobranch in hook-and-line ($P < 0.01$, Extended Data Fig. 2). Notably, both mechanisms did not affect the target catch on average, although the effect size of sensory-based measures was positive before considering the publication bias (Fig. 2; $n = 73$; 0.19, 0.05 to 0.32; trim-fill: 0.08, -0.04 to 0.20).

Effects of specific technical measures

The effects of specific measures greatly varied (Fig. 3 and Supplementary Table 3). There were 70 possible specific combinations (i.e., technical measure-fishing gear-SEMS group), of which only 43% ($n = 30$) had both data on the SEMS bycatch *g* and target catch *g* (Supplementary Table 4 and 5). Of these 30 combinations, 10 reduced SEMS bycatch while maintaining target catch (Supplementary Table 5), such as (i) lead weighting (sample size: $n_{SEMS} = 3$, $n_{target} = 12$) and toriline ($n_{SEMS} = 11$, $n_{target} = 10$) on hook-and-line for seabirds, (ii) illuminators on gillnet for sea turtles ($n_{SEMS} = 5$, $n_{target} = 5$), (iii) monofilament nylon gangion (B) ($n_{SEMS} = 3$, $n_{target} = 3$) and the use of squid bait ($n_{SEMS} = 8$, $n_{target} = 8$) on hook-and-line for elasmobranchs (Fig. 3 and Supplementary Table 3). Out of the four measures (i.e., magnet, pinger, toriline, and exclusion grid) used in more than one fishing gear, only the toriline appeared to consistently reduce the bycatch (Fig. 3; i.e., seabirds in hook-and-lines and trawls). Among the nine measures that had *g* metric for more than one SEMS group, only the use of illuminators showed evidence of reducing more than one SEMS group (Fig. 3; i.e., sea turtle and seabird bycatch in gillnets).

Effects and gaps of RFMOs-adopted measures

Most of the included studies were conducted in the Atlantic ($n = 67$), Mediterranean and Black Sea ($n = 18$), and East Pacific Oceans ($n = 29$) according to the FAO major areas (Extended Data Fig. 3).

Meanwhile, most of the included studies (n = 104, 86%) occurred in the Economic Exclusive Zones (EEZs, hereafter) of countries, of which 92% were from high and upper-middle income (e.g., European countries and the USA, Fig. 4). For RFMOs, most of the included studies were conducted in the Convention Areas of the ICCAT (n = 77), followed by the WCPFC (n = 19) and GFCM (n = 18) (Fig. 4).

In total, 18 of the 42 measures evaluated in this meta-analysis were adopted by the RFMOs (Fig. 5). Most of these measures were used to reduce the bycatch of seabirds and sea turtles in hooks-and-lines (Fig. 5). Across the 15 RFMOs, the CCSBT, WCPFC, SEAFO, IOTC, GFCM, and the IATTC adopted more mitigation measures than others (Fig. 5).

We found some misalignments between the experimental evidence and the technical measures currently adopted by the RFMOs (Fig. 5). First, only 59% of the combinations of technical measures, RFMOs, fishing gears, and SEMS groups were supported to reduce SEMS bycatch and retain target catch by our evaluations (Supplementary Table 6), such as the use of toriline and lead weighting for seabirds and illuminators on gillnets for sea turtles (Fig. 3). Furthermore, 25% of the combinations were considered as data deficient for either the SEMS bycatch g or target catch g. Second, by matching the experimental sites and the adoption information from RFMOs, we found that while each mitigation measure was largely tested in several Convention Areas of RFMOs, it was adopted by other RFMOs (In-situ *vs.* Ex-situ; Fig. 5). Third, the number of measures adopted by RFMOs was not significantly correlated with the number of experimental studies conducted in the RFMOs (P = 0.53, Supplementary Table 7).

Discussion

Reducing fishery bycatches of marine ETP species is one of the key steps to achieve sustainable oceans (i.e., the SDG 14, Life Below Water) [1,2]. To this end, many studies are essentially needed, including (i) designing bycatch-mitigation measures, (ii) evaluating their functional effectiveness and cost-efficiency to inform policymaking, and (iii) assessing their performance in applications and synthesizing the best practices [9,24,25]. Here, based on publicly accessible data, our study is among the first to demonstrate that technical measures (one of the major bycatch-mitigation approaches) generally reduced the bycatch of SEMS and had no statistically significant effect on the target catch on average [18,20]. Given this result was robust even when we considered publication bias, we recommend that future investments in technical measures are worthwhile in managing bycatch of vulnerable marine fauna [9,35]. Importantly, with the best evidence available, we have shown the types of technical measures that could work for a specific taxonomic group in a particular fishing gear, a complex issue that has been a concern among policy makers [15,24,25]. In general, our findings have ramifications for fisheries policy and conservation efforts worldwide and we discussed them as follows.

One of the major contributions of this study is that we quantitatively synthesized the overall effects of many technical measures for various pairs of fishing gears and SEMS groups (Fig. 3). We identified some measures (e.g., illuminators on gillnet for sea turtles) that can reduce the bycatch and maintain the target catch. Meanwhile, some measures can reduce the bycatch but harm to the target catch, such as the use of rare earth metal to deter elasmobranchs [36]. These findings can serve as an update or supplement to previous reviews and meta-analysis, few of which have considered the target catch [7,16,18-20,27-29]. As such, more comprehensive knowledge is now available to managers when it comes to choosing useful technical measures for bycatch management. Our study consolidated the previous findings that the outcome of a technical measure is conditional on the examined fishing gears and SEMS groups in most cases [9,35]. Although many included studies may report data on multiple SEMS groups, a measure that is often designed for one SEMS group may sometimes harm the others [35]. For example, the use of mackerel baits on longlines could reduce sea turtle bycatch but is likely to increase elasmobranch bycatch. In these cases, we need an integrated fisheries and bycatch management system which accounts for these multispecies conflicts so that any avoidable conflicts are mitigated (through complementary measures) and unavoidable tradeoffs are known and deemed acceptable to the stakeholders [23,35]. Importantly, we only found that a few bycatch-mitigation measures (e.g., the use of torilines and illuminators) could work well for multiple fishing gears or SEMS groups [17,35,37]. Although the value of such ‘omnipotent’ measures is apparent and desirable, widespread evidence and case studies are rare and more experiments are required. It is possible that more such measures exist [9,35,38], but they might be naturally scarce given focal taxa have different sensory systems [17,21].

RFMOs have mandates to address SEMS bycatch based on the best scientific evidence [24-26]. Besides the functional effectiveness of mitigation measures we evaluated, it is critical to consider the diverse costs in practice including the financial costs of gears, extra labor for deployment, and operational risk to fishermen. However, in the included studies, few conducted a cost-efficiency analysis simultaneously [39,40]. Notably, It is worth mentioning that since the SEMS may hold cultural significance for people, a certain amount of SEMS-caused losses may be tolerated by fishermen [13,41].

Despite the lack of widespread evidence, we showed that many RFMOs are making progress in adopting technical measures, while the progress varies considerably, five RFMOs (i.e., the NAFO, NASCO, NEAFC, RECOFI, and NPFC) have yet to adopt any specific technical measure. Optimistically, most of the adopted measures in the RFMOs were supported by our evidence. However, some adopted measures (e.g., the use of pingers to alarm cetaceans and artificial shark models to deter sea turtles) yet have no generally supporting evidence [7,16], and a few measures (e.g., iron-oxide gillnet for cetaceans and baffler and toriline in trawl fisheries for seabirds) with some supporting evidence are not actually adopted. Following a sequential evidence hierarchy, we proposed that evaluated measures not supported by scientific evidence should only be considered as precautionary measures if reliable alternatives are unavailable [23]. Measures with some supporting evidence can also be valuable, given that robust evidence requires a large number of experiments [23]. Surprisingly, we showed that relatively few bycatch-mitigation measures were adopted for elasmobranchs by RFMOs, though elasmobranch was the most studied taxon in our dataset. Such a mismatch might result from (i) their widespread interactions with fishing activities and potentially high popularity as research subjects [1], (ii) their commercial value as target species in some regions (so that several RFMOs may be reluctant to treat them as bycatch) [6], and (iii) alternative non-technical measures (e.g., releasing practices and fishing bans) were already in place to protect them [6,42]. Nevertheless, our findings reflect the complexity in adoption of bycatch-mitigation measures by RFMOs, which may be determined by multifaceted factors beyond scientific evidence, such as the interests of contracting parties, and other considerations (cost-efficiency and availability of alternative measures) usually involved in the decision-making process [24,25,43].

Based on a systematic review and analysis, our study highlights several directions for future research on bycatch-mitigation technical measures. First, integrating more knowledge of sensory systems, perceptions, and behaviors of animals into the design of technical measures might be promising [17,21], given that sensory-based measures generally perform better than purely physical ones in reducing the bycatch. Such a novel finding also highlights the importance of conducting basic biological and ecological research on bycatch and target species to aid their management [17,21]. Second, more publicly accessible quantitative studies are needed for most of the examined but data-poor 'technical measure-fishing gear-SEMS group' combinations (57%). This is also true for the fishing gears (e.g., trawls and traps), SEMS groups (e.g., marine mammals), and regions that might be under-represented (partly due to our selection criteria) or under-evaluated in publicly available literature. For instance, we lacked easily-accessible studies from the Indian Ocean, where non-selective fisheries and SEMS fauna are usually concentrated [2,44,45], although such studies may be published in grey literature and/or in local languages that were not covered by our meta-analysis. Third, it is worth evaluating many other implemented and promising technical measures, including the use of non-entangling fishing aggregating devices in purse seine fisheries and alternative gillnet material [38,46], which we were unable to cover due to data deficiency. Given the strict inclusion criteria needed for a solid meta-analysis, we urge future studies to (i) quantitatively examine and report the effects of technical measures on both SEMS bycatch and target catch, and, importantly, (ii) publish these data in peer-reviewed or globally-recognized literature that could be publicly accessed.

To achieve the SDG 14 (Life Below Water) from the perspective of protecting marine ETP species, we need other effective mitigation measures that were beyond the scope of our analysis [9,15,24]. First, operational measures, such as fishing closure to specific fishing gears, prohibition for setting gears around SEMS, night setting, and minimal illumination when setting gears at night, should aim to avoid interactions with SEMS in the first place [7,16]. Second, proper handling practices can reduce immediate mortality and minimize injury and physiological stress leading to sublethal effects and delayed mortality [42]. Therefore, identifying best practices and training fishermen is critical [42]. Third, fishery output controls (e.g., bycatch thresholds and shark finning bans) and trade bans (e.g., the Convention on International Trade of Endangered Species and seafood import restriction of the USA) may help to increase the selectivity of fishing activities [9]. In practice, these measures could be aligned in a sequential mitigation hierarchy (i.e., "avoiding-minimizing-remediating-offsetting" strategy) and produce synergistic effects [9,46]. Moreover, bycatch management governance on the ground (e.g., observer coverage, data analysis and transparency, and mitigation efforts) is critical to ensure compliance [24,25]. Nevertheless, our study should encourage stakeholders to implement technical measures, along with other approaches, to address the ETP-bycatch issue that is presently hindering our progress toward sustainable oceans.

Methods

Literature collection

Using standard systematic review protocols, we collected relevant studies published between 1950 and 2021 through systematic searches in five widely-used search systems, including the Web of Science (www.webofknowledge.com), China National Knowledge Infrastructure (CNKI, https://www.cnki.net/) for Chinese, SciELO (https://scielo.org/en) for Spanish and Portuguese, J-Stage (https://www.jstage.jst.go.jp/browse/-char/en) for Japanese, and Elibrary (https://elibrary.ru/defaultx.asp) for Russian (Supplementary Table 8). In these searches, we generally followed the PICO strategy [32] and used a 'SEMS group+behavior+fishing gears+outcome+intervention" format to define the search rules, such as 'seabird+feed+longline+catch+mitigation'; while the full searching rules are different due to the capacity of a specific searching system (see details in Supplementary Information). For SEMS groups, we included keywords related to seabirds, elasmobranchs, cetaceans, pinnipeds, and sea turtles. For the fishing gears, we used the general term "*fishery*" and specific keywords of fishing gear in six categories according to the classification of the FAO, including hook-and-line (e.g., longline and handline), gillnet and entangling net (e.g., gillnet and driftnet), trawl, surrounding nets (e.g., purse seine); trap (e.g., pot, trap-net, fyke net, and stow net), dredge, and lift net [31].

Initially, a total of 4355 studies were returned (Extended Data Fig. 1 and Supplementary Table 8). To ensure literature coverage, we used two rounds of snowball sampling to collect relevant studies cited by papers from the initial list of literature (Extended Data Fig. 1). For the first round, we collected case studies and relevant reviews cited in the introduction section; for the second round, we only collected case studies. Moreover, we performed complementary searches on Google Scholar (https://scholar.google.com/) (see details in Supplementary Information) and opportunistically collected studies during the online searching process of targeted papers. The literature collection process was recorded following the standard guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (Extended Data Fig. 1).

Inclusion criteria

To ensure the quality of our analysis, we imposed strict criteria to select experimental studies evaluating the effect of mitigation measures for SEMS bycatch in marine capture fisheries. To be included, first, studies must focus on the topic of testing the effects of mitigation measures and be published in the working languages of our review team (i.e., English, Chinese, Spanish, Portuguese, Japanese, and Russian). Studies conducted on aquaculture and recreational fisheries were excluded. Only experimental and quasi-experimental studies (e.g., randomized controlled trials, before-after control-impact, before-after, and control-impact designs) were included and observational or correlative studies without any control of the implementation process were excluded [47]. Experiments had to be replicated in the field for free-ranging wild animals. The chosen control and treatment of experiments were usually conducted simultaneously or within a comparable time interval. Experiments were targeted to test the effectiveness of a specific measure rather than integrative ones. We also required the study to have the data for calculating the *g* metric (e.g., sample size, mean, and variance) for SEMS bycatch and target catch or change ratio for SEMS bycatch. The measurements of catch include the number or weight of catches for each operation/set.

Data extraction and compilation

An experimental comparison was typically defined by the fishing gear, mitigation measure, and taxa of SEMS and target catch. The target species were generally defined by the original studies. We extracted the sample size (e.g., the number of fishing net sets), mean, and variance of the overall catch if the data were available. While many studies reported the individual catch of all target species, we only extracted the data of one or two target species with the largest biomass or number, depending on the direction of the effect (i.e., positive or negative) of measures upon them. If the two effects were in the same direction, we only retained the data for the single major target species; otherwise, if the effects were in opposite directions, we extracted the data for both species. We acknowledged that the use of largest biomass or number as a proxy for the main target catch may not reflect what was the most valuable target species in that fishery. However, the economic values of different target species were rarely reported in studies and were challenging to estimate [19,20]. For the SEMS bycatch data, we attempted to extract similar data as that of the target catch but experiments without reported variance of the mean are also included. We extracted the data for the primary species of SEMS bycatch only when data for multiple species from the same taxonomic order were reported. Given the global concern about the conservation status of elasmobranchs in the recent decade, we included the data in the SEMS bycatch dataset from four case studies in which elasmobranchs (mainly the blue shark *Prionace glauca* and blacktip shark *Carcharhinus limbatiis*) were described as target species and mitigation measures (e.g., change baits) were mainly developed for other taxa (e.g., sea turtles). These studies reported the effects of the measures on the elasmobranchs, and we used these results given they indicated potential effects of adopting similar measures in other fisheries where elasmobranchs were treated as bycatch.

We compiled the information on potential subgroup moderators for experimental comparisons, including fishing sectors and gears, taxa of SEMS and target catch, mitigation measures, and geographical information (e.g., RFMO Convention Areas, countries, and major fishing areas). Two fishing sectors were considered: artisanal and commercial sectors. The former refers to non-industrial fisheries, and small-scale fisheries described as artisanal, while the latter includes industrial and semi-industrial fisheries, and any small-scale fisheries not described as artisanal [7,30]. We defined the fishing gears according to the FAO classification [31]. We assigned each study site (where available) to the Economic Exclusive Zone of a specific country or territory and the major fishing area as defined by the FAO. The economic status of a country or territory was compiled according to the United Nations.

Data analysis

Since there is no universal measure for all the target catches, we calculated a unitless standardized effect size and its variance for each experimental comparison based on the data on sample size (e.g., the number of fishing net sets), mean, and its variance extracted from each case study. For the standardized effect size metric, we used the bias-corrected Hedge's *g*, the mean difference standardized using the pooled standard deviation of a comparison [33], which was calculated using the following equations:

$$g = J \times d$$

$$V_g = J^2 \times V_d$$

Where d and V_d are calculated using the following equations:

$$d = \frac{X_{treatment} - X_{control}}{SD_{within}}$$

$$SD_{within} = \sqrt{\frac{(n_{treatment} - 1)S^2{}_{treatment} - (n_{control} - 1)S^2{}_{control}}{n_{treatment} + n_{control} - 2}}$$

$$V_d = \frac{n_{control} + n_{treatment}}{n_{control} \times n_{treatment}} + \frac{d^2}{2 \times (n_{control} + n_{treatment})}$$

The biased-corrected factor J is defined as:

$$J = 1 - \frac{3}{4(n_{treatment} + n_{control} - 2) - 1}$$

The 95% confidence interval of a g is calculated using the following equations:

$$CI \sim [g - 1.96 * \sqrt{V_d}, g + 1.96 * \sqrt{V_d}]$$

When data were not available to calculate *g* directly, we extracted convertible statistics (e.g., t-test, Chisq-square test, and one-way ANOVA) in the case studies and then calculated *g* using the “esc” package [48]. A positive value of g indicates that the use of a mitigation measure increases the target catch and vice versa. A larger value of g means a larger effect of the measures. As a rule of thumb, g < 0.2 can be interpreted as a small effect, a value around 0.5 as a medium effect, and > 0.8 as a large effect [33].

To estimate the overall effect, we estimated an overall effect size across experimental comparisons from case studies, namely, a weighted mean of the individual effects [33]. In the estimation, we used multilevel mixed-effects models, in which we set the nested structure of multiple effect sizes in a same study as the random effects to control the non-independence in the dataset [49] and subgroup variables as the fixed effects, and each effect size is weighted by the inverse of within-study plus between-study variance (see details in the Supplementary HTML file 1). The above models were calculated using restricted maximum-likelihood estimations. For mitigation measures with only one comparison, the overall effects were represented by the corresponding *g* and 95% confidence interval.

We assessed potential publication bias statistically (i.e., Egger’s regression to test the symmetry of the funnel plot and Kendall's rank correlation) [50]. Publication bias occurs when the case studies included in a meta-analysis are selectively published based on their results including the significance of P values, the magnitude of effect estimates, and sample sizes [34]. Egger's regression was used to test the asymmetry of the funnel plot, which depicts the standardized effect size against the sample size and unbiased data should be funnel-shaped with a wide scatter of effect sizes at low sample sizes and narrowing as sample sizes increase. Kendall's rank correlation examines whether the observed effect sizes or outcomes and the corresponding sampling variances are correlated, and a high correlation would indicate that the funnel plot is asymmetric, which may be a result of publication bias [51]. If one of the two tests showed a publication bias, we used the 'trim and fill' method to conduct a sensitivity analysis, which recalculated the estimated overall effect size by trimming the smaller comparison from the positive side and filling it or mirroring the negative side of funnel plot thereby removing the funnel asymmetry [34]. Since the "trim and fill" model and Egger's regression could not be performed using multilevel mixed-effects models in "metafor" package of R [52], we used random-effects models without multilevel structure for testing publication bias.

For the comparisons with full data (sample size, mean, and its variance) of the SEMS bycatch, we used g metric as the effect size and the standard meta-analysis and publication bias check approaches to synthesize the effects across case studies that are similar to the analysis of the target catch data above. A negative value of SEMS bycatch g indicates that a mitigation measure reduced the SEMS bycatch and vice versa.

Additionally, since the variance of the mean is often not available for SEMS bycatch data, we calculated supplementary effect sizes (i.e., change ratio) to retain some information about the effectiveness of measures. For each experimental comparison, we calculated a change ratio using the following equation:

$$CR = \frac{X_{treatment} - X_{control}}{X_{control}}$$

CR is the change ratio; $X_{\text{treatment}}$ is the mean of the treatment group; and X_{control} is the mean of the control group. If there is no SEMS bycatch in the treatment and control groups, we treated the change ratio as zero. Then, in contrast to the weighted mean of standard meta-analysis, we calculated a simple arithmetic mean (unweighted) to synthesize the effects across case studies. A negative value of the change ratio indicates that a mitigation measure reduced the SEMS bycatch and vice versa.

To determine the conservation and management measures adopted in RFMOs' policies, we reviewed publicly available materials from the 15 RFMO Secretariats, complemented with information from RFMOs' Secretariat staff and the 121 experimental studies we collected in this dataset. The 15 RFMOs include the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), Commission for the Conservation of Southern Bluefin Tuna (CCSBT), General Fisheries Commission for the Mediterranean (GFCM), Inter-American Tropical Tuna Commission (IATTC), International Commission for the Conservation of Atlantic Tunas (ICCAT), Indian Ocean Tuna Commission (IOTC), Northwest Atlantic Fisheries Organization (NAFO), North Atlantic Salmon Conservation Organization (NASCO), North East Atlantic Fisheries Commission (NEAFC), Regional Commission for Fisheries (RECOFI), South East Atlantic Fisheries Organization (SEAFO), Southern Indian Ocean Fisheries Agreement (SIOFA), South Pacific Regional Fisheries Management

Organization (SPRFMO), Western and Central Pacific Fisheries Commission (WCPFC), and North Pacific Fisheries Commission (NPFC) [24,25]. Here, we treated the use of double-weight branch line, lead, and stone as specific measures in the category of line weighting, which is commonly used in the RFMOs. We used the fishing effort data at 0.1 degrees resolution of 2019 from the Global Fishing Watch to visualize global fishing activities (Extended Data Fig. 3) [4].-The maps of RFMOs' coverages, major fishing areas, country and territorial boundaries, and Exclusive Economic Zones of countries and territories were derived from the FAO.

Data Availability

The data supporting the findings of this study are provided in Supplementary Data 1 and Supplementary Data 2.

Code Availability

The analysis processes and codes were recorded in Supplementary HTML file 1.

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Author Contributions Statement

CH, TML, and YL conceived the idea; CH, KWZ, CTW, EPN, PNM, XZ, and YL collected data; CH, YW, and TML analyzed the data; CH, KWZ, XZ, TML, and YL drafted the manuscript with the inputs from JR and AR; and all authors revised and approved the final draft of the manuscript.

Competing Interests Statement

The authors declare no competing interests.

Figure Legends/Captions (for main text figures)

Fig. 1. Technical mitigation measures and their overall effects on the bycatch of seabirds, elasmobranchs, marine mammals (cetaceans and pinnipeds), and sea turtles and the target catch after accounting for publication bias. **a,** Physical and sensory-based measures. The relative height of a node (the vertical bar) and the flow ribbon represents the proportion of related studies. **b,** Illustration of technical mitigation measures. For bait changes, we consider the squid bait as a mitigation measure when targeting elasmobranchs and treat the fish bait as a mitigation measure when targeting sea turtles. The measures of monofilament nylon gangion (B) and multifilament nylon gangion are two inversed experimental comparisons. While one study assumed that multifilament nylon gangion may reduce the SEMS bycatch because of higher detectability and another study assumed that

monofilament nylon gangion (B) may reduce the SEMS bycatch by facilitating the escape. **c,** Overall effects of measures on the SEMS bycatch (the green point) and target catches (the blue point). The error bars represent the 95% confidence interval. The data points in grey are based on the individual effect size (i.e., the bias-corrected Hedge's *g*) for the SEMS bycatch and target catch from the included case studies. The Hedge's *g* is the mean difference standardized using the pooled standard deviation of an experimental comparison. The value in the parenthesis of the y-axis provides the sample size for the SEMS bycatch *g* or the target catch *g*, respectively, for estimating an overall effect size. If a significant overall effect size is affected by publication bias, the result of the trim-and-fill recalculations was plotted instead.

Fig. 2. Effects of measures on subgroups after accounting for publication bias for subgroups with at least three experiments (or three data points) from the included case studies. The plotted data points are the estimated overall *g* metric of the SEMS bycatch (green), the change ratio of SEMS bycatch (grey), and the *g* metric of target catch (blue points) based on all effect sizes across subgroup studies. The error bars represent the 95% confidence interval. The value in the parenthesis of the y-axis indicates the number of the SEMS bycatch *g*, the SEMS bycatch change ratio, and the target catch *g*, respectively, for estimating an overall effect size. If a significant overall effect size is affected by publication bias, the result of the trim-and-fill recalculations was plotted instead. The green tick indicates that the measure benefited a specific subgroup either by reducing the SEMS bycatch (indicated by a dolphin icon) or by increasing the target catch (indicated by a tuna icon) and the grey dot indicates the overall effect was statistically non-significant.

Fig. 3. Effects of a measure for a specific fishing gear and SEMS group after accounting for publication bias for combinations with at least three experiments (or three data points). The plotted data points are the estimated overall *g* metric of the SEMS bycatch (green), the change ratio of SEMS bycatch (grey), and the *g* metric of target catch (blue points) based on the individual effect sizes across case studies of an intervention. The error bars represent the 95% confidence interval. The sample size for estimating an overall effect size was provided in the Supplementary Table 3. The larger point indicates that the sample size is at least three and the smaller point indicates that the sample size is less than three. If a significant overall effect size is affected by publication bias, the result of the trim-and-fill recalculations was plotted instead. A positive value of effect size (*g* metric) means a measure increases the SEMS bycatch or target catch and vice versa. If an effect size of a measure is not significantly different from zero, we treat the effect as “no statistically significant effect”. The pink shade highlighted those measures (with a relatively sufficient sample size) that significantly reduced the SEMS bycatch and retained the target catch.

Fig. 4. Number of included experimental studies interventions by Exclusive Economic Zones of a specific country (in red bubble) and the Convention Areas of RFMOs (in blue bubble) defined by the FAO. The size of each bubble is proportional to the number of studies. The abbreviations for the RMFOs are listed as the following: Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR); Commission for the Conservation of Southern Bluefin Tuna (CCSBT); General Fisheries Commission for the Mediterranean (GFCM); Inter-American Tropical Tuna Commission (IATTC); International Commission for the Conservation of Atlantic Tunas (ICCAT); Indian Ocean Tuna Commission (IOTC); South East Atlantic Fisheries Organization (SEAFO);

Southern Indian Ocean Fisheries Agreement (SIOFA); South Pacific Regional Fisheries Management Organization (SPRFMO); and Western and Central Pacific Fisheries Commission (WCPFC).

Fig. 5. Topography and distribution of technical measures adopted by regional fisheries management organizations (RFMOs). "Ex-situ" and "In-situ" means a measure was tested or not in the Convention Areas of an RFMO, respectively. The relative height of a node (the vertical bar) and the value in parenthesis represent the proportion of the RMFOs associated with each measure.

Extended Data Fig S1. PRISMA workflow of this study.

Extended Data Fig S2. Effect of mitigation mechanism for a specific fishing gear and SEMS group after accounting for publication bias for combinations with at least three experiments (or three effect sizes). The plotted data points are the estimated overall *g* metric of the SEMS bycatch (green), the change ratio of SEMS bycatch (grey), and the *g* metric of target catch (blue points) based on the individual effect sizes across subgroup studies. The error bars represent the 95% confidence interval. The value in the parenthesis indicates the number of the SEMS bycatch *g*, the SEMS bycatch change ratio, and the target catch *g*, respectively, for estimating an overall effect size. The bigger point indicates that the sample size is at least three and the smaller point indicates that the sample size is less than three. If a significant overall effect size is affected by publication bias, the result of the trim-and-fill recalculations was plotted instead. A positive value of effect size (g metric) means a mitigation mechanism increases the SEMS bycatch or target catch and vice versa. If an effect size of a mitigation mechanism is not significantly different from zero, we treat the effect as "no statistically significant effect".

Extended Data Fig S3. Number of included experimental studies by the Exclusive Economic Zones of a specific country (in red bubble) and the major marine areas (in blue bubble) as defined by the Food and Agriculture Organization. The size of each bubble is proportional to the number of included studies. Global fishing effort in 2019 estimated by the Global Fishery Watch (https://globalfishingwatch.org/) in fishing hours using available data from vessels with automatic identification systems (AIS) was plotted in the background and the white space in the sea means no available AIS data.

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