Methods for mitigating sea turtle bycatch in longline fisheries: a meta-analysis

Hao Yan, Cheng Zhou, Jiangfeng Zhu, Rong Wan, Xuefang Wang

College of Marine Sciences, Shanghai Ocean University, Shanghai 201306, China

yanhao0623@foxmail.com

Abstract: Among the various species affected by bycatch, sea turtles are particularly vulnerable due to their low population numbers. Although many methods have been developed to mitigate sea turtle bycatch in longline fisheries, the extent to which these methods reduce the probability of sea turtle bycatch remains unclear. We performed a meta-analysis of 21 publications which included control experiments in longline fisheries comparing the use of mitigation methods to no mitigation methods for the same target species. The results indicate that the use of circle hooks, circle hooks with a wire appendage, fish bait, blue-white lights, and stingray-like bait can mitigate sea turtle bycatch (only circle hooks and fish bait were used in fishing operations). The remaining two types (blue-white lights and stingray-like bait) affected the catch of the target species and did not have the prospect of practical application. We also found that most mitigation measures did not significantly affect the catch of the target species, and some studies did not assess the catch of target species. Setting Hookpod-mini on branch lines and dyeing bait with colors are alternative mitigation methods. However, most of these methods are ineffective or inefficient in mitigating sea turtle bycatch or even unsuitable for applying to actual operations. Our study also identified two ways to mitigate turtle bycatch by affecting their senses (i.e., effective chemical deterrents and auditory systems), which may be promising research directions for the future.

Keywords: longline; sea turtle; bycatch; meta-analysis; risk ratio

1 Introduction

1.1 Overview of sea turtle bycatch in longline fisheries

1.1.1 Status of sea turtle populations

According to the data from the International Union for Conservation of Nature (IUCN), there are currently seven species of turtles in the oceans (IUCN 2022): Leatherback Turtle (*Dermochelys coriacea*), Green Turtle (*Chelonia mydas*), Loggerhead Turtle (*Caretta caretta*), Hawksbill Turtle (*Eretmochelys imbricata*), Olive Ridley Turtle (*Lepidochelys olivacea*), Kemp's Ridley Turtle (*Lepidochelys kempii*), and Flatback Turtle (*Natator depressus*). Among them, the hawksbill turtle and kemp's ridley turtle are listed as critically endangered species by the IUCN, the green turtle is listed as an endangered species, leatherback turtle, loggerhead turtle, and olive ridley turtle are listed as vulnerable species, and the population status of flatback turtles remains unknown due to a scarcity of data. (IUCN 2022). Despite various measures taken by many countries and organizations, such as establishing marine protected areas, combating the illegal trade of turtle products, protecting turtle nesting beaches, mandatory use of bycatch reduction devices in fisheries, and international laws for turtle conservation, the population of most turtle species is still declining according to the data from the IUCN (IUCN 2022). Along with the decrease in adult individuals, the survival environment of most turtles has become extremely fragile due to human activities such as commercial fishing. Consequently, the current situation of turtle populations is not optimistic, and addressing the issue of turtle bycatch in fisheries is urgent.

1.1.2 Sea turtle bycatch in longline fisheries

Longline fishing is an essential operation in pelagic fisheries, with many countries worldwide using fleets of varying scales for longline fishing operations in oceans or sea areas. These fleets contribute significantly to the total number of vessels and the fishing yields in the global fishing industry. Longline fishing in the industry is categorized into different types based on the target species, such as tuna (Thunnini) longline fishing, swordfish (*Xiphias gladius*) longline fishing, and ribbonfish (*Trichiurus lepturus*) longline fishing. Although longline fishing can be adjusted flexibly according to the mentioned fish species, bycatch of turtles is still common in longline fishing, as most turtles often migrate from their foraging areas to their nesting sites (López-Castro and Cecilia 2013). During these migration processes, turtles are impacted by longline fleets from various oceans, resulting in the bycatch of different turtle species in large numbers. This can affect the population and body size of certain turtle species in specific areas and may even escalate the operational expenses of longline fishing concerning handling hooks or other equipment.

Different turtles inhabit different water layers and have distinct nesting and habitat areas. For example, hawksbill turtles, mainly distributed in the Atlantic and Pacific, usually inhabit shallow waters (Bjorndal and Bolten 2010). These waters do not overlap significantly with the operating water layers of most longline fishing activities. Additionally, due to their relatively low population and being rarely caught as bycatch, hawksbill turtles are seldom caught in longline fishing. Olive Ridley turtles are predominantly found in waters ranging from 80 to 110 meters deep, which overlaps with the areas where longline hooks are deployed for targeting tuna and swordfish. There is a greater probability of bycatch in this species. Loggerhead turtles, leatherback turtles, and green turtles also share overlapping habitats with longline fishing, and their bycatch data constitute a considerable portion of turtle bycatch in the longline fishery.

In addition to the relationship between longline hook depth and sea turtle bycatch described above, other factors contribute to turtle bycatch, such as turtles getting entangled and drowning due to the size or shape of the hooks or the preference of certain turtle species for bait that can lead to accidental ingestion of hooks. Additionally, operational factors, seasonal variations, and other elements may be associated with turtle bycatch. There are various reasons for turtle bycatch in longline fishing, research and mitigation efforts primarily focus on hook and bait types, likely due to the limited maturity or effectiveness of available methods to alleviate bycatch for other turtle species, based on the availability of oceanic research and data on these specific aspects.

1.2 Purpose and Significance

Currently, many species of sea turtles worldwide are affected by longline bycatch and face a series of impacts, such as habitat changes and illegal killings, resulting in a continued decline in population numbers. Even though longline fishing vessels in many countries have been equipped with some measures to mitigate sea turtle bycatch, such as using circle hooks instead of J hooks (Swimmer *et al*. 2017) and using fish bait instead of squid bait (Catarina *et al*. 2020), there is still a lack of quantitative evaluation on the effectiveness of existing methods to mitigate sea turtle bycatch and to determine the relationship between the methods mentioned in the literature and the mitigation of sea turtle bycatch. To identify further research directions or practical applications for these mitigation methods, we conducted a meta-analysis of peer-reviewed literature, gray literature, and conference proceedings to assess the effectiveness of existing methods in reducing the probability of sea turtle bycatch in longline fishing. We first evaluated whether the mitigation techniques or methods mentioned in this literature are practical or feasible and whether they have been field-tested at sea with control groups. Our study retrieved almost all relevant studies, including different hooks, bait types, or other methods, and conducted a preliminary comparison of data on sea turtle bycatch in traditional longline fishing and by the existing mitigation techniques. We also assessed the effectiveness of different mitigation methods for different turtle species. The evaluation in our study primarily focused on the bycatch of four common species of sea turtles in longline fishing: the leatherback turtle, loggerhead turtle, green turtle, and olive ridley turtle. These four turtle species were chosen because they inhabit similar water layers to the operational water layers of longline fishing, and the effectiveness of mitigation measures should be assessed across different turtle species. By studying the effectiveness of different mitigation methods for different turtle species and examining whether existing methods are effective for all common bycatch species, this research provides a reasonable reference for future studies on mitigating sea turtle bycatch. In circumstances where data permits, to emphasize the benefits of maintaining the target fish species while alleviating the bycatch of sea turtles, we have also compared the impact of these mitigation measures on the catch efficiency of the target fish species as much as possible. Target fish species comprised swordfish (*Xiphias gladius*) and tunas such as bigeye tuna (*Thunnus obesus*), yellowfin tuna (*Thunnus albacares*), and albacore (*Thunnus alalunga*). Some publications focus on the target species of dolphinfish (mahi-mahi).

2 Method

2.1 Sources of data

We used a meta-analysis approach to quantitatively analyze the overall effectiveness of turtle bycatch mitigation methods applied in longline fishing. The data used in our study mainly comes from literature that provides control experimental data. Springer, ScienceDirect, and Wiley Online Library were the three primary databases searched for our study. Additionally, newly published or accidentally encountered literature not indexed in the databases were included. The review followed PRISMA best-practice protocols (Moher *et al*. 2015).

The inclusion criteria established for our study were threefold. First, the literature must include experiments with a control group, meaning there must be data on both the “control group” longline fishing gear without modification and the "experimental group" longline fishing gear using turtle bycatch mitigation methods. Second, the turtle bycatch mitigation methods must apply to longline fishing gear, especially those targeting tuna, swordfish, and marlin, without significantly altering the commercial fisheries or increasing fishing costs. Third, the data in the literature must be obtained through field experiments at sea; data obtained from laboratory testing were not included in our study. The selected mitigation methods for our study were not necessarily designed to mitigate turtle bycatch; they may have been designed to mitigate the bycatch of other species, such as seabirds. We included them if these methods have effectively collected data on turtle bycatch in field experiments. Our study included all formally published literature or conference records and unpublished peer-reviewed literature that met these three criteria (Figure 1). To ensure that no relevant publications were missed, the keywords used for the search were “turtle”, “longline” and “bycatch” that broad English terms.

2.2 Research Methods

Our study uses the relative risk ratio (RR) (Ospina *et al*. 2012) as a measurement standard to quantify the impact of turtle bycatch mitigation methods. To fully utilize the data included in our study, all control experiment data in each literature were recorded and processed, including the number of hooks used in the control group and the experimental group (using mitigation methods), the total number of turtles caught on the hooks in both the control and experimental groups and the number of hooks that caught different species of turtles. The calculation formula for the relative risk ratio is as follows:

$$RR\ (Risk\ Ratio) = (event.e/n.e) / (event.c/n.c)$$

The event.e and event.c represents the number of turtles caught with or without using bycatch mitigation methods; the n.e and n.c represents the total number of hooks used with or without mitigation methods in our study.

Our study also calculated the relative risk ratio (relative bycatch rate) for different species of turtles with events.e and event.c represents the number of different species of turtles caught with or without mitigation methods. In addition, our study also noted the number of target fish species caught, which provides a reference for evaluating the practicality or research potential of a mitigation method. The reason for using the RR (Risk Ratio) is that, compared to the OR (Odds Ratio), the literature included in our study has recorded the total number of hooks used in the experiments rather than just the probability of bycatch. For the RR (Risk Ratio), a statistically significant effect on turtle bycatch was indicated when the 95% confidence interval of the model coefficient did not exceed 1. We applied the same method to the analysis of the target fish species.

We identified eight different methods for mitigating turtle bycatch (table 1; table 2; table 3; table 4), which are summarized as follows: (i) Replacing J hooks with circle hooks in longline fishing operations (Bolten *et al*. 2004; Gilman *et al*. 2007; Yokota *et al*. 2006; Garcíacortés *et al*. 2008; Piovano *et al*. 2009; Sales *et al*. 2010; Piovano *et al*. 2012; Pacheco *et al*. 2011; Cambiè *et al*. 2012; Domingo *et al*. 2012; Foster *et al*. 2012; Santos *et al*. 2012; Andraka *et al*. 2013; Coelho *et al*. 2015; Santos *et al*. 2015). Circle hooks are round-shaped hooks applied in longline fishing with varying sizes, ranging from 14/0 to 18/0. Unlike traditional J hooks, circle hooks do not hook into sea turtles but get caught in their limbs or mouths. They have been recognized in many literature sources as having the ability to mitigate turtle bycatch and improve the survival rate of released turtles to some extent. (ii) Using fish bait instead of squid bait, such as using mackerel as bait (Yokota *et al*. 2006; Foster *et al*. 2012; Santos *et al*. 2012; Coelho *et al*. 2015; Swimmer *et al*. 2010; Boggs and Swimmer 2007), this method can mitigate the possibility of turtles swallowing the whole hook. If the turtles are attracted by the bait on the longline fishing hook, fish bait can be easily bitten off by the turtles. In contrast, squid bait gets entangled on the hook, making it difficult for turtles to remove, resulting in sea turtles being bycatch. (iii) Using circle hooks with a wire appendage (Boggs and Swimmer 2007). The width of the hook has been widened based on the circle hook, preventing smaller marine organisms from easily swallowing the hook and getting caught as bycatch. (iv) Dyeing the bait used blue in longline fishing (Yokota *et al*. 2009) aims to mitigate the visibility of by-catch species. (v) Further changing the bait by replacing fish bait with stingray bait (Echwikhi *et al*. 2010), as data from the included literature in the analysis suggest, may have the potential to mitigate turtle bycatch further. (vi) Using offset hooks, where the bent part of the circle or J hook is not parallel to the connecting branch line and instead forms a certain angle, usually between 0° and 30° (Swimmer *et al*. 2010). (vii) Deploying a Hookpod-mini" device on the branch lines, with literature included in this study reporting both turtle and seabird bycatch (Gianuca *et al*. 2021). (viii) Conducting controlled experiments with different lights at the end of longline fishing branch lines, such as white light, blue light, and green light, to determine which light frequency can improve the selectivity of longline fishing gear (Afonso *et al*. 2020).

2.3 Statistical analysis

2.3.1 Data classification

There are many methods for mitigating sea turtle bycatch. Our analysis included 21 studies and most of the mitigation methods for sea turtle bycatch involved circle hooks and fish bait. Moreover, there may be heterogeneity due to the variations in oceanic and offshore experimental conditions. Our study will categorize these two types of mitigation methods separately for meta-analysis. Our study aims to determine the effectiveness of these mitigation methods on sea turtle species heavily impacted by longline fishing and to assess their overall effectiveness on all sea turtle species. Therefore, the primary data for the meta-analysis were classified. Among the 21 studies included in this study, 54 research data sets could be subjected to meta-analysis. When the included literature for the offshore experiments had multiple independent control studies, this study calculated the separate effect size for each study. The data were divided into three categories: circular hooks, fish bait, and other mitigation methods. There were 35 datasets for meta-analysis regarding the use of circular hooks in place of J-hooks, ten datasets for meta-analysis regarding the use of fish bait as a mitigation method, and nine datasets for meta-analysis regarding other methods of mitigating sea turtle bycatch (examining the overall effect of different mitigation methods on sea turtle bycatch). Since all the data in our study were binary variables, we performed heterogeneity tests using the Metabin function in the Meta package (Balduzzi *et al*. 2019) in RStudio. We selected the appropriate model for data analysis. It should be noted that although all the research methods in the use of circular hooks mitigation were based on field experiments using longline fishing, there could be variations in the sizes of circle hooks used, which may affect the results of the heterogeneity test in our study. We also collected data on the target fish species documented in the selected publications for subsequent data analysis——There are 29 sets of records on the data of target fish species in these 21 publications that meet the characteristics of the above three sets of data simultaneously.

2.3.2 Heterogeneity tests, publication bias tests, and other analyses

We conducted a total of four data analyses. The first three analyses examined the effectiveness of the three data types mentioned earlier in mitigating sea turtle bycatch and we analyzed the data on target fish species in the publications to assess whether the mitigation methods would affect their catch. Due to the anticipated heterogeneity in these four types of data, resulting from different species of sea turtles and target fish species, different experimental locations, or the use of different sizes of fishing hooks, our study was inclined towards using a random-effects model for data analysis when conducting heterogeneity tests. The random-effects model was more suitable when there was relatively high heterogeneity among studies. When using the Metabin function for heterogeneity tests, our study focused on the results of the Q test (Huedo-Medina *et al.* 2006) and the I^2 (Huedo-Medina *et al*. 2006). For the classification data with a small number of study groups, our study mainly focuses on the result of the I^2 (the I^2 statistic could potentially overestimate heterogeneity when there are more research samples). For the data with a more significant number of study groups using the circle hook mitigation method, our study primarily emphasizes the result of the Q test. This is because even if the meta-analysis result shows no heterogeneity, the Q test might still have statistical significance when many studies are included, even if heterogeneity exists, the Q test might not have statistical significance when fewer studies are included. our study also obtained the results of the tau^2 test when using the Metabin function and compared it with the results of the Q test to validate the heterogeneity test results (Balduzzi *et al*. 2019; Huedo-Medina *et al*. 2006).

After completing the heterogeneity test, models were established based on the heterogeneity results of the four types of data, and a visual forest plot was generated using functions in the Meta package (Huedo-Medina *et al*. 2006). Sensitivity analysis was then conducted using the Metainf function in the Meta package (Huedo-Medina *et al*. 2006). This function allows the analysis to be carried out by excluding each included dataset one by one and observing the results. If excluding a specific study alters the heterogeneity or causes the confidence interval to exceed 1, resulting in a loss of statistical significance, further analysis should be conducted on that specific study. Various aspects, such as the experimental location and sample size, should be analyzed and discussed to identify the source of heterogeneity. Suppose the results remain stable and the heterogeneity does not change significantly or still holds statistical significance after excluding each dataset. In that case, the next step of subgroup analysis should be performed (heterogeneity analysis can also proceed in parallel). Subgroup analysis primarily categorized the turtle species. By selecting the turtle species using the Metabin function, we used random and common effects models in subgroup analysis. Since subgroup analysis is likely to identify studies with homogeneity, using these two models for analysis is more prudent. If heterogeneity still exists within a subgroup, it is likely due to differences in immersion time and geographical regions, but it is not easy to categorize due to significant differences in latitude and longitude between the experimental locations and inconsistencies or lack of recorded immersion time. we did not conduct a subgroup analysis on these factors, but their influence as a source of heterogeneity still objectively exists.

Publication bias testing was required. According to the Intervention Measures Systematic Review Manual (Higgins *et al*. 2008), We used the funnel function in RStudio to generate funnel plots for sub-group studies with a sample size greater than or equal to 10. We also conducted the Peters test using the Metabias function (Huedo-Medina *et al*. 2006). For other mitigation methods with a sample size of less than 10, the manual does not recommend conducting the test; only the creation of a funnel plot is necessary. The distribution of each study in the funnel plot should be approximately symmetric, with an even distribution on both sides of the dashed line in the middle of the funnel plot. If the funnel plot shows asymmetry, our study will use the trim-and-fill method to adjust. The Trimfill function (Huedo-Medina *et al*. 2006) in the Meta package estimates the number of missing studies and proceeds with a meta-analysis. Our study used the Meta package (Huedo-Medina *et al*. 2006) in the R for all analyses.

3 Results

3.1 Meta-analysis results of turtle bycatch mitigation using circle hooks

Our literature search yielded 323 publications, including research papers, reviews, conference reports, etc. After removing duplicate and irrelevant publications, 21 articles were eligible for inclusion in the present meta-analysis (Figure 1). Our 21 publications yielded 35 studies using circle hooks to mitigate turtle bycatch that met the inclusion criteria for our meta-analysis (table 1). The heterogeneity test result showed significant heterogeneity (I^2 = 84.9%, 95% CI = 79.9% to 88.6%; tau^2 = 0.3067, 95% CI = 0.1464 to 0.5653; Q = 225.25, df = 34, p < 0.0001), a random-effects model was utilized to conduct a meta-analysis on the data from these 35 studies. The Effectiveness of using circle hooks to mitigate turtle bycatch has indeed been effective in reducing sea turtle bycatch (exp (RR) = 0.50, 95% CI = 0.40 to 0.63; Figure 2). Sensitivity analyses were performed in this study subgroup because of the presence of heterogeneity. After seriatim eliminating each research data, the results remained robust without any outliers, indicating that the 95% confidence interval did not exceed 1 (Figure 3). Sub-group analysis was subsequently conducted in this study using both common-effects and random-effects models. The models were constructed based on four species: leatherback, loggerhead, olive ridley, and green turtle, which formed the basis for sub-group analysis. The results of this study subgroup indicated that the green turtles group showed homogeneity, meaning that the I^2 was less than 40% and p-values greater than 0.05 for the Q test. Additionally, the sub-group analysis for green turtles revealed complete homogeneity and confidence intervals exceeding 1. This implies that the circle hook is less effective in mitigating impacts on green turtles than other turtle species (Figure 4). Furthermore, heterogeneity still existed in the subgroups of other turtle species (both I^2 were more excellent than 40%, and the p-value of the Q-test was still less than 0.01), most likely due to the wide range of habitats of other turtle species in all oceans, the significant differences in sea areas or latitudes and longitudes of each group of study data, and the differences in soaking time or duration of operations. The heterogeneity analysis showed that the circle hooks' mitigation effect varied for common sea turtle bycatch species. This study subgroup also examined the presence of publication bias within the selected literature, and the results indicated no publication bias in this study subgroup included in the analysis. (The funnel plot exhibits a balanced distribution from left to right; Figure 5).

3.2 Results of a meta-analysis on the use of fish bait to mitigate sea turtle bycatch

As above, data from 10 separate studies using fish bait to mitigate sea turtle bycatch in 21 publications were included in the meta-analysis of this study subgroup (table 2). The heterogeneity test indicated significant heterogeneity (I^2 = 74.4%, 95% CI = 52.2% to 86.3%; tau^2 = 0.1206, 95% CI = 0.0298 to 0.9584; Q = 35.20, df = 9, p < 0.0001) and the random-effects model was also used for the meta-analysis of these ten studies. Regarding the effect of using fish bait to mitigate sea turtle bycatch, it was found to mitigate it somewhat (exp (RR) =0.54, 95% CI = 0.41 to 0.72; Figure 6). Also, due to heterogeneity, this study subgroup continued to use a random effects model for sensitivity analysis (Figure 7), and no outliers were seen after removing each study data individually (95% confidence interval did not exceed 1), with robust results. The species of sea turtles were still defined as the criteria for sub-group analysis in this study subgroup and the taxonomic categories were changed to include loggerheads, olive ridley, leatherback, and combined species. There was only one study of olive ridley and combined species; the two subgroups' analyses were not statistically significant and were only listed on the graph in this study subgroup (Figure 8), with no corresponding results for this species; the study of the leatherback was even completely homogeneous (I^2 = 0%, p-value of 0.56 for Q-test); the subgroup analyses of loggerhead still maintained a high degree of heterogeneity, and the source of heterogeneity for loggerheads may be since different control studies were conducted in waters inhabited by different subspecies of loggerhead turtles(I^2 = 77%, tau^2 = 0.3803; Figure 8). Publication bias was also assessed for these ten studies, and the results indicated the presence of publication bias. Four additional studies were added on the right side of the funnel plot to conduct a trim-and-fill analysis and reassess the meta-analysis. The estimated combined effect size did not change significantly (RR value before trim-and-fill: 0.54, RR value after trim-and-fill: 0.6649, both with confidence intervals not exceeding 1). The influence of publication bias on the results was minimal, and the results remained statistically significant (Figure 9).

3.3 Results of a meta-analysis of other methods to mitigate sea turtle bycatch

In addition to the two methods of mitigating sea turtle bycatch with more study data above, the remaining mitigation methods were combined for meta-analysis in our study, for a total of nine different studies that mitigated sea turtles in other ways (table 3). The results of the test for heterogeneity between mitigation methods showed a high degree of heterogeneity (I^2 = 89%, 95% CI = 81.1% to 93.5%; tau^2 = 0.7607, 95% CI = 0.4886 to 1.8587; Q = 72, df = 8, p < 0.0001). A random effects model was used for the meta-analysis, and the confidence interval for the combined effect values obtained in this study subgroup was large (exp (RR) = 0.46, 95% CI = 0.24 to 0.88; Figure 10), and the confidence interval for the separate analyses of the data from multiple studies spanned 1. The effect of its effect on turtle bycatch was highly variable and did not indicate that it necessarily had a mitigating effect on turtle bycatch. Among these studies, Study 1 was a circle hook with a wire appendage (Boggs and Swimmer 2007); Studies 2 and 3 used blue bait (Yokota *et al*. 2009); Study 4 used stingray bait instead of fish bait (Echwikhi *et al*. 2010); Studies 5 and 6 were offset circle hooks versus non-offset circle hooks (Swimmer *et al*. 2010); Study 7 was Hookpod-mini (Gianuca *et al*. 2021); and Studies 8 and 9 (Afonso *et al*. 2020) used different lights at the end of the branch line (using white and blue light compared to green light; Figure 10). Unlike the above two heterogeneity analyses conducted with the same mitigation methods using sea turtle species as subgroups, the present study conducted a subgroup analysis with mitigation methods as a source of heterogeneity, showing that excluding a single study, the data from the remaining studies showed complete homogeneity and different mitigation methods all had different effects on the bycatch probability of sea turtles (Figure 11). In addition, studies 1, 4, 8, and 9 reduced the relative probability of sea turtle bycatch. In contrast, the data from the remaining five studies did not present a significant effect on the mitigation of sea turtle bycatch and failed to mitigate sea turtle bycatch. Despite the source of heterogeneity from the effects of different mitigation method experiments, sensitivity analyses were conducted in this study subgroup to confirm whether any data significantly affected the robustness of the combined effect values of this study's model. The results showed that the combined effect values of the random effects model exceeded one after removing studies 4, 8, and 9, respectively. The effect values of the remaining studies combined were not statistically significant. The confidence interval after excluding study 1 is about to exceed 1, which indicates that the results of the random effects model in this study subgroup were not robust and vulnerable to individual studies with larger sample sizes (Figure 12). This study subgroup was also tested for publication bias. The results showed publication bias (Figure 13). The results of this study subgroup were still not statistically significant (exp (RR) = 0.7283, 95% CI = 0.3265 to 1.6243) after adding two studies to the funnel plot using the trim-and-fill method (Trimfill function).

3.4 Meta-analysis results of the target fish species

Among these 21 publications, there are data records for 29 groups of target fish species (table 4). Groups 1 to 19 represent data on target fish species caught using circular hooks to mitigate sea turtle bycatch. Groups 20 to 24 represent data on other target fish species caught while mitigating sea turtle bycatch. Groups 25 to 29 represent data on target fish species caught using bait to mitigate sea turtle bycatch. Overall, the use of these mitigation methods did not significantly reduce the capture of target fish species (exp (RR) = 0.85, 95% CI = 0.72 to 0.99; Figure 14), and the overall model showed a high degree of heterogeneity (I^2 = 99.3%, 95% CI = 99.2% to 99.4%; tau^2 = 0.1635, 95% CI = 0.0941 to 0.2968; Q = 4162.41, df = 28, p < 0.0001). The tested heterogeneity was due to significant differences in the experimental methods between the various sea turtle bycatch mitigation techniques. Among them, only the two groups (23 and 24) using different lighting to replace green lights significantly reduced the capture of target fish species (exp (RR) = 0.35, 95% CI = 0.32 to 0.39; exp (RR) = 0.26, 95% CI = 0.24 to 0.30), and no outliers were observed after sensitivity analysis (Figure 15). We conclude that the impact of these sea turtle bycatch mitigation methods on capturing target fish species is not highly variable. Some publications did not provide data on target fish species, so we will separately analyze the content of these articles in subsequent discussions. After using the trim-and-fill method (8 added studies), we found that the confidence interval did not exceed 1 (exp (RR) = 0.7326, 95% CI = 0.6273 to 0.8557, p<0.0001; Figure 16), and the results were still statistically significant.

4 Discussion

4.1 General Description

The significance of using meta-analysis in our study is its mature statistical research method, which enables the reanalysis of research findings on similar topics in publications. It can analyze the typical relationship between two variables based on the combined effect size and determine the impact of these mitigation methods on all species of turtles (previous studies often only conducted meta-analysis on one species of turtle or did not quantitatively analyze the impact of different mitigation methods on all turtles). In addition, meta-analysis can reveal or expose uncertainties and differences between studies. The meta-analysis results of our study on longline fishing indicate that different bycatch mitigation methods have varying effects. Some methods can significantly mitigate sea turtle bycatch based on the data alone (e.g., the use of circle hooks can reduce turtle bycatch by about half; Figure 2), while other methods have little to no effect on mitigating turtle bycatch (e.g., the use of hookpod-mini only reduces turtle bycatch by about 11%; Figure 10). Since meta-analysis tends to select studies with significant results, the results obtained using random effects models in our study may be biased. Consequently, we conducted publication bias tests separately for the meta-analysis results of bycatch——only performing "Peters" test on studies with a sample size greater than or equal to 10 (Higgins *et al*. 2008). Only one, which includes different methods for mitigating sea turtle bycatch, showed publication bias, and caution should be exercised when interpreting the meta-analysis results for this category. The meta-analysis in our study only included publications on mitigating sea turtle bycatch with control data, and there may be other more effective methods for mitigating sea turtle bycatch that have not been tested in the field or controlled experiments. There may also be other mitigation methods that are not classified or have a small sample size, making them unsuitable for meta-analysis but potentially effective. These methods are beyond our study's scope of analysis and discussion. We incorporate the analysis results of the target fish species into the subsequent classification discussion.

4.2 Analysis of the results of using circle hooks to mitigate sea turtle bycatch

Circle hooks are among the most studied gears to mitigate sea turtle bycatch. Many regional fishery organizations have started to require longline fishing vessels from different countries to use circle hooks instead of J hooks. According to the meta-analysis conducted in our study, even when the same mitigation method was used, there was still heterogeneity (Figure 2). Although the subgroup analysis of our study shows that sea turtle species are one source of heterogeneity, heterogeneity still exists in the subgroups. This heterogeneity may be due to different sizes or specifications of circle hooks, which may impact sea turtle bycatch differently. Although circle hooks are more effective in reducing sea turtle bycatch compared to traditional J hooks, our study still believes that further discussion is needed on various types of circle hooks, as not all types of circle hooks have shown promising results for all species of sea turtles, as shown in the forest plot of the meta-analysis (Figure 2). Furthermore, among the 35 studies included in this sub-study, there were indeed control data using circle hooks of different sizes or a combination of different sizes. According to the literature examined in this study, we found longline fishing data from Ecuador, Costa Rica, and Panama in the eastern Pacific from 2004 to 2010 (Andraka *et al*. 2013). The field-measured data showed that for longline fishing targeting dolphinfish and swordfish, as well as for longline fishing targeting dolphinfish (*Coryphaena hippurus*), the use of 14/0 and 15/0 circle hooks resulted in reduced sea turtle bycatch compared to J hooks, but the difference in reduction between 15/0 and 14/0 was not significant. For longline fishing targeting tunas and swordfish, the bycatch reduction was better with 18/0 circle hooks compared to 16/0 circle hooks. These are overall effects for all sea turtle species. If we classify and examine the effects of each circle hook for each sea turtle species separately, the green sea turtle and Pacific ridley turtle showed the most significant reduction. In contrast, the critically endangered hawksbill turtle did not show a particularly significant effect. There was no record of hawksbill turtles being caught again after the adoption of circle hooks by the fishing fleet. The field-measured data compared different circle hooks; larger circle hooks are more effective than smaller ones. This finding is consistent with an article we reviewed (Stokes *et al*. 2011), which found that as hook size increases, the probability of sea turtles swallowing the hook decreases, and smaller sea turtles are unlikely to swallow larger hooks. However, using circle hooks in longline fishing targeting dolphinfish led to a significant decrease in catch, in contrast to almost no change in longline fishing targeting tunas and swordfish. This may hinder the promotion of circle hooks in this type of longline fishing (as the cost of circle hooks does not vary significantly compared to J hooks, and they do not readily reduce the catch of target species in tuna longline fishing).

According to the literature data and relevant studies included in our research, it is suggested that the heterogeneity of sources is likely not solely determined by hook types but also related to the soaking time of longline fishing, the size of turtles, and the positioning of hooks on turtles. For instance, hooking locations of J-hooks and circle hooks on leatherback and loggerhead turtles have been reported previously (Watson *et al*. 2005). Furthermore, the study (Watson *et al*. 2005) compared the relative advantage of circle hooks with and without a 10° angle regarding similar soaking time and sea surface temperature. The data revealed that the difference in relative advantage between circle hooks with and without an angle was insignificant. Although the meta-analytical results of our study indicate that circle hooks can mitigate turtle bycatch, further research is still needed to investigate whether circle hooks are effective for all turtle species and whether they affect the catch of target fish species in longline fishing. Additionally, consideration should be given to the soaking time during longline fishing operations in different oceans or fleets and the post-capture survival rate of turtles.

It is worth mentioning that the sensitivity analysis of this classification study yielded robust results. The included studies did not have any dominating data that would significantly influence the combined effect size of the random effects model. In other words, there were no datasets with large sample sizes that would impact the overall results of the meta-analysis. Additionally, the publications corresponding to the data of 35 studies showed no tendency according to the test results of our study. This indicates that although the meta-analytical results of our study still exhibit some heterogeneity, the use of circle hooks to mitigate turtle bycatch is objectively credible, and circle hooks are a promising and practical choice to mitigate turtle bycatch.

4.3 Analysis of the results of using fish bait to mitigate sea turtle bycatch

The results of our study show that the heterogeneity in the use of bait to alleviate turtle bycatch not only stems from the turtle species but also often originates from the research data included in our study. This is because the impact of bait types on turtle bycatch is mainly reflected in the texture of the bait itself and the turtles' olfactory or visual perception of the bait. In the publications included in our study and other studies that were not included, we found that using circle hooks with mackerel bait significantly reduced the bycatch of leatherback turtles and loggerhead turtles (Watson *et al*. 2005). Fish bait significantly reduced the number of loggerhead turtles remaining on hooks but did not significantly affect the hook retention of swordfish or blue sharks (*Prionace glauca*) (Santos *et al*. 2012). We also found that the number of sea turtles caught as bycatch using only fish bait was significantly lower than those caught using a squid and fish bait mixture (Ba´ez *et al*. 2010). Meanwhile, a study conducted laboratory experiments and field tests in the Mediterranean, the remote areas in the northeastern Atlantic, and the western North Pacific, which showed that when squid and mackerel were used as bait simultaneously, turtles were more likely to feed on squid rather than mackerel (Echwikhi *et al*. 2010). The results of the above studies, along with our meta-analysis (RR=0.54, 95% CI = 0.41 to 0.72), all indicate that using fish as bait can, to some extent, reduce turtle bycatch or hook retention. In addition, we found that, regarding fish bait such as sardines (*Sardina* *pilchardus*), sea turtles are more likely to tear and consume fish meat fragments or completely detach the fish from the hook for consumption. In contrast, the flesh of squid is harder to tear or detach from the hook, and most turtles tend to eat the squid completely. This results in squid bait usually covering the hook until the turtle swallows the hook (Stokes *et al*. 2011). When using fish as bait, turtles may better observe or perceive the presence of the hook and sometimes actively avoid the hook when in contact with metal.

In the longline fishing industry in the upper to middle layers of the Western North Pacific, a study conducted field experiments using longline fishing techniques (Yokota *et al*. 2009). They employed a Generalized Linear Model (GLM) with a Poisson distribution to analyze the impact of bait types (mackerel and squid) on the bycatch of loggerhead turtles. They also considered potential factors affecting turtle bycatch, such as bait types, bait color, catch of other species, and sea surface temperature, as controlled variables. The model analysis results indicated that bait type significantly affected loggerhead turtle bycatch. Compared to squid bait, mackerel bait reduced the probability of loggerhead turtle bycatch by 75% (Yokota *et al*. 2009). The selection of fish bait can be highly effective in reducing loggerhead turtle bycatch in the upper to middle layers of longline fishing. However, in our study, the confidence interval of the results for leatherback turtles was close to 1, indicating that the effect of reducing leatherback turtle bycatch was not statistically significant. These results further suggest that using fish bait may have different effects on different species of sea turtles. Some turtles may interact with longline fishing hooks by biting them and getting hooked in other parts of their bodies, such as fins (Watson *et al*. 2005). This could be one of the reasons for heterogeneity in the meta-analysis conducted in our study.

Overall, the selected models in our study are relatively robust, even when incorporating literature with smaller and larger sample sizes. Meanwhile, although the bias test for publication bias in our study indicated the presence of publication bias in these ten studies, this type of study may tend to publish research findings that show the effectiveness of fish bait in reducing sea turtle bycatch. However, after applying the trim-and-fill method, it was found that the results of our study were not significantly influenced by publication bias. The results demonstrating that fish bait can reduce the bycatch of certain turtle species still provide some reference for mitigating turtle bycatch. Additionally, based on the research data of target fish species recorded in the publications included in our study, the use of fish bait does not significantly reduce the catch of target fish species (Figure 14).

4.4 Analysis of the results of other sea turtle bycatch mitigation methods

There are many ways to mitigate or reduce sea turtle bycatch, and the two mentioned above are both feasible and cost-effective, given the present technological capabilities. Many longline fishing companies have started using circle hooks and fish bait for their operations. However, sea turtle bycatch is a complex behavior influenced by various factors, such as sea turtle's vision, sense of smell, and marine environment. It is necessary to find the mitigation of sea turtle bycatch from multiple aspects and perspectives. As a result, our meta-analysis also includes some other mitigation methods: One of the studies we included found that rays are more effective in reducing sea turtle bycatch than mackerel but could impact the catch of targeted fish species (Echwikhi *et al*. 2010). We also found that one of the studies investigated the impact of color (blue and non-blue) on sea turtle bycatch using a generalized linear model (GLM) with a Poisson distribution (Yokota *et al*. 2009). The model's analysis indicated that blue bait did not mitigate sea turtle bycatch. The laboratory study we did not include confirmed the model's predictions (Swimmer *et al*. 2005). Kemp's Ridley turtles and loggerhead turtles preferred untreated squid bait over squid bait dyed blue (though Kemp's Ridley turtles appeared to favor red bait in laboratory conditions), but field trials showed that blue-colored bait did not reduce sea turtle bycatch. While dyeing squid bait, blue has been proven to be an effective method to mitigate seabird bycatch in longline fishing (Kobayashi *et al*. 2003). It can be easily implemented in longline operations, and it seems to have no potential to mitigate sea turtle bycatch. Similarly, offset and non-offset hooks did not show any mitigation effects. These studies do not seem suitable methods for mitigating sea turtle bycatch.

Our study also found (Gianuca *et al*. 2021) a device called Hookpod at the branch end of longline fishing, which had no significant impact on sea turtle bycatch and the catch of targeted fish species but showed mitigation effects on seabird bycatch. Based on their data from experiments conducted in the southern Brazilian waters, both vessels equipped with Hookpod and untreated vessels had higher bycatch rates during the warm seasons (spring and summer) than in the cold seasons (autumn and winter). On the other hand, one of the studies we referenced found higher sea turtle bycatch numbers in the spring and autumn seasons during their offshore experiments in the southwestern Atlantic. In contrast, lower bycatch was observed during the summer and winter (Sales *et al*. 2010). Although there are some discrepancies between the two results, they still indicate a specific correlation between sea turtle bycatch and seawater temperature in different seasons, suggesting a seasonal variation. This aspect could potentially be considered in future policymaking to regulate the fishing seasons for longline fishing vessels.

Both sea turtles and tuna-like species are predators that rely to some extent on their vision, indicating that visual perception might play a role in sea turtle bycatch. In many longline fishing operations, using blue and green chemiluminescent lights is expected as the lights attract the targeted fish species, thus increasing the catch per unit effort (CPUE). Current research suggests that sea turtles can also perceive light within the blue-green range, which could affect them towards longline fishing vessels——mitigating sea turtle bycatch to some extent can be achieved by prohibiting the use of green vessel lights in the waters of Hawaii (Pradhan *et al*. 2006). However, one other study in our analysis revealed that although reducing the use of green lights can decrease sea turtle bycatch, it also reduces the catch of targeted fish species (Afonso *et al*. 2020). If a light wavelength could be found that is invisible to most targeted fish species in longline fishing operations but has an impact solely on sea turtles (as the color perception range of green and loggerhead turtles is more comprehensive than that of pelagic fish; Yokota *et al*. 2009), this method still holds great potential.

In addition, we identified a potentially effective method for mitigating sea turtle bycatch in these studies—— circle hooks with a wire appendage (Boggs and Swimmer 2007), effectively mitigating the bycatch of olive ridley turtles. Further increasing the circle hook's size reduces the chances of sea turtles being caught. The results of the meta-analysis show that it can mitigate over half of the sea turtle bycatch, with a small 95% confidence interval (0.34 to 0.55). This could provide a helpful reference in future research on methods to reduce sea turtle bycatch.

Our study found heterogeneity and publication bias among the nine-research data. Heterogeneity is due to different research methods for different mitigation measures. Through sensitivity analysis, this study revealed that Studies 4, 8, and 9 significantly impact the combined effect size of the articles. The reason is that these studies did not focus on a single turtle species but included statistics for all turtle species without separate records, while other literature included in the analysis recorded data separately by species. This could lead to differences in results. As a result, our study excluded these three sets of research data separately, rendering the study statistically insignificant and not demonstrating the effectiveness of mitigating turtle bycatch. Moreover, there is publication bias, indicating that the meta-analysis results of our study are not significant in mitigating turtle bycatch and are heavily influenced by the methods with mitigation effects. The combined effect size is unreliable, and further selection and exclusion of included literature may be necessary.

4.5 Prospects and Conclusions

Many countries and regional fishery organizations worldwide have implemented different policies to protect sea turtles. These measures have, to some extent, alleviated the issue of bycatch of sea turtles, such as implementing observer programs for supervision, establishing marine protected areas in the habitats where turtles aggregate to prohibit hooking, using larger circle hooks, switching to bait such as mackerel, and mandating the use of turtle excluder devices (Gianuca *et al*. 2021). Although these measures may have been influenced by the literature selected for our study, there is still room for improvement in mitigating sea turtle bycatch. Many studies have compared the common bycatch data on hooks and bait. However, they have rarely further considered the impact of other marine environmental factors or human-induced factors, such as water temperature and different soak times of longline fishing vessels in various countries (SONG Liming *et al*.2021). These factors may affect the bycatch rates of sea turtles, and there may also be variations in bycatch rates among different turtle species. While some studies have listed the bycatch rates of different turtle species, there is a lack of further discussion on the response of different turtle species to different mitigation measures. Moreover, due to the differences in hydrological conditions in the different areas where the field experiments were conducted, the results are likely inconsistent (which may also be one of the sources of heterogeneity in meta-analysis).

Currently, the combination of circle hooks and bait has been adopted by many longline fishing teams, and there may be many potential methods to mitigate sea turtle bycatch in the future. For example, research on sea turtle senses (olfaction or audition) is an area that still needs further exploration. A study not included in the meta-analysis (no control experiment was set) aimed to find one or more effective chemical deterrents to be applied to bait (Swimmer *et al*. 2007). The research showed that sea turtles still consumed bait treated with natural defensive compounds (*Aplysia* ink and *Loligo* spp. ink) or pungent and bitter compounds. Interestingly, parallel experiments conducted simultaneously on yellowfin and skipjack tuna showed that these target fish species also consumed squid bait treated with the same types of chemicals. Although these treated baits did not achieve the desired results, green turtles could detect various chemicals underwater (Manton *et al*. 1972). Loggerhead turtles could also detect chemicals in bait and identify the sources of these chemicals from the food items (Southwood *et al*. 2007). These studies indicate that olfactory interventions on bait for sea turtles are a promising research direction. However, field conditions at sea are often complex, and further research is needed to determine the effectiveness of these treated baits during in-situ tests. Additionally, using the auditory system of sea turtles for deterrent and mitigation of bycatch is worth considering. Since sea turtles and target fish species in longline fishing can detect sounds within similar frequency ranges, setting up sound deterrents for sea turtles may also deter target fish species, decreasing their capture rates. This method is still not mature and calls for in-depth research on the auditory system of sea turtles (Southwood *et al*. 2008).

The research on mitigating sea turtle bycatch can also include considerations of seawater temperature and seasonal variations and improvements in fishing methods. For longline fisheries targeting different species, the soaking time of the gear should be examined to study its relationship with sea turtle bycatch. Moreover, conducting field surveys at sea is necessary, as laboratory tests cannot completely simulate the marine environment. It should be noted that mitigating sea turtle bycatch should not only focus on reducing sea turtle ingestion of hooks but also pay attention to the reactions of different sea turtle species to the hooks. Increasing survival rates and release success after sea turtles are hooked, and their overall survival after being returned to the sea should be considered. Further tracking and data collection may be required in this regard. In the future, if various factors can be integrated into a comprehensive and mandatory set of protection measures, the mitigation of sea turtle bycatch can further advance based on the existing foundation, making significant contributions to conserving sea turtles and other marine animals. However, to mitigate sea turtle bycatch, the promotion or development of methods to prevent sea turtles from being caught on longline hooks and improve sea turtle release techniques must be achieved without compromising the catch rates of target fish species. Otherwise, it would not be easy to attract or encourage these methods by fishermen or fishing companies. Under the conditions allowed by these literature data, our study also analyzed whether these mitigation methods impact the catch of the target species rate or fishing effort. We found that most of these mitigation methods did not significantly impact the catch of the target species. The ideal methods for mitigating sea turtle bycatch should differ from fishing closures, protected areas, and other restrictive management measures. They should offer fishermen or fishing companies the ability to maintain their fishing operations at lower costs, enabling the implementation of sea turtle bycatch mitigation methods in longline fisheries.

The sea turtle bycatch in longline fisheries occurs worldwide and affects turtle species globally. Our study has three main conclusions. Firstly, although using circle hooks as a substitute for J hooks in longline operations effectively mitigates sea turtle bycatch (Replacing squid bait with fish bait can also reduce sea turtle bycatch, the studies we included have not found practical ways to mitigate sea turtle bycatch that are more efficient than these two categories), subgroup analysis results indicate that the effectiveness of circle hooks varies for different turtle species (the method of replacing squid bait with fish bait also yielded similar conclusions). It can be said that a single mitigating method to reduce sea turtle bycatch in longline fisheries for all turtle species has not been found yet. Secondly, many experimental data from the publications included in the meta-analysis are available, and most mitigation methods will not reduce the catch of the target fish species. However, some studies did not record the catch of target fish species or the hooking positions of these turtles (as some turtles are not caught by swallowing hooks). This neglect should be emphasized in future research. Lastly, insufficient studies (with small sample sizes) or mitigation methods not included in the meta-analysis may be the future direction for mitigating sea turtle bycatch. As mentioned earlier, further research and experiments are needed in turtle visual, olfactory, and auditory perception.

References

IUCN (2022) IUCN *Red List of Threatened Species*. Version 2022.2. Available at: www.iucnredlist.org (accessed 18 July 2023).

López-Castro and Cecilia, M. (2013) Evaluating Connections between Oceanic and Neritic Foraging Areas of Sea Turtles in the Atlantic Ocean with Biochemical Markers. *Marine Ecology Progress Series* **490**, 233-246.

Bjorndal, K.A and Bolten, A.B. (2010) Hawksbill Sea turtles in seagrass pastures: success in a peripheral habitat. *Mar Biol* **157**, 135–145.

Swimmer, Y., Gutierrez, A., Bigelow, K. et al. (2017) Sea Turtle Bycatch Mitigation in U.S. Longline Fisheries. *Frontiers in Marine Science* **4**, 260.

Catarina, C.S., Rosa, D. and Coelho, R. (2020) Progress on a meta-analysis for comparing hook, bait and leader effects on target, bycatch and vulnerable fauna interactions. *Collect Vol Sci Pap ICCAT* **77**, 182-217.

Moher, D., Shamseer, L., Clarke, M. et al. (2015) Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. *Systematic Reviews* **4(1)**, 1-9.

Ospina, P.A., Nydam, D.V. and Diciccio, T.J. (2012) Technical note: The risk ratio, an alternative to the odds ratio for estimating the association between multiple risk factors and a dichotomous outcome. *Journal of Dairy Science* **95(5)**, 2576-2584.

Bolten, A., Martins, H., Isidro, E. et al. (2004) Experiment to evaluate gear modification on rates of sea turtle bycatch in the swordfish longline fishery in the Azores -- Phase 1 and Phase 2.

Gilman, E., Kobayashi, D., Swenarton, T. et al. (2007) Reducing sea turtle interactions in the Hawaii-based longline fishery. *Biological Conservation* **139(1)**, 19-28.

Yokota, K., Minami, H. and Nobetsu, T. (2006). Research on mitigation of the interaction of sea turtle with pelagic longline fishery in the western North Pacific. In: Proceedings of the 3rd International Symposium on SEASTAR2000 and Asian Bio-logging Science (The 7th SEASTAR2000 workshop). SeaStar 2000 workshop, p7.

Garcíacortés, B., Mejutogarcía, J. and Ramoscartelle, A. (2008) Trials using different hook and bait types in the configuration of the surface longline gear used by the Spanish swordfish (Xiphias gladius) fishery in the Atlantic Ocean. Collect Vol Sci Pap ICCAT **62**, 1662–1670.

Piovano, S., Swimmer, Y. and Giacoma, C. (2009) Are circle hooks effective in reducing incidental captures of loggerhead sea turtles in a Mediterranean longline fishery? *Aquatic Conservation: Marine and Freshwater Ecosystems* **19(7)**, 779-785.

Sales, G., Giffoni, B.B. and Fiedler, F.N. et al. (2010) Circle hook effectiveness for the mitigation of sea turtle bycatch and capture of target species in a Brazilian pelagic longline fishery. *Aquatic Conservation Marine & Freshwater Ecosystems* **20(4)**, 428-436.

Piovano, S., Basciano, G., Swimmer, Y. and Giacoma, C. (2012) Evaluation of a bycatch reduction technology by fishermen: a case study from sicily. *Marine Policy* **36(1)**, 272-277.

Pacheco, J.C., Kerstetter, D.W., Hazin, F.H., Hazin, H., Segundo, R. S. S. L., Graves, J.E. et al. (2011) A comparison of circle hook and j hook performance in a western equatorial atlantic ocean pelagic longline fishery. *Fisheries Research* **107(1-3)**, 39-45.

Cambiè, G., Muio, R., Freire, J. et al. (2012) Effects of small (13/0) circle hooks on loggerhead sea turtle bycatch in a smallscale, italian pelagic longline fishery. *Bulletin of Marine Science* **(3)**, 88.

Domingo, Andrés., Pons, M., Jiménez, Sebastián. et al. (2012) Circle Hook Performance in the Uruguayan Pelagic Longline Fishery. *Bulletin of Marine Science*, **88(88)**, 499-511.

Foster, D.G., Epperly, S.P., Shah, A.K. et al. (2012) Evaluation of Hook and Bait Type on the Catch Rates in the Western North Atlantic Ocean Pelagic Longline Fishery. *Bulletin of Marine Science -Miami-* **88(3)**, págs. 529-545.

Santos, M.N., Coelho R, Fernandez-Carvalho J, et al. (2012) Effects of Hook and Bait on Sea Turtle Catches in an Equatorial Atlantic Pelagic Longline Fishery. *Bulletin of Marine Science* **88(3)**, 683–701.

Andraka, S., Moisés, Mug., Hall, M. et al. (2013) Circle hooks: Developing better fishing practices in the artisanal longline fisheries of the Eastern Pacific Ocean. *Biological Conservation* **160(1)**, 214-224.

Coelho, R., Santos, M.N., Fernandez-Carvalho, J. et al. (2015) Effects of hook and bait in a tropical northeast Atlantic pelagic longline fishery: Part I—Incidental sea turtle bycatch. *Fisheries Research* **164**, 302-311.

Santos M N, Coelho R, Fernandez-Carvalho J, et al. (2015) Effects of 17/0 circle hooks and bait on fish catches in a Southern Atlantic swordfish longline fishery. *Aquatic Conservation Marine & Freshwater Ecosystems* **23(5)**, 732-744.

Swimmer, Y., Arauz, R., Wang, J. et al. (2010) Comparing the effects of offset and non-offset circle hooks on catch rates of fish and sea turtles in a shallow longline fishery. *Aquatic Conservation: Marine and Freshwater Ecosystems* **20(4)**, 445-451.

Boggs., C.H., Swimmer, Y. (2007) Developments (2006-2007) in scientific research on using modified fishing gear to reduce longline bycatch of sea turtles. 3rd Regular Session of the Scientific Committee / Ecosystem and Bycatch SWG Working Papers, Honolulu, United States of America.

Yokota, K., Kiyota, M. and Okamura, H. (2009) Effect of bait species and color on sea turtle bycatch and fish catch in a pelagic longline fishery. *Fisheries Research* **97(1-2)**, 53-58.

Echwikhi, K., Jribi, I., Bradai, M.N. et al. (2010) Effect of type of bait on pelagic longline fishery–loggerhead turtle interactions in the Gulf of Gabes (Tunisia). *Aquatic Conservation Marine & Freshwater Ecosystems* **20(5)**, 525-530.

Gianuca, D., Canani, G., Silva-Costa, A. et al. (2021) Trialling the new hookpod-mini, configured to open at 20 m depth, in pelagic longline fisheries off southern Brazil (report & presentation). In: IATTC - 11th Meeting of the Working Group on Bycatch. IATTC BYC-11 INF-D, Online, p13.

Afonso, A.S., Mourato, B.L., Hazin, H. et al. (2020) The effect of light attractor color in pelagic longline fisheries. *Fisheries Research* **235,** 105822. doi: 10.1016/j.fishres.2020.105822.

Balduzzi, S., Rücker, G. and Schwarzer, G. (2019) How to perform a meta-analysis with R: a practical tutorial. *Evidence-Based Mental Health* **22**, 153-160.

Huedo-Medina, T.B., Julio Sánchez-Meca, Fulgencio Marín-Martínez, et al. (2006) Assessing heterogeneity in meta-analysis: Q statistic or I^2 index? *Psychological Methods* **11(2)**, 193.

Higgins, J.P. and Green, S. (2008) Cochrane Handbook for Systematic Reviews of Interventions. *Wiley-Blackwell*, 187-241.

Carruthers, E.H., Schneider, D.C. and Neilson, J.D. (2009) Estimating the odds of survival and identifying mitigation opportunities for common bycatch in pelagic longline fisheries. *Biological Conservation* **142(11)**, 2620-2630.

Stokes, L.W., Hataway, D., Epperly, S.P. et al. (2011) Hook ingestion rates in loggerhead sea turtles Caretta caretta as a function of animal size, hook size, and bait. *Endangered Species Research* **14(1)**,1-11.

Watson, J.W., Epperly, S.P., Shah, A.K. and Foster, D.G. (2005) Fishing methods to reduce sea turtle mortality associated with pelagic longlines. *Canadian Journal of Fisheries and Aquatic Sciences* **62**, 965–981.

Baez, J.C., Real, R., Macias, D.de la Serna, J. M.Bellido, J. J.Caminas, J. A. (2010) Captures of swordfish Xiphias gladius Linnaeus 1758 and loggerhead sea turtles Caretta caretta (Linnaeus 1758) associated with different bait combinations in the Western Mediterranean surface longline fishery. *Journal of Applied Ichthyology* **26(1)**, 126-127.

Swimmer, Y., Arauz, R., Higgins, B. et al. (2005) Food color and marine turtle feeding behavior: Can blue bait reduce turtle bycatch in commercial fisheries? *Marine Ecology Progress Series* **295(6)**, 273-278.

Kobayashi, D.R., Martin, S., Cook, J. et al. (2003) Performance assessment of underwater setting chutes, side-setting, and blue-dyed bait to minimize seabird mortality in Hawaii pelagic longline tuna and swordfish fisheries. Western Pacific Regional Fishery Management Council, Honolulu, USA.

Pradhan, N.C., Leung, P.S. (2006). A Poisson and negative binomial regression model of sea turtle interactions in Hawaii's longline fishery.

Fisheries Research **78(2)**, 309-322.

SONG, Liming., XU, Hui., SUI, Hengshou. et al. (2021) A review on the mitigation measures of the incidental sea turtles catch in tuna pelagic longline fisheries. *Fishery Modernization*, 2021, **48(3)**, 11.

Swimmer, Y., McNaughton, L., Southwood, A., Brill, R. (2007) Tests of repellent bait to reduce turtle bycatch in longline fisheries. *Bycatch Commun Network Newsl* **5**, 18-20.

Manton, M., Karr, A., Ehrenfeld, D.W. (1972) Chemoreception in the migratory sea turtle, Chelonia mydas. *Biology Bulletin* **143**: 184-195.

Southwood, A., Higgins, B., Brill, R. et al. (2007) Chemoreception in Loggerhead Sea Turtles: An Assessment of the Feasibility of Using Chemical Deterrents to Prevent Sea Turtle Interactions with Longline Fishing Gear. Pacific Islands Fisheries Science Center, Honolulu, Hawaii.

Southwood, A., Fritsches, K., Brill, R. et al. (2008) Sound, chemical, and light detection in sea turtles and pelagic fishes: sensory-based approaches to bycatch reduction in longline fisheries. *Endang Species Res* **5(2-3)**, 225-238.

Table 1. General information of the included studies (circle hook)

study	event.e	n.e	event.c	n.c	area	author	species	year
1	85	46040	147	92080	Atlantic	Alan B.Bolten	Loggerhead Turtle	2000
2	30	58766	14	29383	Atlantic	Alan B.Bolten	Loggerhead Turtle	2001
3	27	2150674	182	1282748	Pacific	Eric Gilman	Loggerhead Turtle	2007
4	13	2150674	42	1282748	Pacific	Eric Gilman	Leatherback Turtle	2007
5	13	5400	22	10498	Pacific	Kosuke Yokota	Loggerhead Turtle	2007
6	2	4200	3	7982	Pacific	Kosuke Yokota	Loggerhead Turtle	2007
7	86	286826	87	143473	Pacific	Jaime Mejuto	Loggerhead Turtle	2008
8	158	286826	77	143473	Pacific	Jaime Mejuto	Leatherback Turtle	2008
9	17	286826	10	143473	Pacific	Jaime Mejuto	Olive Ridley	2008
10	6	14664	20	14590	Mediterranean	Susanna Piovano	Loggerhead Turtle	2009
11	53	72914	117	72914	Atlantic	Gilberto Sales	Loggerhead Turtle	2010
12	7	72914	20	72914	Atlantic	Gilberto Sales	Leatherback Turtle	2010
13	1	72914	1	72914	Atlantic	Gilberto Sales	Green Turtle	2010

14	2	13287	9	13286	Mediterranean	Susanna Piovano	Loggerhead Turtle	2011
15	4	25085	12	25085	Atlantic	J.C. Pacheco	Leatherback Turtle	2011
16	4	25085	6	25085	Atlantic	J.C. Pacheco	Green Turtle	2011
17	3	25085	1	25085	Atlantic	J.C. Pacheco	Olive Ridley	2011
18	9	2320	14	2322	Mediterranean	Giulia Cambiè	Loggerhead Turtle	2012
19	11	22571	20	22571	Atlantic	Andrés Domingo	Loggerhead Turtle	2012
20	36	19911	48	19911	Atlantic	Andrés Domingo	Loggerhead Turtle	2012
21	177	369359	126	93780	Atlantic	Daniel G Foster	Loggerhead Turtle	2012
22	170	369359	113	93780	Atlantic	Daniel G Foster	Leatherback Turtle	2012
23	3	203568	7	101784	Atlantic	Miguel N Santos	Loggerhead Turtle	2012
24	21	203568	37	101784	Atlantic	Miguel N Santos	Leatherback Turtle	2012
25	72	203568	89	101784	Atlantic	Miguel N Santos	Olive Ridley	2012
26	0	11174	1	11195	Pacific	Sandra Andraka	Loggerhead Turtle	2013
27	0	177942	3	178732	Pacific	Sandra Andraka	Leatherback Turtle	2013
28	16	177942	24	178732	Pacific	Sandra Andraka	Green Turtle	2013
29	2	34619	10	40890	Pacific	Sandra Andraka	Green Turtle	2013
30	15	65603	15	69040	Pacific	Sandra Andraka	Green Turtle	2013
31	63	177942	155	178732	Pacific	Sandra Andraka	Olive Ridley	2013
32	29	34619	72	40890	Pacific	Sandra Andraka	Olive Ridley	2013
33	78	65603	73	69040	Pacific	Sandra Andraka	Olive Ridley	2013
34	87	169680	96	84840	Atlantic	Rui Coelho	Leatherback Turtle	2015
35	122	297600	138	148800	Atlantic	Sérgio Amorim	Loggerhead Turtle	2015

Table 2. General information of the included studies (fish bait)

study	event.e	n.e	event.c	n.c	area	author	species	method	year
1	11	6075	27	6075	Mediterranean	Christofer H.Boggs and Yonat Swimmer	Loggerhead Turtle	bait（fish and squid）	2007
2	2	4200	13	5400	Pacific	Kosuke Yokota	Loggerhead Turtle	bait（fish and squid）	2007
3	3	7982	22	10498	Pacific	Kosuke Yokota	Loggerhead Turtle	bait（fish and squid）	2007
4	4	18240	18	18240	Pacific	Kosuke Yokota	Loggerhead Turtle	bait（fish and squid）	2009
5	67	143136	164	162216	Atlantic	Miguel N Santos	Combined Species	bait（fish and squid）	2012
6	45	143136	116	162216	Atlantic	Miguel N Santos	Olive Ridley	bait（fish and squid）	2012
7	22	143136	36	162216	Atlantic	Miguel N Santos	Leatherback Turtle	bait（fish and squid）	2012
8	177	369359	143	255297	Atlantic	Daniel G Foster	Loggerhead Turtle	bait（fish and squid）	2012
9	170	369359	135	255297	Atlantic	Daniel G Foster	Leatherback Turtle	bait（fish and squid）	2012
10	29	84840	42	84840	Atlantic	Rui Coelho	Leatherback Turtle	bait（fish and squid）	2015

Table 3. General information of the included studies (other methods)

study	event.e	n.e	event.c	n.c	sea area	author	species	method	year
1	89	12515	212	12828	pacific	Christofer H.Boggs and Yonat Swimmer	Olive Ridley	appendage circle hook	2007
2	9	9120	9	9120	pacific	Kosuke Yokota	Loggerhead Turtle	colour（blue）	2009

3	2	9120	2	9120	pacific	Kosuke Yokota	Loggerhead Turtle	colour（blue）	2009
4	3	13800	26	22150	Mediterranean	Khaled Echwikhi	Combined Species	bait（fish and rays）	2010
5	315	16938	320	16938	pacific	Yonat Swimmer	Olive Ridley	offset and non-offset（14/0）circle	2010
6	6	16938	5	16938	pacific	Yonat Swimmer	Green Turtle	offset and non-offset（14/0）circle	2010
7	47	45289	43	36700	Atlantic	Dimas Gianuca	Combined Species	hookpod	2021
8	5	11800	46	11800	Atlantic	Andr´e S. Afonso	Combined Species	blue light bait	2021
9	5	11800	46	11800	Atlantic	Andr´e S. Afonso	Combined Species	white light bait	2021

Table 4. General information of the included studies (target species)

study	year	event.e	n.e	event.c	n.c	area	author
1	2000	264	46040	723	92080	Atlantic	Alan B.Bolten
2	2001	357	58766	203	29383	Atlantic	Alan B.Bolten
3	2008	15051	286826	7484	143473	Pacific	Jaime Mejuto
4	2009	191	14664	213	14590	Mediterranean	Susanna Piovano
5	2010	1907	72914	1632	72914	Atlantic	Gilberto Sales
6	2011	108	13287	149	13286	Mediterranean	Susanna Piovano
7	2011	330	25085	343	25085	Atlantic	J.C. Pacheco
8	2012	18	2320	14	2322	Mediterranean	Giulia Cambiè
9	2012	148	22571	139	22571	Atlantic	Andrés Domingo
10	2012	148	19911	195	19911	Atlantic	Andrés Domingo
11	2012	16780	369359	9077	93780	Atlantic	Daniel G Foster
12	2013	1189	11174	1732	11195	Pacific	Sandra Andraka
13	2013	4401	177942	3489	178732	Pacific	Sandra Andraka
14	2013	1084	11930	1789	12197	Pacific	Sandra Andraka
15	2013	736	34619	750	40890	Pacific	Sandra Andraka
16	2013	1108	65603	1282	69040	Pacific	Sandra Andraka
17	2013	1351	36834	947	38207	Pacific	Sandra Andraka

18	2013	2506	74474	2242	77199	Pacific	Sandra Andraka
19	2015	2928	297600	2046	148800	Atlantic	Sérgio Amorim
20	2009	7	9120	7	9120	pacific	Kosuke Yokota
21	2009	6	9120	3	9120	pacific	Kosuke Yokota
22	2021	411	45289	264	36700	Atlantic	Dimas Gianuca
23	2021	475	11800	1360	11800	Atlantic	Andr´e S. Afonso
24	2021	359	11800	1360	11800	Atlantic	Andr´e S. Afonso
25	2010	827	16938	853	16938	pacific	Yonat Swimmer
26	2009	22	18240	17	18240	Pacific	Kosuke Yokota
27	2009	9	18240	14	18240	Pacific	Kosuke Yokota
28	2012	10341	231570	2855	71150	Atlantic	Daniel G Foster
29	2012	1126	231570	590	71150	Atlantic	Daniel G Foster

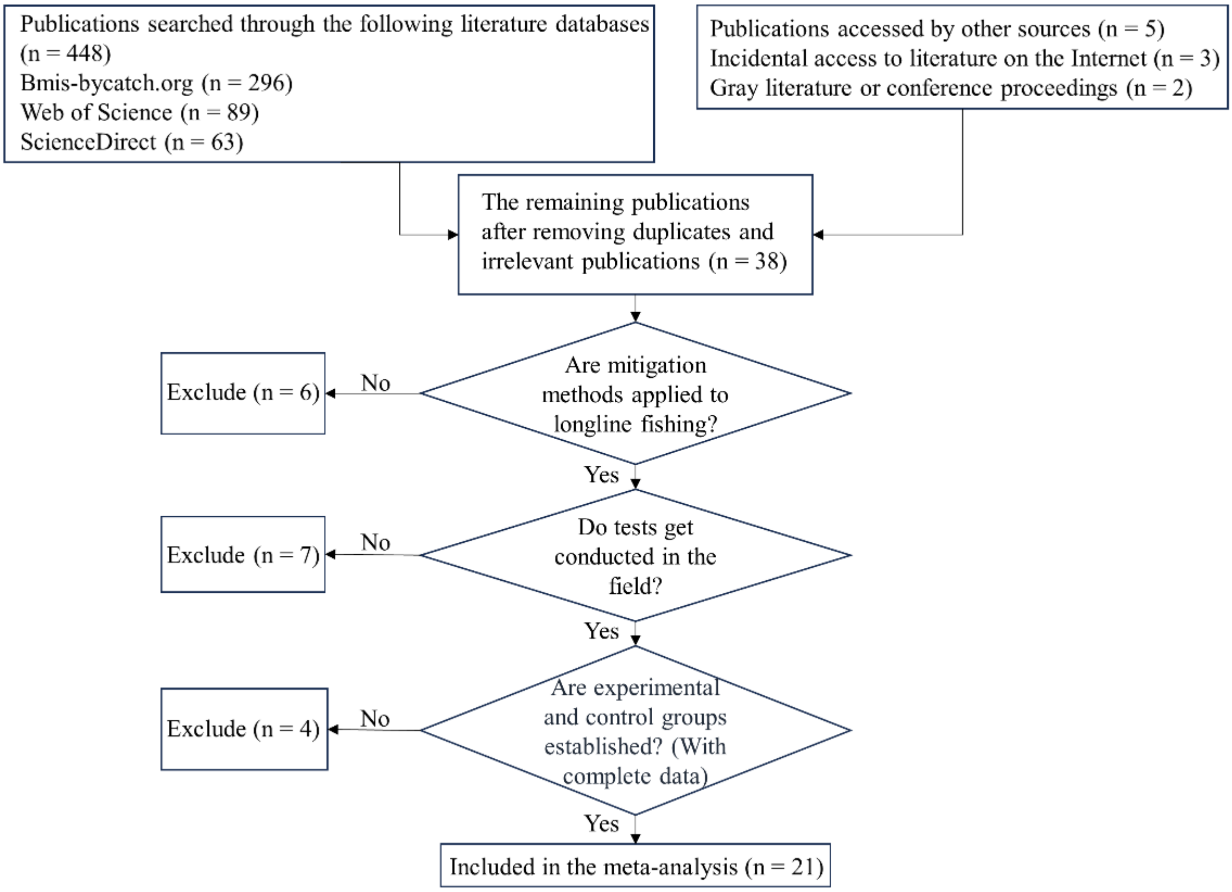


Fig.1 Standard flow chart for incorporating meta-analytic publications

Study	Experimental Events	Experimental Total	Control Events	Control Total	RR	95%-CI	Weight
1	85	46040	147	92080	1.16	[0.89; 1.51]	4.0%
2	30	58766	14	29383	1.07	[0.57; 2.02]	3.2%
3	27	2150674	182	1282748	0.09	[0.06; 0.13]	3.8%
4	13	2150674	42	1282748	0.18	[0.10; 0.34]	3.2%
5	13	5400	22	10498	1.15	[0.58; 2.28]	3.1%
6	2	4200	3	7982	1.27	[0.21; 7.58]	1.2%
7	86	286826	87	143473	0.49	[0.37; 0.67]	4.0%
8	158	286826	77	143473	1.03	[0.78; 1.35]	4.0%
9	17	286826	10	143473	0.85	[0.39; 1.86]	2.8%
10	6	14664	20	14590	0.30	[0.12; 0.74]	2.5%
11	53	72914	117	72914	0.45	[0.33; 0.63]	3.9%
12	7	72914	20	72914	0.35	[0.15; 0.83]	2.6%
13	1	72914	1	72914	1.00	[0.06; 15.99]	0.6%
14	2	13287	9	13286	0.22	[0.05; 1.03]	1.4%
15	4	25085	12	25085	0.33	[0.11; 1.03]	2.1%
16	4	25085	6	25085	0.67	[0.19; 2.36]	1.8%
17	3	25085	1	25085	3.00	[0.31; 28.84]	0.8%
18	9	2320	14	2322	0.64	[0.28; 1.48]	2.7%
19	11	22571	20	22571	0.55	[0.26; 1.15]	2.9%
20	36	19911	48	19911	0.75	[0.49; 1.15]	3.7%
21	177	369359	126	93780	0.36	[0.28; 0.45]	4.1%
22	170	369359	113	93780	0.38	[0.30; 0.48]	4.1%
23	3	203568	7	101784	0.21	[0.06; 0.83]	1.7%
24	21	203568	37	101784	0.28	[0.17; 0.48]	3.4%
25	72	203568	89	101784	0.40	[0.30; 0.55]	4.0%
26	0	11174	1	11195	0.33	[0.01; 8.20]	0.4%
27	0	177942	3	178732	0.14	[0.01; 2.78]	0.5%
28	16	177942	24	178732	0.67	[0.36; 1.26]	3.2%
29	2	34619	10	40890	0.24	[0.05; 1.08]	1.5%
30	15	65603	15	69040	1.05	[0.51; 2.15]	3.0%
31	63	177942	155	178732	0.41	[0.30; 0.55]	4.0%
32	29	34619	72	40890	0.48	[0.31; 0.73]	3.7%
33	78	65603	73	69040	1.12	[0.82; 1.55]	3.9%
34	87	169680	96	84840	0.45	[0.34; 0.61]	4.0%
35	122	297600	138	148800	0.44	[0.35; 0.56]	4.1%
Random effects model		**8205128**		**4996338**	**0.50**	**[0.40; 0.63]**	**100.0%**

Heterogeneity: $I^2 = 85\%$, $\tau^2 = 0.3067$, $p < 0.01$

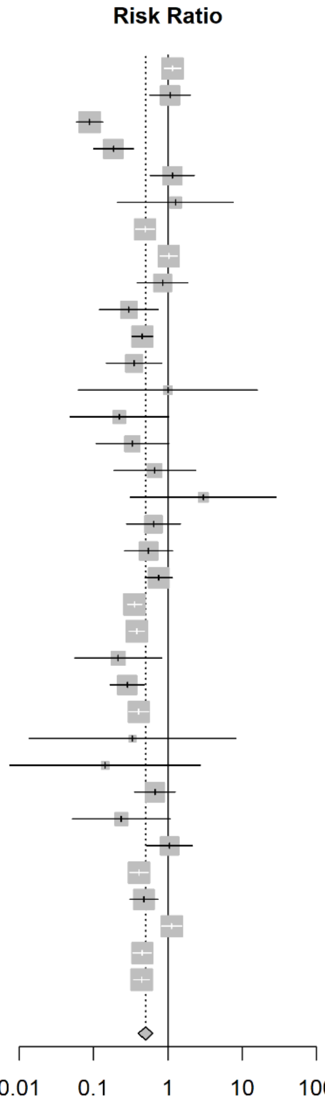


Fig.2 Effect of replacing J-hook with circle hook on the probability of by-catch for all sea turtle species

Study	RR	95%-CI	P-value	Tau2	Tau	I2
Omitting 1	0.48	[0.39; 0.60]	< 0.01	0.2861	0.5349	82%
Omitting 2	0.49	[0.39; 0.61]	< 0.01	0.3013	0.5489	85%
Omitting 3	0.54	[0.45; 0.65]	< 0.01	0.1819	0.4265	78%
Omitting 4	0.52	[0.41; 0.65]	< 0.01	0.2876	0.5363	85%
Omitting 5	0.49	[0.39; 0.61]	< 0.01	0.2991	0.5469	85%
Omitting 6	0.50	[0.39; 0.62]	< 0.01	0.3080	0.5550	85%
Omitting 7	0.50	[0.40; 0.63]	< 0.01	0.3223	0.5677	85%
Omitting 8	0.49	[0.39; 0.61]	< 0.01	0.2961	0.5442	83%
Omitting 9	0.49	[0.39; 0.62]	< 0.01	0.3111	0.5578	85%
Omitting 10	0.51	[0.40; 0.64]	< 0.01	0.3114	0.5581	85%
Omitting 11	0.50	[0.40; 0.63]	< 0.01	0.3216	0.5671	85%
Omitting 12	0.51	[0.40; 0.64]	< 0.01	0.3144	0.5607	85%
Omitting 13	0.50	[0.40; 0.63]	< 0.01	0.3086	0.5555	85%
Omitting 14	0.51	[0.40; 0.64]	< 0.01	0.3083	0.5553	85%
Omitting 15	0.50	[0.40; 0.63]	< 0.01	0.3127	0.5592	85%
Omitting 16	0.50	[0.40; 0.63]	< 0.01	0.3131	0.5596	85%
Omitting 17	0.49	[0.39; 0.62]	< 0.01	0.3041	0.5515	85%
Omitting 18	0.50	[0.39; 0.63]	< 0.01	0.3160	0.5622	85%
Omitting 19	0.50	[0.40; 0.63]	< 0.01	0.3181	0.5640	85%
Omitting 20	0.49	[0.39; 0.62]	< 0.01	0.3144	0.5607	85%
Omitting 21	0.51	[0.40; 0.64]	< 0.01	0.3166	0.5627	85%
Omitting 22	0.51	[0.40; 0.64]	< 0.01	0.3188	0.5647	85%
Omitting 23	0.51	[0.40; 0.64]	< 0.01	0.3073	0.5543	85%
Omitting 24	0.51	[0.41; 0.64]	< 0.01	0.3083	0.5552	85%
Omitting 25	0.50	[0.40; 0.64]	< 0.01	0.3200	0.5657	85%
Omitting 26	0.50	[0.40; 0.63]	< 0.01	0.3084	0.5553	85%
Omitting 27	0.50	[0.40; 0.63]	< 0.01	0.3075	0.5546	85%
Omitting 28	0.50	[0.39; 0.62]	< 0.01	0.3167	0.5628	85%
Omitting 29	0.51	[0.40; 0.64]	< 0.01	0.3089	0.5558	85%
Omitting 30	0.49	[0.39; 0.61]	< 0.01	0.3036	0.5510	85%
Omitting 31	0.50	[0.40; 0.64]	< 0.01	0.3202	0.5659	85%
Omitting 32	0.50	[0.40; 0.63]	< 0.01	0.3211	0.5667	85%
Omitting 33	0.48	[0.39; 0.61]	< 0.01	0.2900	0.5386	83%
Omitting 34	0.50	[0.40; 0.64]	< 0.01	0.3219	0.5673	85%
Omitting 35	0.50	[0.40; 0.64]	< 0.01	0.3218	0.5673	85%
Random effects model	**0.50**	**[0.40; 0.63]**	**< 0.01**	**0.3067**	**0.5538**	**85%**

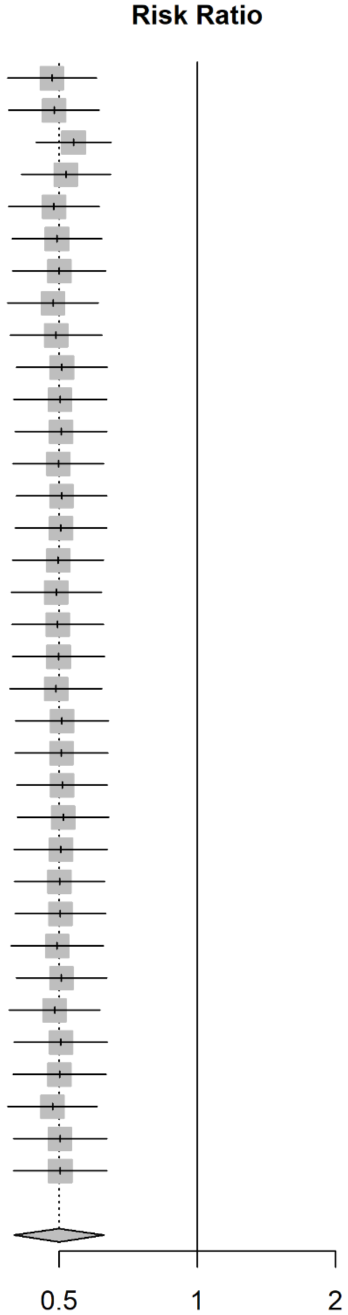
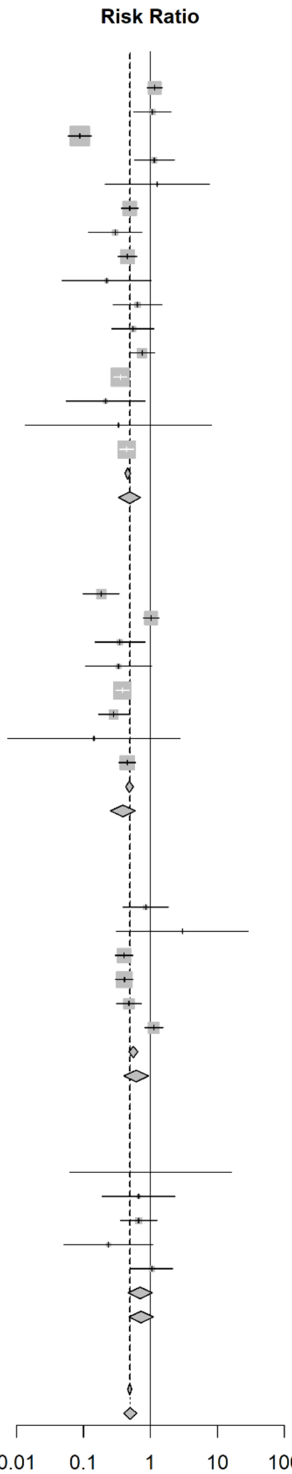


Fig.3 Sensitivity analysis of 35 research data

Study	Experimental Events	Experimental Total	Control Events	Control Total	RR	95%-CI	Weight (common)	Weight (random)
species = Loggerhead Turtle								
1	85	46040	147	92080	1.16	[0.89; 1.51]	4.6%	4.0%
2	30	58766	14	29383	1.07	[0.57; 2.02]	0.9%	3.2%
3	27	2150674	182	1282748	0.09	[0.06; 0.13]	10.7%	3.8%
5	13	5400	22	10498	1.15	[0.58; 2.28]	0.7%	3.1%
6	2	4200	3	7982	1.27	[0.21; 7.58]	0.1%	1.2%
7	86	286826	87	143473	0.49	[0.37; 0.67]	5.4%	4.0%
10	6	14664	20	14590	0.30	[0.12; 0.74]	0.9%	2.5%
11	53	72914	117	72914	0.45	[0.33; 0.63]	5.5%	3.9%
14	2	13287	9	13286	0.22	[0.05; 1.03]	0.4%	1.4%
18	9	2320	14	2322	0.64	[0.28; 1.48]	0.7%	2.7%
19	11	22571	20	22571	0.55	[0.26; 1.15]	0.9%	2.9%
20	36	19911	48	19911	0.75	[0.49; 1.15]	2.3%	3.7%
21	177	369359	126	93780	0.36	[0.28; 0.45]	9.4%	4.1%
23	3	203568	7	101784	0.21	[0.06; 0.83]	0.4%	1.7%
26	0	11174	1	11195	0.33	[0.01; 8.20]	0.1%	0.4%
35	122	297600	138	148800	0.44	[0.35; 0.56]	8.6%	4.1%
Common effect model		**3579274**		**2067317**	**0.46**	**[0.41; 0.50]**	**51.7%**	**--**
Random effects model					**0.49**	**[0.33; 0.71]**	**--**	**46.7%**
Heterogeneity: $I^2 = 89\%$, $\tau^2 = 0.4355$, $p < 0.01$								
species = Leatherback Turtle								
4	13	2150674	42	1282748	0.18	[0.10; 0.34]	2.5%	3.2%
8	158	286826	77	143473	1.03	[0.78; 1.35]	4.8%	4.0%
12	7	72914	20	72914	0.35	[0.15; 0.83]	0.9%	2.6%
15	4	25085	12	25085	0.33	[0.11; 1.03]	0.6%	2.1%
22	170	369359	113	93780	0.38	[0.30; 0.48]	8.5%	4.1%
24	21	203568	37	101784	0.28	[0.17; 0.48]	2.3%	3.4%
27	0	177942	3	178732	0.14	[0.01; 2.78]	0.2%	0.5%
34	87	169680	96	84840	0.45	[0.34; 0.61]	6.0%	4.0%
Common effect model		**3456048**		**1983356**	**0.49**	**[0.43; 0.56]**	**25.8%**	**--**
Random effects model					**0.39**	**[0.25; 0.60]**	**--**	**24.0%**
Heterogeneity: $I^2 = 85\%$, $\tau^2 = 0.2599$, $p < 0.01$								
species = Olive Ridley								
9	17	286826	10	143473	0.85	[0.39; 1.86]	0.6%	2.8%
17	3	25085	1	25085	3.00	[0.31; 28.84]	0.0%	0.8%
25	72	203568	89	101784	0.40	[0.30; 0.55]	5.6%	4.0%
31	63	177942	155	178732	0.41	[0.30; 0.55]	7.3%	4.0%
32	29	34619	72	40890	0.48	[0.31; 0.73]	3.1%	3.7%
33	78	65603	73	69040	1.12	[0.82; 1.55]	3.3%	3.9%
Common effect model		**793643**		**559004**	**0.56**	**[0.48; 0.65]**	**19.9%**	**--**
Random effects model					**0.61**	**[0.40; 0.94]**	**--**	**19.2%**
Heterogeneity: $I^2 = 84\%$, $\tau^2 = 0.2007$, $p < 0.01$								
species = Green Turtle								
13	1	72914	1	72914	1.00	[0.06; 15.99]	0.0%	0.6%
16	4	25085	6	25085	0.67	[0.19; 2.36]	0.3%	1.8%
28	16	177942	24	178732	0.67	[0.36; 1.26]	1.1%	3.2%
29	2	34619	10	40890	0.24	[0.05; 1.08]	0.4%	1.5%
30	15	65603	15	69040	1.05	[0.51; 2.15]	0.7%	3.0%
Common effect model		**376163**		**386661**	**0.70**	**[0.47; 1.07]**	**2.6%**	**--**
Random effects model					**0.73**	**[0.48; 1.11]**	**--**	**10.0%**
Heterogeneity: $I^2 = 0\%$, $\tau^2 = 0$, $p = 0.51$								
Common effect model		**8205128**		**4996338**	**0.49**	**[0.46; 0.53]**	**100.0%**	**--**
Random effects model					**0.50**	**[0.40; 0.63]**	**--**	**100.0%**



Heterogeneity: $I^2 = 85\%$, $\tau^2 = 0.3067$, $p < 0.01$
Test for subgroup differences (common effect): $\chi^2_3 = 7.54$, df = 3 ($p = 0.06$)
Test for subgroup differences (random effects): $\chi^2_3 = 4.74$, df = 3 ($p = 0.19$)

Fig.4 Subgroup analysis of 35 research data

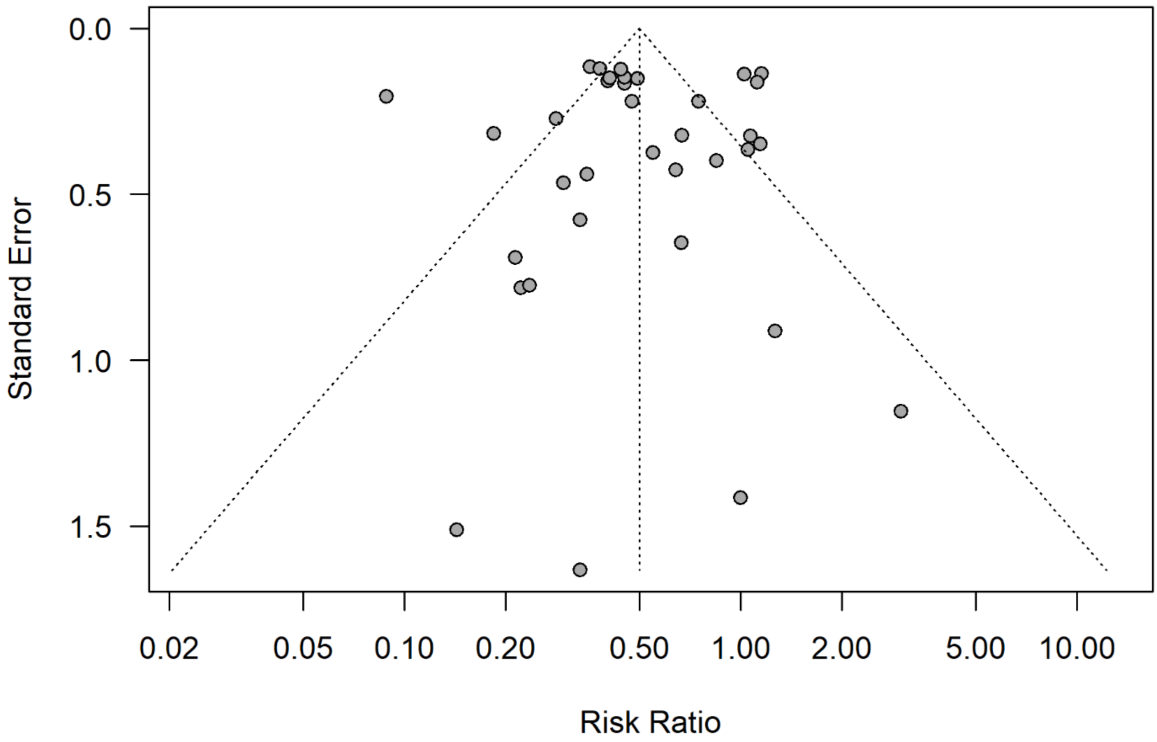


Fig.5 Publication bias test - Funnel chart (Circle Hook)

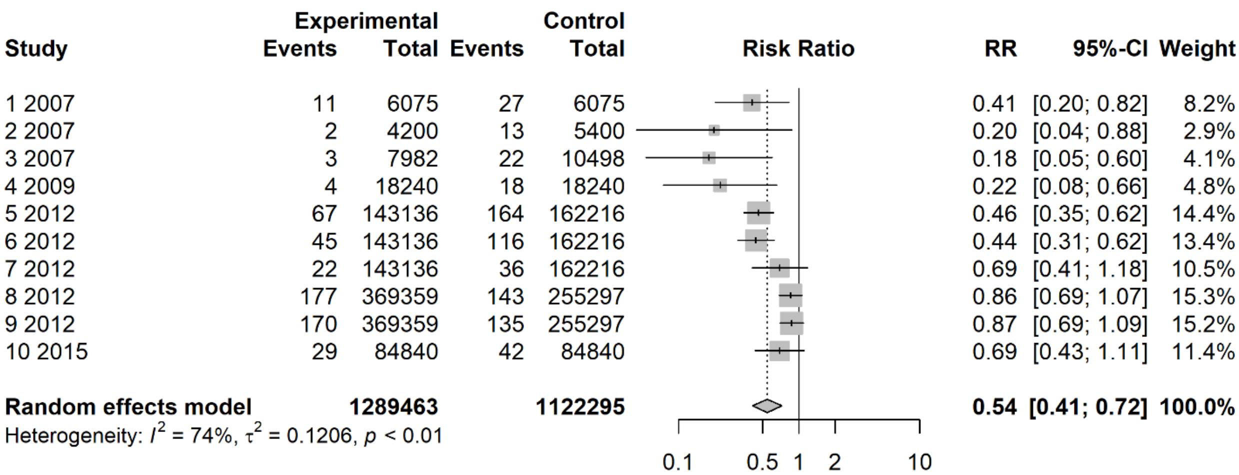


Fig.6 Effect of replacing squid bait with fish bait on the probability of by-catch for all sea turtle species

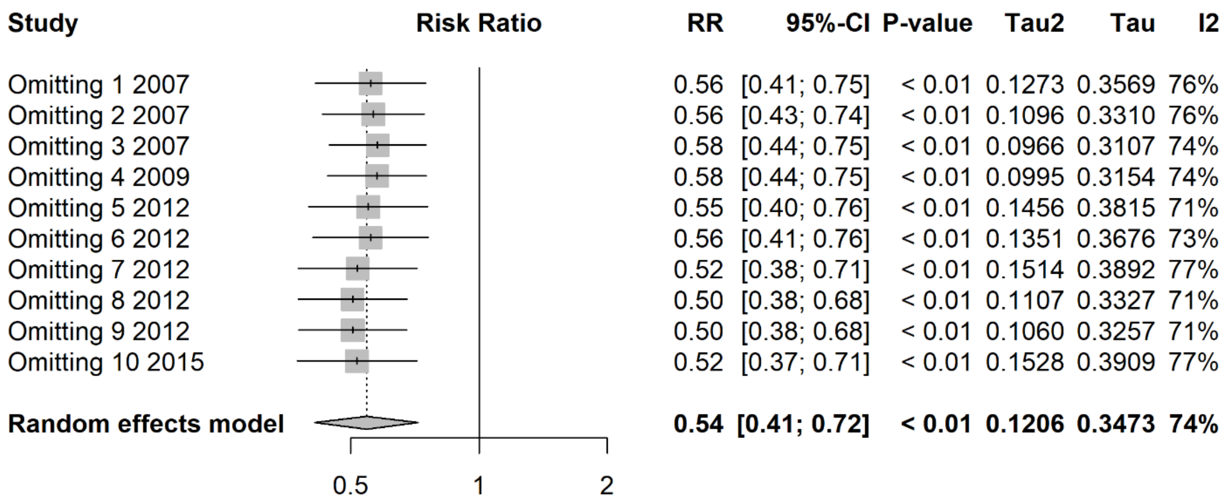


Fig.7 Sensitivity analysis of 10 research data

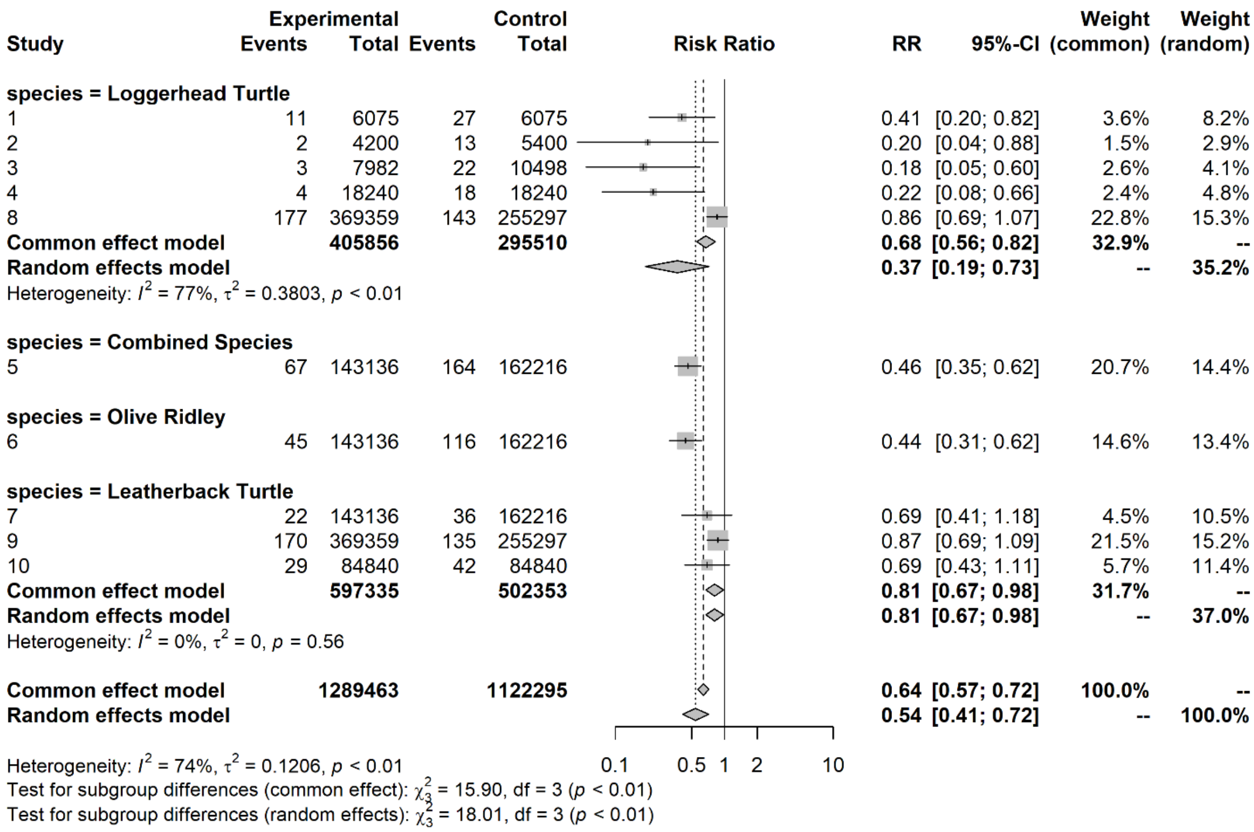


Fig.8 Subgroup analysis of 10 research data

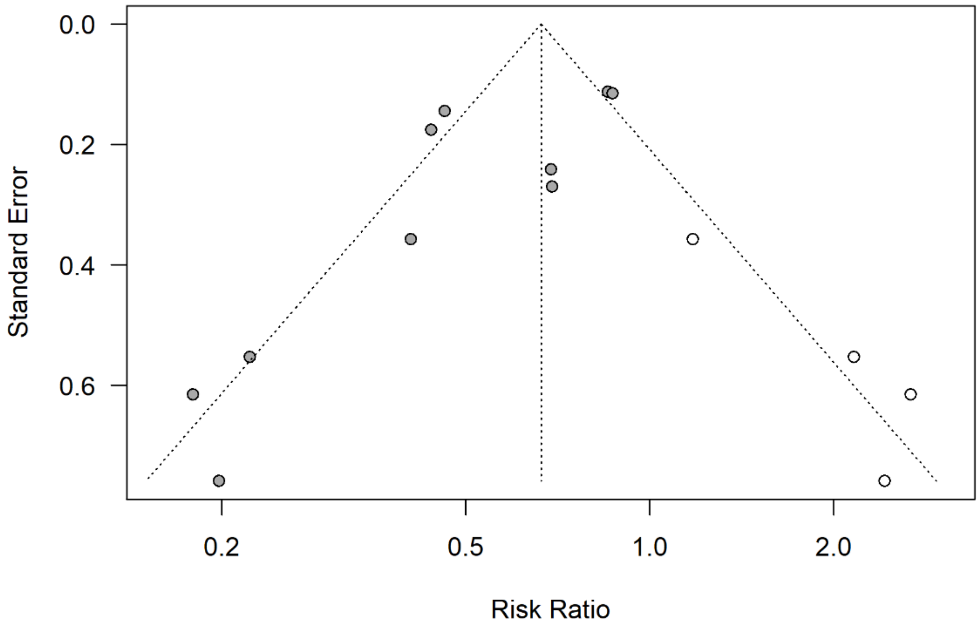


Fig.9 Publication bias test - Funnel chart using trim and filling method (Fish Bait)

Study	Experimental Events	Experimental Total	Control Events	Control Total	RR	95%-CI	Weight
1 2007	89	12515	212	12828	0.43	[0.34; 0.55]	14.0%
2 2009	9	9120	9	9120	1.00	[0.40; 2.52]	11.0%
3 2009	2	9120	2	9120	1.00	[0.14; 7.10]	6.2%
4 2010	3	13800	26	22150	0.19	[0.06; 0.61]	9.6%
5 2010	315	16938	320	16938	0.98	[0.84; 1.15]	14.1%
6 2010	6	16938	5	16938	1.20	[0.37; 3.93]	9.6%
7 2021	47	45289	43	36700	0.89	[0.59; 1.34]	13.5%
8 2021	5	11800	46	11800	0.11	[0.04; 0.27]	11.0%
9 2021	5	11800	46	11800	0.11	[0.04; 0.27]	11.0%
Random effects model		**147320**		**147394**	**0.46**	**[0.24; 0.88]**	**100.0%**

Heterogeneity: $I^2 = 89\%$, $\tau^2 = 0.7607$, $p < 0.01$

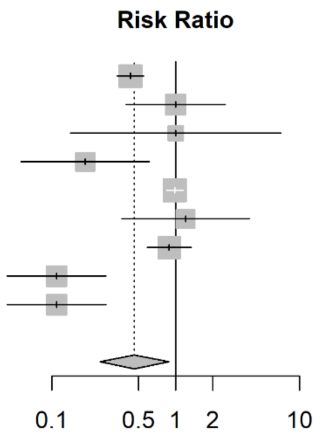


Fig.10 Effect of other mitigation methods on the probability of by-catch for all sea turtle species

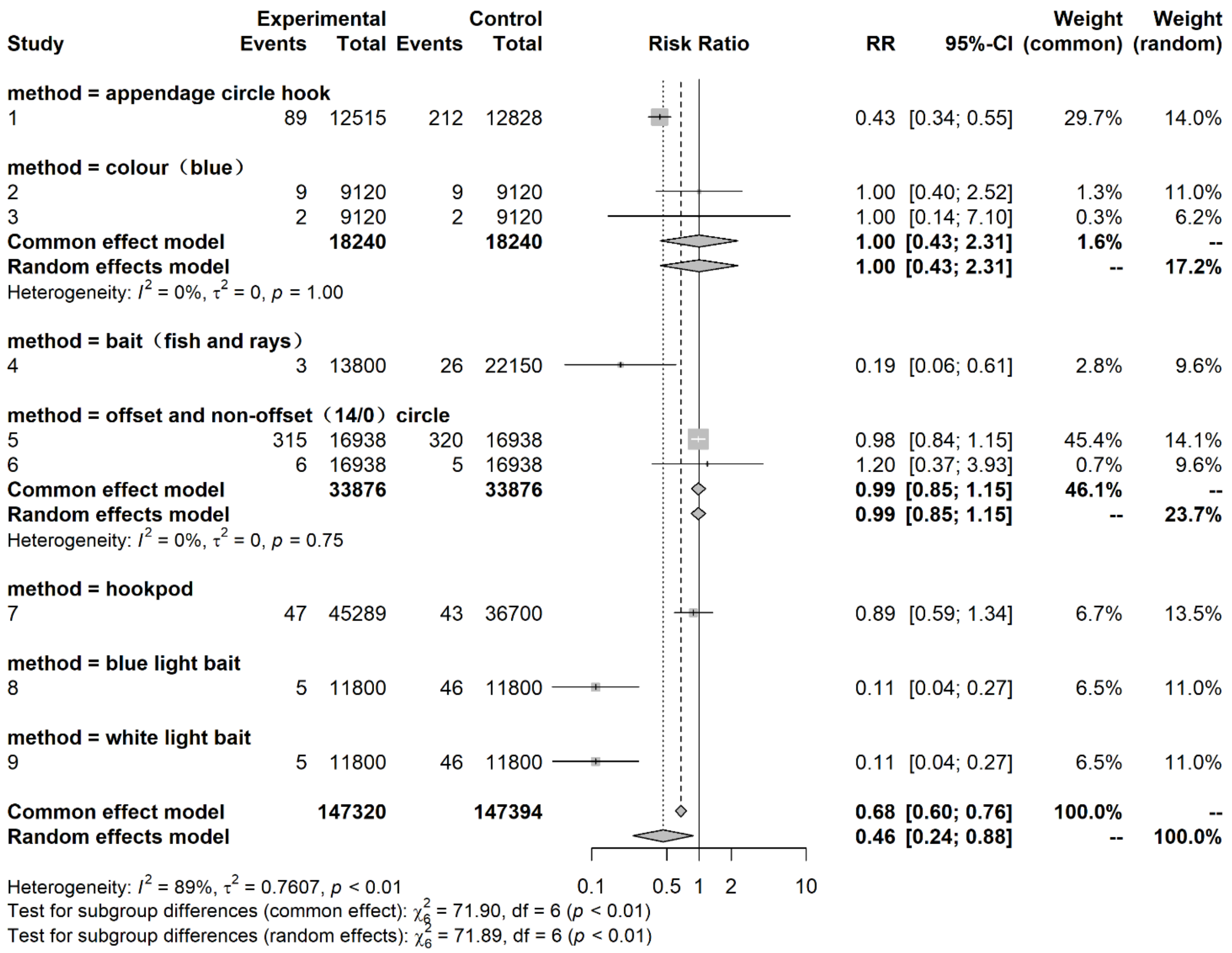


Fig.11 Results of subgroup analysis using mitigation methods as impact factors

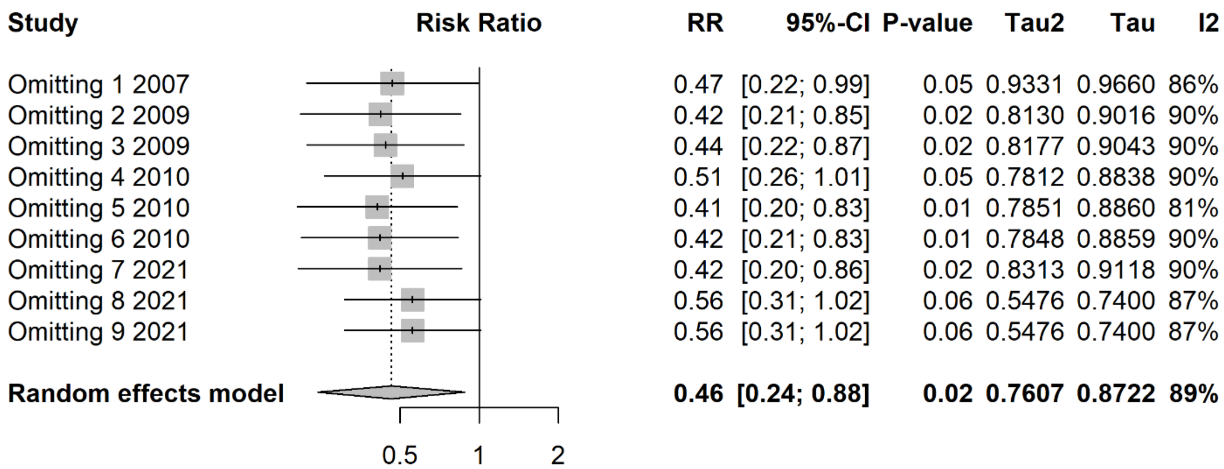


Fig.12 Sensitivity analysis of 9 research data

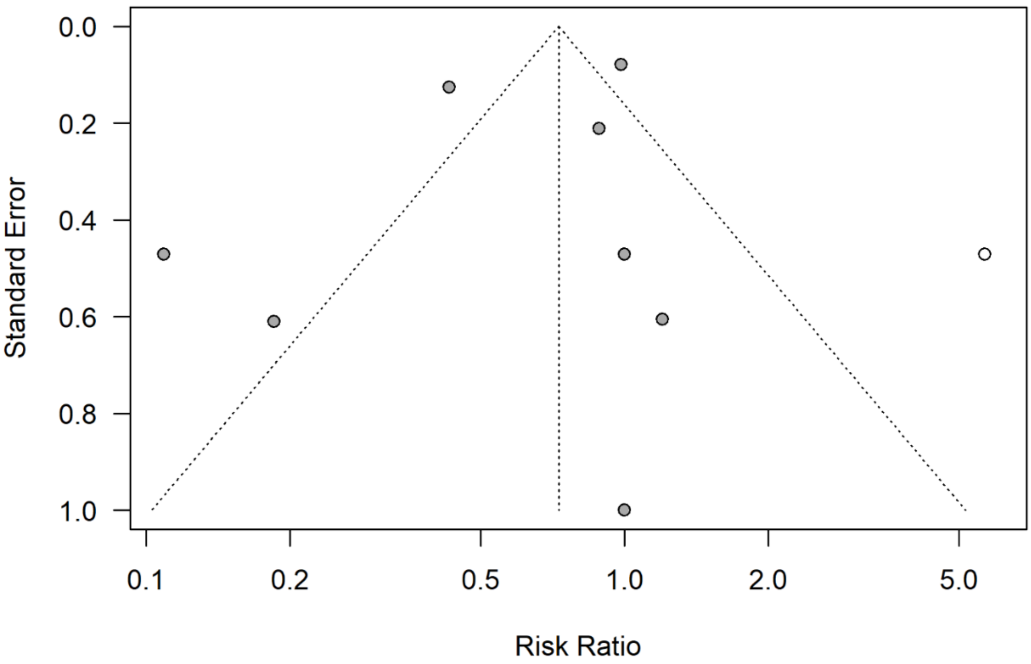


Fig.13 Funnel chart made using trim and filling method (Other Mitigation Methods)

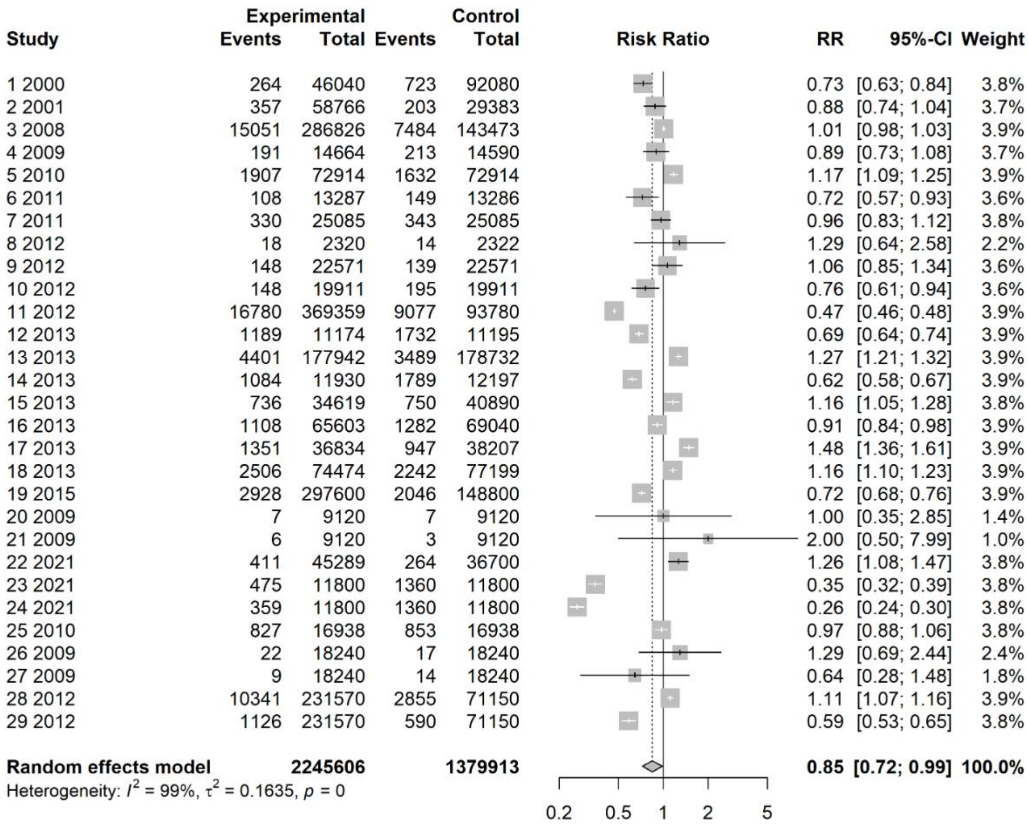


Figure 14 Meta-analysis results of mitigation methods for target fish species

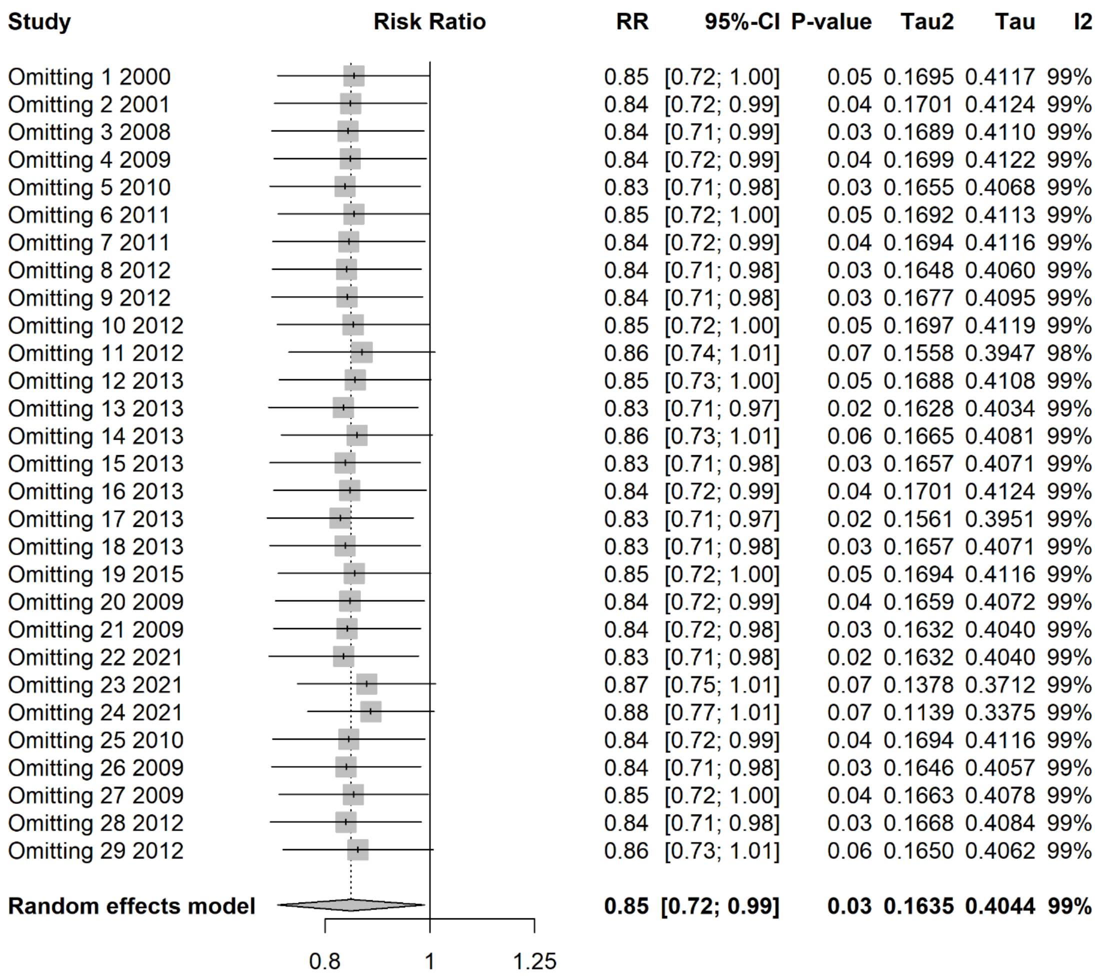


Figure 15 Sensitivity analysis of 29 research data

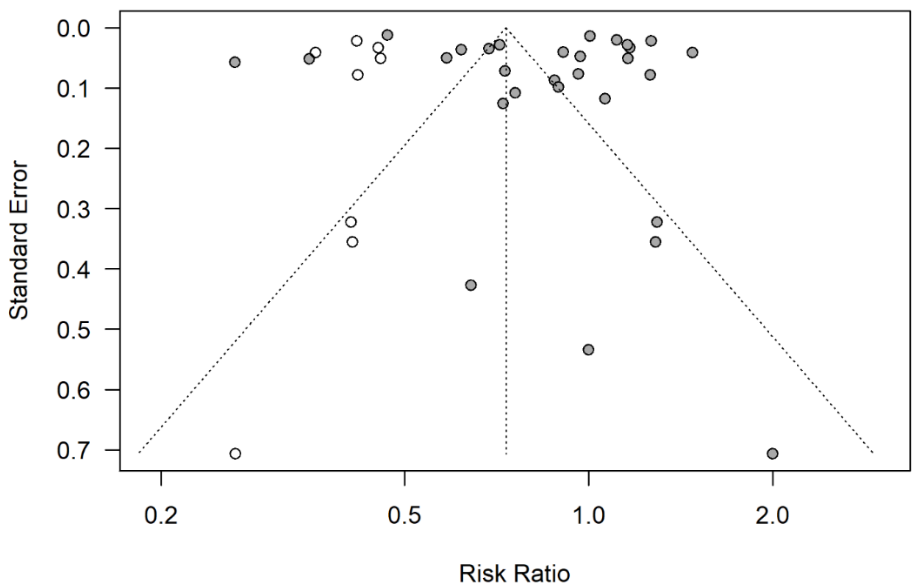


Figure 16 Funnel chart made using trim and filling method (Target fish species)