A review of the effect of circle hooks on the retention and at-vessel mortality of sharks

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Abstract

Elasmobranchs (sharks, skates, and rays) are characterized by life histories that include slow growth, late maturity, and low fecundity. These traits collectively contribute to the high vulnerability of elasmobranchs to exploitation by fisheries. Modifications to both fishing gear and behavior have been effective in mitigating bycatch, reducing injury rates, and decreasing overall fishing mortality. One example includes the use of circle hooks. Here we compare the effects of circle hooks vs. J-hooks on the retention rates and at-vessel mortality of sharks (and rays). After reviewing two meta-analyses, we updated the analysis to remove the effect of confounding variables and present estimates of the relative risk of retention on circle vs. J-hooks for ten frequently encountered species in pelagic longline fisheries. Two of the ten species considered exhibited significant increases in retention rates due to circle hook use, one had a significant decrease in retention rates due to circle hook use, and there were no significant differences for the remaining seven. While some point estimates indicate higher retention rates on circle hooks vs. J-hooks, we suspect increased rates of gut-hooking and subsequent bite offs artificially deflate retention on J-hooks as hooked sharks are likely to evade capture and therefore not be counted. This behavior, and subsequent erroneous counting, has been demonstrated in the literature and is plausible as circle hook use results in significantly less gut-hooking and bite offs. In addition to the re-analysis, we also review the effects of circle hook use on at-vessel mortality of sharks. Collectively, this review discusses the utility of circle hooks in pelagic longline operations and the viability of the gear to increase the effectiveness of conservation measures.

KEYWORDS
Circle hook, J-hook, bycatch mortality, mitigation, terminal gear

Introduction

Fisheries interactions with elasmobranchs can occur through targeted or incidental catch. Given the particular life history of elasmobranchs that results in a high vulnerability to exploitation, mitigating bycatch and the associated mortality is critical to the sustainability of the populations. Scientists and managers alike have therefore investigated both fishing gear and behavioral modifications to mitigate bycatch and decrease injuries for those animals that are incidentally caught.

While some Regional Fisheries Management Organizations (RFMOs) are now considering adopting the use of circle hooks in their longline fisheries, research has focused on this terminal gear for decades. Dozens of studies have addressed the effects of circle hook use on retention, injury, catch composition, and more. The body of work surrounding circle hook use is exhaustive, with some studies deploying millions of hooks per treatment. Taking into account the abundance of studies conducted on the topic, enough statistical power is available to answer a number of scientific questions regarding bycatch mitigation.

A hallmark of large circle hook use is the effective mitigation for sea turtle bycatch (Swimmer et al., 2017; Santos et. al, 2012; Gilman et al., 2007). The significant reductions in sea turtle bycatch can also be accompanied by an increase in retention for certain target species, such as the tunas (Reinhardt et al. 2017, Coelho et al. 2020). Swordfish, on the other hand, may experience a decrease in retention rates associated to circle hook use (Reinhardt et al. 2017, Coelho et al. 2020). In addition, circle hook use has also shown to decrease injury and at-vessel mortality for a number of sharks and marlin. Despite these potential advantages, uncertainty still exists regarding the effect of circle hook use on the retention rates of sharks as different studies have shown conflicting results (Gilman et al., 2016)

Given the relatively low capture rates of certain shark species (e.g., 0.26 shortfin mako per 1000 hooks in Kerstetter and Graves, 2006), many experiments lack the statistical power necessary to carry out robust statistical tests. Considering this, efforts have been made to pool data across individual studies in meta-analyses in order to increase the rigor of the analyses. To that end, two recent meta-analyses pooled data from numerous experiments to examine the effect of hook type on retention rates for sharks (Reinhardt et al., 2017; Coelho et al., 2020).

While meta-analyses are useful for scientific analysis on rare species, one potential weakness is the inclusion of confounding variables across studies which can lead to unequal assumptions between studies and/or a spurious interpretation of overall results. The overall objective of this research was to better understand the effect of circle hook use, relative to J-hook use, on the retention rates of sharks. We reviewed the source material used in both meta-analyses with two goals: 1) to determine if confounding variables may have affected the overall findings regarding the retention rates, and 2) to re-examine the statistical tests used after accounting for any such confounding variables. In addition, we also provide a brief review on the effects of circle hook use on at-vessel mortality and anatomical hooking location.

Methods

Data exploration

We reviewed the source material referenced in two meta-analyses: Reinhardt et al. (2017) and Coelho et al. (2020) for ten elasmobranchs: Bigeye thresher – *Alopias superciliosus*, Silky shark – *Carcharhinus falciformis,* Oceanic whitetip – *C. longimannus,* Night shark – *C. signatus,* Shortfin mako – *Isurus oxyrhinchus,* Porbeagle – *Lamna nasus,* Blue shark –

Prionace glauca, , Crocodile shark – *Pseudocarcharias kamoharai,* , Pelagic stingray – *Pteroplatytrygon violacea,* and Scalloped hammerhead – *Sphyrna lewini.*

For each meta-analysis, we reviewed each cited study related to the retention of sharks where hook type was considered as an explanatory variable or experimental treatment. For our present research, retention was defined as the number of sharks landed per unit effort (weight or number/hooks or hook-hours). Similar to Reinhardt et al., (2017), we considered a referenced study to comprise “unique” experiments if they varied within-study with respect to an attribute, including bait or gear type, fishing location or time of year. This classification meant that a referenced study could be represented by multiple experiments. For example, Domingo et al. (2012) used two different longline styles (American vs. Spanish), so this referenced study was classified as two unique experiments.

In review of the source material, the interpretation of one study was found to be problematic for assessing the effect of hook type on retention rates. Foster et al. (2012) deployed a total of 973,736 hooks, with approximately 40.8% of the circle hooks baited with squid, whereas over 78.2% of the J-hooks were baited with squid. Within each meta-analysis, the increased effort of squid baited J-hooks was not incorporated into the statistical analysis. This is problematic as Foster et al. (2012) reported significant effects of bait type of catch composition. For example, they found that mackerel yielded significantly higher catch rates (between 162 to 329%, $p \leq 0.001$) of shortfin mako. The overall CPUE of J-hooks, as presented by Reinhardt et al. (2017) and Coelho et al. (2020), is therefore inclusive of a bait effect due to the higher effort associated with squid-baited J-hooks relative to squid-baited circle hooks where bait type significantly affects catch rates. Significant effects of bait on the catch rates of porbeagle and blue shark were also described. To account for this, we divided Foster et al. (2012) into two experiments, one that used mackerel and one that used squid, thereby controlling for the experimental variation.

In addition to correcting for the effect of bait, we also sought to increase the number of studies referenced in the meta-analyses by combining sources from each meta-analysis. As our primary objective was to assess the effect of circle hook use vs. J-hooks on retention rates, we did not include experiments that used tuna hooks as a control. This approach mirrors that employed by Coelho et al. (2020). Unlike Coelho et al. (2020), we did not include the data collected by the U.S. NMFS Southeast Fisheries Science Center Pelagic Observer Program in our analysis. This dataset contains data on J-hook and circle hook use across two temporally distinct periods (1992-2003 and 2005-2011, respectively) and we cannot be certain that this timespan did not confound fisheries interactions. Finally, we reviewed the # of hooks deployed and sharks caught for each study to verify no transcription errors occurred. The studies included in this study are listed in Table 1.

Statistical analyses

We calculated Relative Risk (RR), which denotes the percent change associated with experimental treatments relative to the control, expressed as 1.0. We considered circle hooks the experiment treatment and J-hooks the control, therefore any value > 1.0 would represent higher retention on circle hooks relative to J-hooks and any value < 1.0 would represent the opposite. The RR is equal to:

$$RR = \frac{C_i}{{n_i}^1} \Big/ \frac{J_i}{{n_i}^2}$$

Where $C_i/n_i{}^1$ represents the number of observations (C_i) associated with circle hooks divided by the total number of circle hooks deployed ($n_i{}^1$). $J_i/n_i{}^2$ therefore represents the number of observations associated with J-hooks (J_i) divided by the total number of J-hooks deployed ($n_i{}^2$). We used 'metafor' to estimate the RR and associated confidence intervals for each experiment (Viecthbauer, 2010).

The RR for each study was incorporated into a Random Effects (RE) model that was used to calculate a global mean effect size, based on a weighted mean of each experiment's effect size. More weight is placed on experiments with estimates of greater precision and with lower between-study variance (Reinhardt et al., 2017). After computing the global mean effect size, a two-side Wald-type Z test was used to determine if the observed effect varied significantly from zero. Heterogeneity was calculated as I^2, or the total variation across experiments due to the observed variation between experiments (Higgins et al., 2003). I^2 ranges from 0 % to 100% with larger values indicating variation was due to variables other than hook type. Full details regarding the RE models and heterogeneity calculations are available in Reinhardt et al. (2017).

Results

Retention rates

Bigeye thresher – *Alopias superciliosus* (Figure 1)

We present an updated RR for retention associated with circle hook vs. J-hook use of 0.90 (95% CI: 0.80 to 1.01), indicating that hook type use (circle or J-hook) did not result in a difference that was statistically significant (Z-value = -1.74, df=3, p-value = 0.08). The model did not fail the assumption of homogeneity (I^2= 0%, Q(df=3)=1.20, p-value =0.753).

Silky shark – *Carcharhinus falciformis* (Figure 2)

We present an updated RR for retention associated with circle hook vs. J-hook use of 1.19 (95% CI: 0.87 to 1.61), indicating that hook type use (circle or J-hook) did not result in a difference that was statistically significant (Z-value = 1.10, df=6, p-value = 0.272). The model did not fail the assumption of homogeneity (I^2= 38.30%, Q(df=6)=10.02, p-value =0.124).

Oceanic whitetip – *Carcharhinus longimannus* (Figure 3)

We present an updated RR for retention associated with circle hook vs. J-hook use of 1.10 (95% CI: 0.81 to 1.48), indicating that hook type use (circle or J-hook) did not result in a difference that was statistically significant (Z-value = 0.61, df=4, p-value = 0.543). The model did not fail the assumption of homogeneity (I^2= 25.92%, Q(df=4)=5.86, p-value =0.210).

Night shark – *Carcharhinus signatus* (Figure 4)

We present an updated RR for retention associated with circle hook vs. J-hook use of 1.87 (95% CI: 0.75 to 4.66), indicating that hook type use (circle or J-hook) did not result in a difference that was statistically significant (Z-value = 1.35, df=1, p-value = 0.177). The model did not fail the assumption of homogeneity (I^2= 71.7%, Q(df=1)=3.54, p-value =0.060).

Shortfin mako – *Isurus oxyrhinchus* (Figure 5)

We present an updated RR for retention associated with circle hook vs. J-hook use of 1.17 (95% CI: 0.98 to 1.40), indicating that hook type use (circle or J-hook) did not result in a difference that was statistically significant (Z-value = 1.74, df=10, p-value = 0.081). The model failed the assumption of homogeneity (I^2= 76.28%, Q(df=10)=45.97,p-value <0.0001), suggesting the data are not homogenous and the experimental variation was not fully accounted for by the model terms.

Porbeagle – *Lamna nasus* (Figure 6)

We present an updated RR for retention associated with circle hook vs. J-hook use of 1.04 (95% CI: 0.78 to 1.39), indicating that hook type use (circle or J-hook) did not result in a difference that was statistically significant (Z-value = 0.24, df=4, p-value = 0.81). The model did not fail the assumption of homogeneity (I^2= 54.46%, Q(df=4)=8.12, p-value =0.09).

Blue shark – *Prionace glauca* (Figure 7)

We present an updated RR for retention associated with circle hook vs. J-hook use of 1.15 (95% CI: 1.04 to 1.26), indicating that circle hook use did result in a significant increase in retention rates (Z-value = 2.72, df=17, p-value = 0.0065). The model failed the assumption of homogeneity (I^2= 96.56%, Q(df=17)=305.72, p-value < 0.0001), suggesting the data are not homogenous and the experimental variation was not fully accounted for by the model terms.

Crocodile shark – *Pseudocarcharias kamoharai* (Figure 8)

We present an updated RR for retention associated with circle hook vs. J-hook use of 1.43 (95% CI: 1.05 to 1.97), indicating that circle hook use did result in a significant increase in retention rates (Z-value = 2.24, df=4, p-value = 0.025). The model failed the assumption of homogeneity (I^2= 81.83%, Q(df=4)=14.16, p-value = 0.007), suggesting the data are not homogenous and the experimental variation was not fully accounted for by the model terms.

Pelagic stingray – *Pteroplatytrygon violacea* (Figure 9)

We present an updated RR for retention associated with circle hook vs. J-hook use of 0.25 (95% CI: 0.17 to 0.37), indicating that circle hook use did result in a significant decrease in retention (Z-value = -6.93, df=8, p-value < 0.0001). The model failed the assumption of homogeneity (I^2= 72.75%, Q(df=8)=26.44, p-value = 0.0009), suggesting the data are not homogenous and the experimental variation was not fully accounted for by the model terms.

Scalloped hammerhead – *Sphyrna lewini* (Figure 10)

We present an updated RR for retention associated with circle hook vs. J-hook use of 0.67 (95% CI: 0.25 to 1.76), indicating that hook type use (circle or J-hook) did not result in a difference that was statistically significant (Z-value = -0.82, df=3, p-value = 0.41). The model did not fail the assumption of homogeneity (I^2= 35.60%, Q(df=3)=4.26, p-value =0.235).

At-vessel mortality

Regarding at-vessel mortality (AVM), numerous studies have reviewed the effects of circle hook use on AVM for sharks. In review of the published literature, Godin et al. (2012) reports finding either no difference in AVM based on hook use or a significant reduction due to circle hook use. Similarly, across the 11 elasmobranchs studied by Reinhardt et al. (2017), they also report either no significant differences (n=8) or significant decreases in AVM (n=3) due to circle hook use. Gilman et al. (2016) found that circle hook use reduced AVM and deep hooking relative to J-hooks (of the same or narrower width). Finally, Coelho et al. (2020) found no significant differences across the 10 assessed elasmobranchs. Across these reviews, we find that circle hook use either significantly decreased or had no significant effect of at-vessel mortality for sharks.

Hooking location

Afonso et al. (2011) found all species (n=10) captured with circle hooks were more often hooked externally relative to J-hooks, with the latter resulting in more gut hooking. Significant differences between hook type and hooking location were found for three species – oceanic whitetip, night shark, and blue shark. Epperly et al. (2012) found hook type to be one of the most important variables for predicting hooking location. Further, hooking location was found to be largely informative for predicting the odds of at-vessel mortality. For blue shark and porbeagle, hook type was a significant factor in predicting if a fish was gut hooked (Epperly et al., 2012). In review of the published literature, Godin et al. (2012) noted that a higher percentage of sharks are hooked externally on circle hooks vs. J-hooks, and that this finding has been noted across most studies, but some indicated hook type has no significant effect on hooking location. In another review, Gilman et al. (2016) stated that circle hooks reduced deep hooking relative to J-hooks. Collectively, there is strong evidence that circle hook use results in an increase of external hooking in the mouth or jaw.

Discussion

An increase in retention rates associated with the use of circle hooks has been highlighted for some shark species, suggesting that, depending on management strategy, circle hooks may be ineffective for conservation. Some research has shown an increase in shark catch rates due to circle hook use. For example, Gilman et al. (2016) found a significant increase of capture for sharks on circle hooks. Here, we update estimates for the relative risk of retention for circle vs. J-hook use. Across the ten species we re-assessed, we found 7 species with no significant difference in retention rates, two demonstrating a significant increase in retention rates due to circle hooks, and one exhibiting a significant decrease in retention due to circle hook use. These results are different from previous meta-analysis for some of the species cited in this paper. While only two of the species we assessed exhibited a significant increase in retention rates, other point estimates (n=5) were above 1. These estimates contribute to the notion that circle hook use would lead to increased mortality relative to J-hooks. This argument fails to address two key tenets.

Firstly, higher catch rates associated with circle hooks may not be due to increased hooking efficiency, but decreased bite offs and increased retention (Afonso et al., 2012). For example, shortfin mako caught on circle hooks have been shown to be twice as likely to be mouth hooked vs. those caught on J-hooks (Carruthers et al., 2009; Epperly et al., 2012). The increased rate of gut hooking associated with the use of J-hooks has been hypothesized to allow hooked sharks to more easily bite off the gangion/leader and, therefore, avoid retention.

Watson et al. (2005) was perhaps the first to hypothesize that the increased catch rates of sharks on circle hooks could be misleading as sharks captured on J-hooks were more likely to be hooked internally, which would also increase the likelihood of the animal biting through the leader and evading capture. Developing this theory further, Afonso et al. (2012) tested four treatments in pelagic longline operations: J-hook with steel leaders, J-hook with nylon leaders, circle hook with steel leaders, and circle hook with nylon leaders. Bite-offs occurred almost entirely on nylon leaders (97%). Assuming the bite-offs were indeed sharks that evaded capture, then the differences in shark catch rates between hook type would not be significant. Therefore, the differences in retention may be attributable to bite offs when using nylon leads, with fishing interactions remaining consistent between hook types, but with sharks hooked on J-hooks evading capture. These deep-hooked sharks that bite off the leaders and swim away with a trailing leader may experience elevated levels of mortality. This form of cryptic mortality attributable mostly to J-hook use is unlikely to be zero and should be addressed in any total mortality estimates comparing hook types (Afonso et al., 2012).

In addition to bite offs, it is also important to consider the effect of circle hook use on post-release mortality. The effect of anatomical hooking location on injury and mortality is clear: J-hooks have been shown to result in significantly higher rates of deep hooking than circle hooks (Carruthers et al., 2009; Epperly et al., 2012) and deep hooking (either gut or foul-hooking) has been shown to be more lethal for certain species (Epperly et al., 2012). The significant increase in at-vessel mortality associated with J-hooks is, therefore, related to the physiological effects resulting from the anatomical hooking location imposed by hook type (see Godin et al., 2012). The physiological effects associated with anatomical hooking location may increase post-release mortality, as retained hooks can lead to penetration of the pericardium and vital organs, in addition to significant disease (Borucinska et al., 2003; Kneebone et al., 2013). Therefore, to assume there is no difference in post-release mortality rates between hook types would indicate that injuries caused by hooking location have no effects after capture. Given the effect of hook type on anatomical hooking location and the related injuries for sharks, it should not be *assumed* that post-release mortality rates are the same between hook types.

In conclusion, we find retention rates for elasmobranchs increased significantly due to circle hook use for two species (blue and crocodile shark) of the ten assessed. One species (pelagic stingray) experienced a significant decrease in retention due to circle hook use. Other reviews describe either a significant decrease or no change in at-vessel mortality due to circle hook use (Godin et al. 2012; Gilman et al. 2016; Reinhardt et al. 2017; Coelho et al. 2020). While inter-specific variation is apparent, we find it unlikely that total mortality associated with circle hook use is higher than J-hooks for sharks. With the additional factors described in this paper (reduced injury and at-vessel mortality associated with circle hooks use, cryptic mortalities, and injuries due to increased bite offs with J-hooks), the total mortality associated with circle hook use is not expected to be higher than that associated with J-hook use. These results contribute to the growing body of literature that indicates circle hooks are an effective conservation tool for mitigating bycatch mortality and enhancing the effectiveness of management measures focused on vulnerable taxa.

Literature Cited

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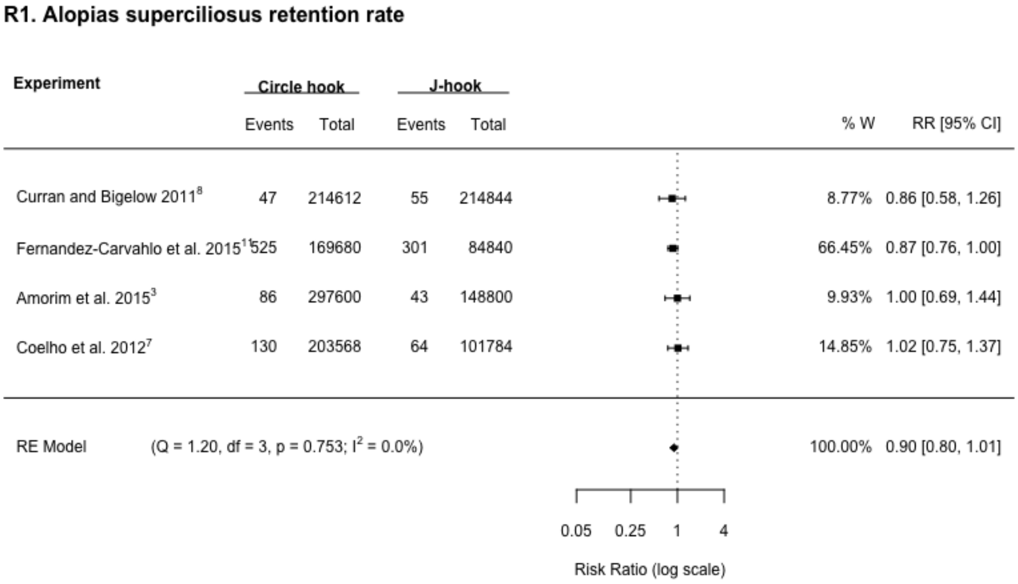
Table 1. A list of the experiments used in our analyses

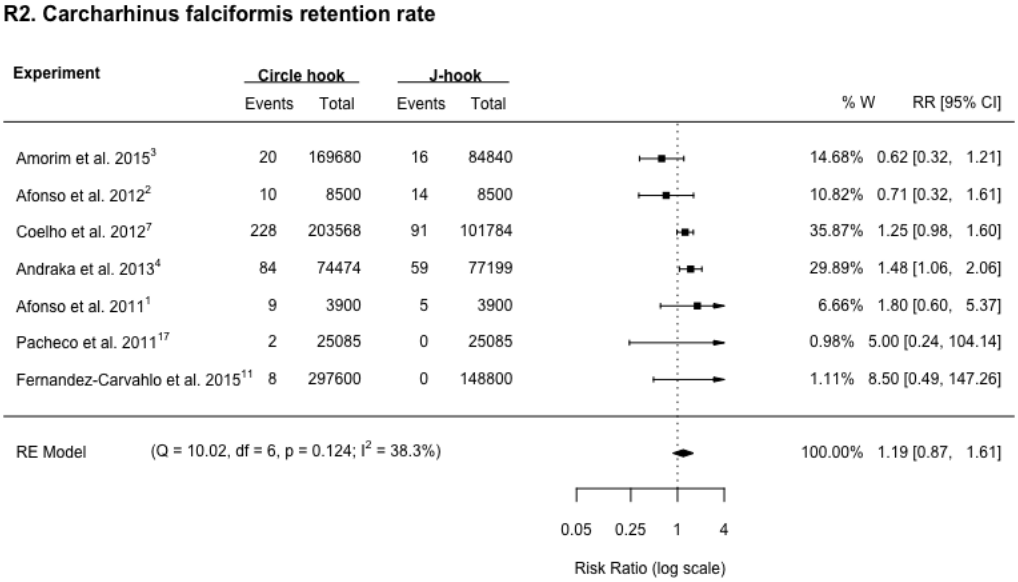
Citation	**Experiment.ID**
Afonso et al. 2011	1
Afonso et al. 2012	2
Amorim et al. 2015	3
Andraka et al. 2013	4
Bolten and Bjorndal 2005	5
Bolten and Bjorndal 2005	19
Cambiè et al. 2012	6
Coelho et al. 2012	7
Curran and Bigelow 2011	8
Domingo et al. 2012	9
Domingo et al. 2012	10
Fernandez-Carvahlo et al. 2015	11
Foster et al. 2012	12
Foster et al. 2012	13
Kerstetter and Graves 2006	14
Largacha et al. 2005	15
Mejuto et al. 2008	16
Pacheco et al. 2011	17
Sales et al. 2010	18

Figure 1. Effect size of hook type on retention rate for the bigeye thresher, *Alopias superciliosus*. A RR > 1 indicates increased retention was calculated on circle hooks compared to J-hooks. Weighting (%W) and the 95% confidence interval (CI) is shown for each study.


R1. Alopias superciliosus retention rate

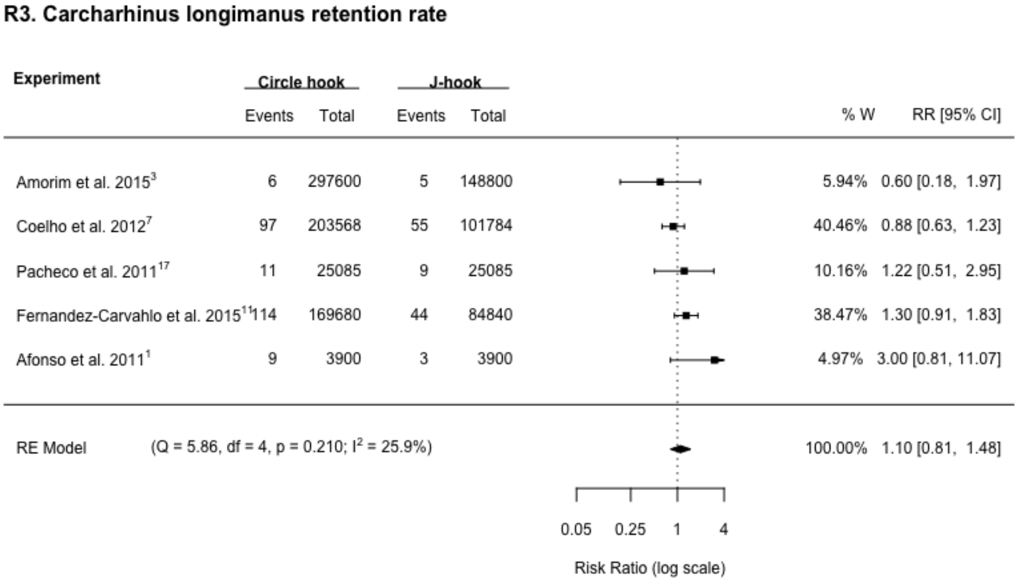
Experiment	Circle hook Events	Circle hook Total	J-hook Events	J-hook Total	% W	RR [95% CI]
Curran and Bigelow 2011[8]	47	214612	55	214844	8.77%	0.86 [0.58, 1.26]
Fernandez-Carvahlo et al. 2015[11]	525	169680	301	84840	66.45%	0.87 [0.76, 1.00]
Amorim et al. 2015[3]	86	297600	43	148800	9.93%	1.00 [0.69, 1.44]
Coelho et al. 2012[7]	130	203568	64	101784	14.85%	1.02 [0.75, 1.37]
RE Model (Q = 1.20, df = 3, p = 0.753; I^2 = 0.0%)					100.00%	0.90 [0.80, 1.01]

Figure 2. Effect size of hook type on retention rate for the silky shark, *Carcharhinus falciformis*. A RR > 1 indicates increased retention was calculated on circle hooks compared to J-hooks. Weighting (%W) and the 95% confidence interval (CI) is shown for each study.


R2. Carcharhinus falciformis retention rate

Experiment	Circle hook Events	Circle hook Total	J-hook Events	J-hook Total	% W	RR [95% CI]
Amorim et al. 2015[3]	20	169680	16	84840	14.68%	0.62 [0.32, 1.21]
Afonso et al. 2012[2]	10	8500	14	8500	10.82%	0.71 [0.32, 1.61]
Coelho et al. 2012[7]	228	203568	91	101784	35.87%	1.25 [0.98, 1.60]
Andraka et al. 2013[4]	84	74474	59	77199	29.89%	1.48 [1.06, 2.06]
Afonso et al. 2011[1]	9	3900	5	3900	6.66%	1.80 [0.60, 5.37]
Pacheco et al. 2011[17]	2	25085	0	25085	0.98%	5.00 [0.24, 104.14]
Fernandez-Carvahlo et al. 2015[11]	8	297600	0	148800	1.11%	8.50 [0.49, 147.26]
RE Model (Q = 10.02, df = 6, p = 0.124; I^2 = 38.3%)					100.00%	1.19 [0.87, 1.61]

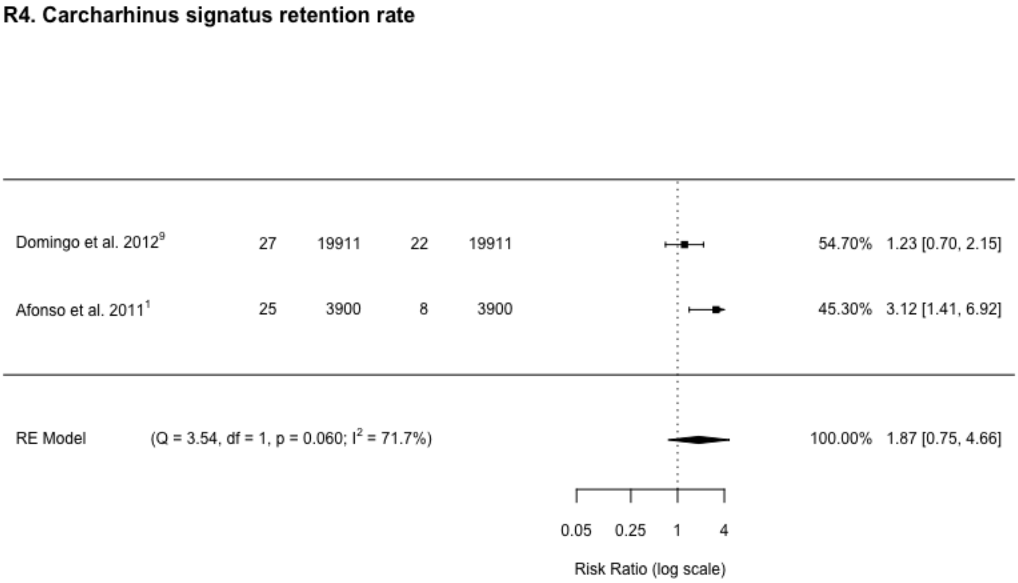
Figure 3. Effect size of hook type on retention rate for the oceanic whitetip, *C. longimannus*. A RR > 1 indicates increased retention was calculated on circle hooks compared to J-hooks. Weighting (%W) and the 95% confidence interval (CI) is shown for each study.



R3. Carcharhinus longimanus retention rate

Experiment	Circle hook Events	Circle hook Total	J-hook Events	J-hook Total	% W	RR [95% CI]
Amorim et al. 2015[3]	6	297600	5	148800	5.94%	0.60 [0.18, 1.97]
Coelho et al. 2012[7]	97	203568	55	101784	40.46%	0.88 [0.63, 1.23]
Pacheco et al. 2011[17]	11	25085	9	25085	10.16%	1.22 [0.51, 2.95]
Fernandez-Carvahlo et al. 2015[11]	114	169680	44	84840	38.47%	1.30 [0.91, 1.83]
Afonso et al. 2011[1]	9	3900	3	3900	4.97%	3.00 [0.81, 11.07]
RE Model (Q = 5.86, df = 4, p = 0.210; I^2 = 25.9%)					100.00%	1.10 [0.81, 1.48]

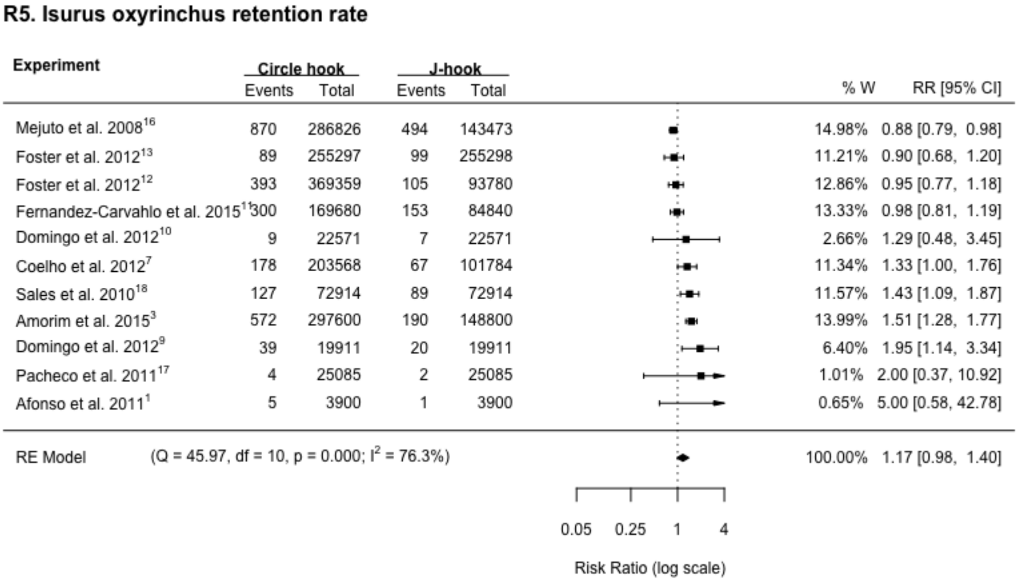
Figure 4. Effect size of hook type on retention rate for the night shark, *C. signatus*. A RR > 1 indicates increased retention was calculated on circle hooks compared to J-hooks. Weighting (%W) and the 95% confidence interval (CI) is shown for each study.



R4. Carcharhinus signatus retention rate

Domingo et al. 2012[9]	27	19911	22	19911	54.70%	1.23 [0.70, 2.15]
Afonso et al. 2011[1]	25	3900	8	3900	45.30%	3.12 [1.41, 6.92]
RE Model (Q = 3.54, df = 1, p = 0.060; I^2 = 71.7%)					100.00%	1.87 [0.75, 4.66]

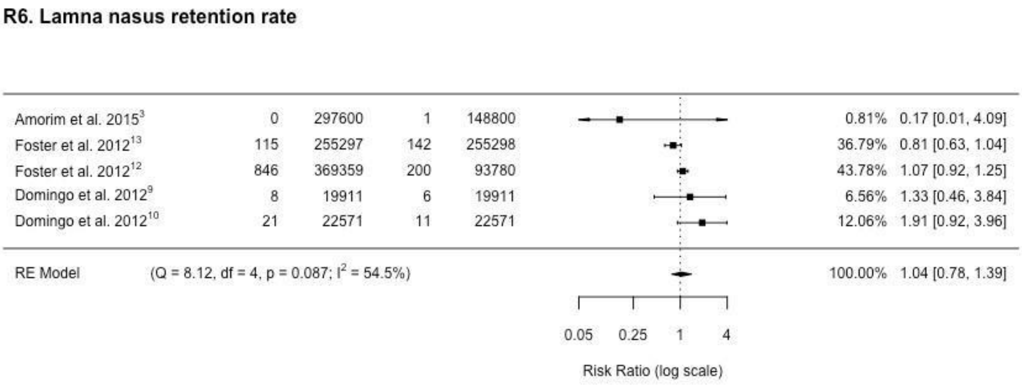
Figure 5. Effect size of hook type on retention rate for the shortfin mako, *Isurus oxyrhinchus*. A RR > 1 indicates increased retention was calculated on circle hooks compared to J-hooks. Weighting (%W) and the 95% confidence interval (CI) is shown for each study.



R5. Isurus oxyrinchus retention rate

Experiment	Circle hook Events	Circle hook Total	J-hook Events	J-hook Total	% W	RR [95% CI]
Mejuto et al. 2008[16]	870	286826	494	143473	14.98%	0.88 [0.79, 0.98]
Foster et al. 2012[13]	89	255297	99	255298	11.21%	0.90 [0.68, 1.20]
Foster et al. 2012[12]	393	369359	105	93780	12.86%	0.95 [0.77, 1.18]
Fernandez-Carvahlo et al. 2015[11]	300	169680	153	84840	13.33%	0.98 [0.81, 1.19]
Domingo et al. 2012[10]	9	22571	7	22571	2.66%	1.29 [0.48, 3.45]
Coelho et al. 2012[7]	178	203568	67	101784	11.34%	1.33 [1.00, 1.76]
Sales et al. 2010[18]	127	72914	89	72914	11.57%	1.43 [1.09, 1.87]
Amorim et al. 2015[3]	572	297600	190	148800	13.99%	1.51 [1.28, 1.77]
Domingo et al. 2012[9]	39	19911	20	19911	6.40%	1.95 [1.14, 3.34]
Pacheco et al. 2011[17]	4	25085	2	25085	1.01%	2.00 [0.37, 10.92]
Afonso et al. 2011[1]	5	3900	1	3900	0.65%	5.00 [0.58, 42.78]
RE Model (Q = 45.97, df = 10, p = 0.000; I^2 = 76.3%)					100.00%	1.17 [0.98, 1.40]

Figure 6. Effect size of hook type on retention rate for the porbeagle, *Lamna nasus*. A RR > 1 indicates increased retention was calculated on circle hooks compared to J-hooks. Weighting (%W) and the 95% confidence interval (CI) is shown for each study.



R6. Lamna nasus retention rate

Amorim et al. 2015[3]	0	297600	1	148800	0.81%	0.17 [0.01, 4.09]
Foster et al. 2012[13]	115	255297	142	255298	36.79%	0.81 [0.63, 1.04]
Foster et al. 2012[12]	846	369359	200	93780	43.78%	1.07 [0.92, 1.25]
Domingo et al. 2012[9]	8	19911	6	19911	6.56%	1.33 [0.46, 3.84]
Domingo et al. 2012[10]	21	22571	11	22571	12.06%	1.91 [0.92, 3.96]
RE Model (Q = 8.12, df = 4, p = 0.087; I^2 = 54.5%)					100.00%	1.04 [0.78, 1.39]

Figure 7. Effect size of hook type on retention rate for the blue shark, *Prionace glauca*. A RR > 1 indicates increased retention was calculated on circle hooks compared to J-hooks. Weighting (%W) and the 95% confidence interval (CI) is shown for each study.

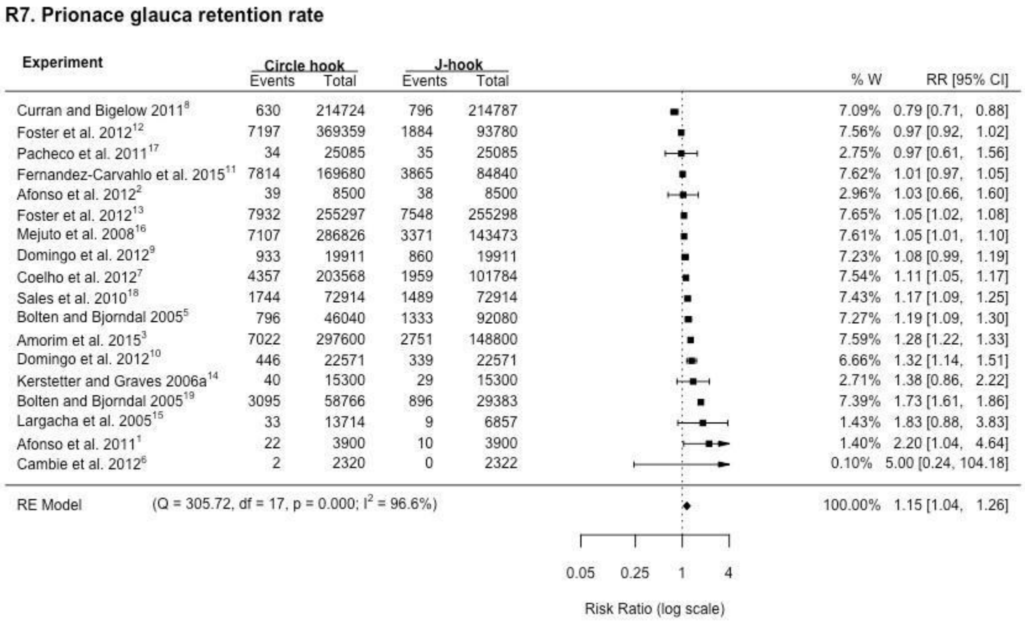


Figure 8. Effect size of hook type on retention rate for the crocodile shark, *Pseudocarcharias kamoharai*. A RR > 1 indicates increased retention was calculated on circle hooks compared to J-hooks. Weighting (%W) and the 95% confidence interval (CI) is shown for each study.

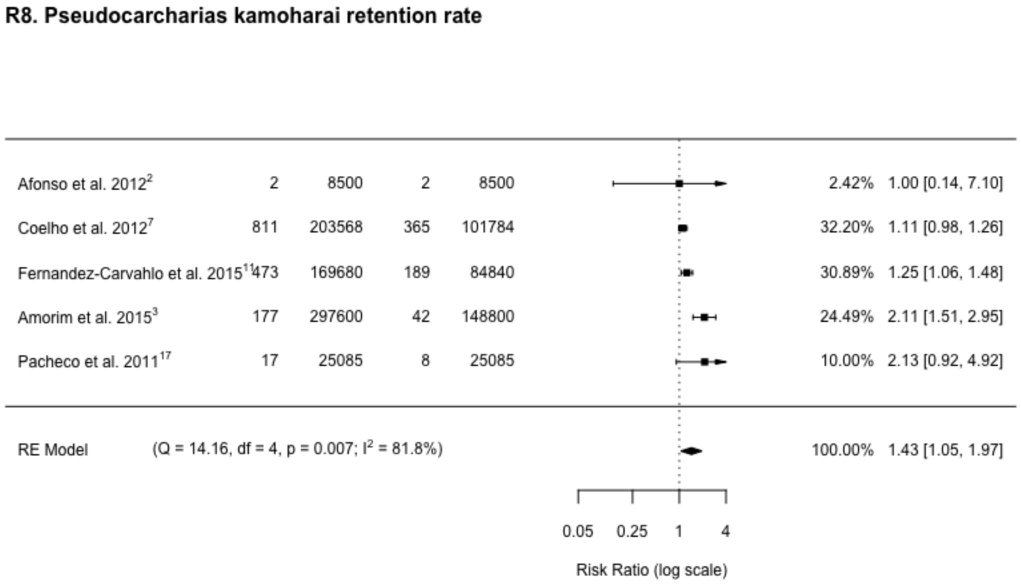
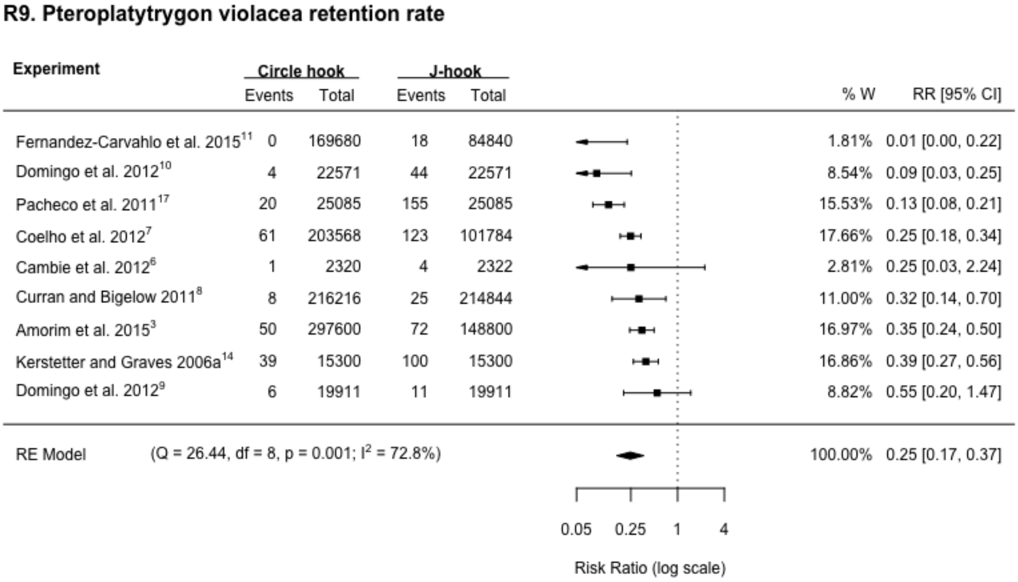
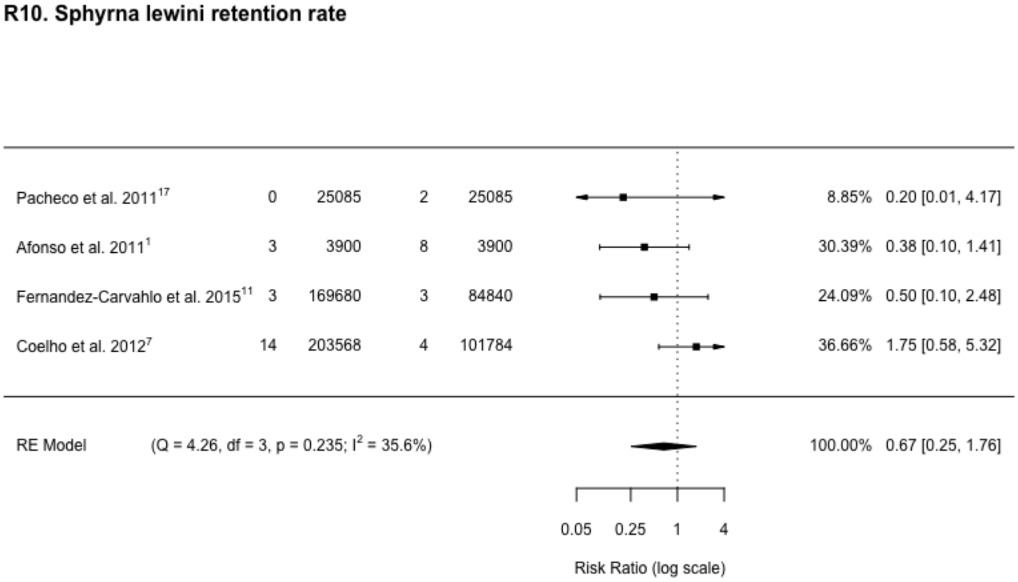


Figure 9. Effect size of hook type on retention rate for the pelagic stingray, *Pteroplatytrygon violacea*. A RR > 1 indicates increased retention was calculated on circle hooks compared to J-hooks. Weighting (%W) and the 95% confidence interval (CI) is shown for each study.



Experiment	Circle hook Events	Circle hook Total	J-hook Events	J-hook Total	% W	RR [95% CI]
Fernandez-Carvahlo et al. 2015[11]	0	169680	18	84840	1.81%	0.01 [0.00, 0.22]
Domingo et al. 2012[10]	4	22571	44	22571	8.54%	0.09 [0.03, 0.25]
Pacheco et al. 2011[17]	20	25085	155	25085	15.53%	0.13 [0.08, 0.21]
Coelho et al. 2012[7]	61	203568	123	101784	17.66%	0.25 [0.18, 0.34]
Cambie et al. 2012[6]	1	2320	4	2322	2.81%	0.25 [0.03, 2.24]
Curran and Bigelow 2011[8]	8	216216	25	214844	11.00%	0.32 [0.14, 0.70]
Amorim et al. 2015[3]	50	297600	72	148800	16.97%	0.35 [0.24, 0.50]
Kerstetter and Graves 2006a[14]	39	15300	100	15300	16.86%	0.39 [0.27, 0.56]
Domingo et al. 2012[9]	6	19911	11	19911	8.82%	0.55 [0.20, 1.47]
RE Model (Q = 26.44, df = 8, p = 0.001; I^2 = 72.8%)					100.00%	0.25 [0.17, 0.37]

Figure 10. Effect size of hook type on retention rate for the scalloped hammerhead, *Sphyrna lewini*. A RR > 1 indicates increased retention was calculated on circle hooks compared to J-hooks. Weighting (%W) and the 95% confidence interval (CI) is shown for each study.



Pacheco et al. 2011[17]	0	25085	2	25085	8.85%	0.20 [0.01, 4.17]
Afonso et al. 2011[1]	3	3900	8	3900	30.39%	0.38 [0.10, 1.41]
Fernandez-Carvahlo et al. 2015[11]	3	169680	3	84840	24.09%	0.50 [0.10, 2.48]
Coelho et al. 2012[7]	14	203568	4	101784	36.66%	1.75 [0.58, 5.32]
RE Model (Q = 4.26, df = 3, p = 0.235; I^2 = 35.6%)					100.00%	0.67 [0.25, 1.76]