THE EFFECT OF TERMINAL GEAR MODIFICATIONS ON THE TOTAL MORTALITY OF THE SHORTFIN MAKO, *ISURUS OXYRINCHUS*

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SUMMARY

Due to the overfished status of the North Atlantic shortfin mako, Isurus oxyrinchus, ICCAT has identified the need to better understand the effect of terminal gear modification as a mitigation measure in longline fisheries. Here we update two meta-analyses as one of the referenced studies was found to have a confounding variable that resulted in interpreting a bait effect as a hook effect. In both cases, significant differences in catchability are lost between hook types. For at-haulback mortality, the cited sources from the two meta-analyses were combined to maximize sample size; an updated model demonstrates a significant reduction of 10% in at-haulback mortality due to circle hook use relative to J-hook use. In review of additional publications, shortfin mako caught with circle hooks vs. J-hooks were twice as likely to be mouth hooked vs. foul or gut hooked, with the latter two being at least 4.5 times more lethal than mouth hooking. Overall, our paper demonstrates circle hook use is effective for reducing total mortality of the species and improves the probability of survival of shortfin mako incidentally captured in longlining fishing operations.

KEYWORDS

Circle hook, J-hook, bycatch mortality, post-release mortality, mitigation

1. Introduction

Shortfin mako sharks, *Isurus oxyrinchus,* are globally distributed throughout tropical and temperate seas (Compagno 1984). Females reach maturity at 2.8 m (L_{F50}) (Natanson et al. 2020), and current age-at-length metrics estimate this maturity status is reached between 19 and 22 years of age (Natanson et al. 2006, Rosa et al. 2017). Due to its life history, the species is vulnerable to population depletion, and the North Atlantic shortfin mako stock is currently overfished and undergoing overfishing (Anonymous 2019). The status of the South Atlantic stock is undetermined. However, ICCAT's Standing Committee on Research and Statistics (SCRS) recommended that precautionary measures should be considered due to the biological similarities to the northern stock and overall vulnerability of the species. Given that shortfin mako is hooked incidentally to longline target catch, reducing bycatch mortality is a critical component of achieving an overall reduction in fishing mortality. In keeping with this goal, ICCAT has indicated the need to further assess the effectiveness of the use of circle hooks and other terminal gear modifications as a mitigation measure (ICCAT Recs. 17-08, 19-05].

Keller et al. (2020) reviewed the effects of hook type on the catchability of the shortfin mako. Twenty-four studies assessed the effect of hook type on shortfin mako catchability, with two of these studies being meta-analyses. Overall, only one individual study (Domingo et al. 2012) found that the use of circle hooks was associated with significantly higher catch rates as compared to J hooks, while another (Mejuto et al. 2008) found catch rates were significantly higher on J-hooks as compared to circle hooks. Due to the relatively infrequent capture rates of shortfin mako (0.26 sharks per 1000 hooks in Kerstetter and Graves, 2006, for example), many

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experiments lacked the statistical power to run independent tests. Pooling data across the individual studies, Rosa et al. 2020 and Reinhardt et al. 2018, found that the use of circle hooks significantly increased catch rates for the shortfin mako. These meta-analyses also assessed at-haulback mortality, with both finding the use of circle hooks significantly decreased at-haulback mortality relative to J-hooks.

A benefit of meta-analyses is that pooling data for rare species allows statistical thresholds for minimal sample sizes to be met. However, a potential weakness is the inclusion of confounding variables that can sometimes lead to unequal assumptions between studies and spurious interpretation of overall results. This paper aims to review the available source data for meta-analyses to assess if any of the cited data includes confounding variables that would result in a spurious interpretation of the results. In addition, we reviewed available literature that detailed the effects of hook type on anatomical hooking location for the shortfin mako.

2. Methods

We conducted a review of published meta-analyses and related source material, including peer-reviewed papers, reviews, and SCRS documents related to gear modifications as a bycatch mitigation measure for shortfin mako. For the purpose of this review, catchability refers to catch (weight or count) per unit effort (hooks or hook-hours) (CPUE). At-haulback mortality is defined by observations of mortality upon retrieval of fishing gear, specifically if an animal was alive or dead at haulback. Anatomical hooking location refers to the location where a hook is embedded and was typically divided into three categories: mouth, gut, or foul hooking. Mouth hooking involves the hook being set within the mouth or jaw of the animal, while gut and foul hooking refer to the hook being set within the esophagus/stomach or on some exterior body feature, respectively.

2.1 Review of meta-analyses and primary research

We reviewed the methodology in each paper referenced in Reinhardt et al. 2018 and Rosa et al. 2020. The latter was recently updated by Coelho et al. 2020, so we used the new paper as a reference. Each source paper was assessed to determine that no confounding variables associated with bait or leader type were included that would cause spurious interpretations in the meta-analysis. In situations where reported data were imbalanced, we controlled for these variables by considering the study as two experiments, with this division allowing for the statistical effect of the confounded variable to be controlled. After dividing the study into two experiments, we reran the relevant statistics. See Reinhardt et al. (2018) for a summary of methodology for calculating Relative Risk (RR) and Random Effects (RE) models. To provide meaningful results, we reran the Random Effects models of Reinhardt et al. (2018) and Coelho et al. (2020) to include any modifications made pursuant to the above methodology.

3. Results

3.1 Catchability

3.1.1 Initial results

The two meta-analyses had found catch rates were significantly higher with circle hooks for the shortfin mako (Reinhardt et al. 2018; Rosa et al. 2020). Through review of Reinhardt et al. (2018), a transcription error was noted that resulted in the underreporting of circle hook effort, so we updated the number of hooks deployed per study to match those presented by Coelho et al. (2020). These updates resulted in a lower RR associated with circle hooks (from RR: 1.71, 95% CI: 1.57-1.86 to RR: 1.22, 95% CI: 0.98 to 1.52). The updated results, presented in **Figure 1**, demonstrate there is no significant difference in catchability between hook types.

In review of the source data cited in Reinhardt et al. (2018) and Coelho et al. (2020), the interpretation of one study was found to be problematic. Foster et al. (2012) reported catch rates for circle and J-hooks using both squid and mackerel as bait, with a total of 973,736 hooks deployed (624,657 circle hooks, 349,079 J-hooks). Approximately 40.87% of circle hooks were baited with squid, whereas 73.13% of J-hooks were baited with squid. This use of multiple bait treatments within a study is common, and there is no statistical issue when effort is equal amongst all other variables (see Domingo et al. 2012, for an example). When these data were pooled in the meta-analyses, however, the statistical effect of the substantially higher proportion of effort for squid-baited J-hooks was not accounted for. This is problematic as the use of mackerel was shown to significantly increase catch rates of shortfin mako within the same study (by 162% to 329%, $p \leq 0.001$, Foster et al. 2012). The overall CPUE of J-hooks for this study, as interpreted in Reinhardt et al. (2018) 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. To control for this bait effect, we divided Foster et al. (2012) into two studies, one that used squid and one that used mackerel. This treatment does not eliminate any data and increases the resolution of the analysis by controlling for the confounding variable. By updating Foster et al. (2012) into two studies, the RE model in paragraph 1 of Section 3.1 (**Figure 1)** was updated and resulted in a decreased RR associated with catchability of shortfin mako for circle hooks vs. J-hooks. The previous RR (**Figure 1**) was 1.22 (95% CI: 0.98 to 1.52), while the updated RR is 1.13 (95% CI: 0.90 to 1.42). The updated results, presented in **Figure 2**, demonstrate there is no significant difference in catchability between hook types.

There were different studies cited in Reinhardt et al. (2018) and Coelho et al. (2020). Considering these papers are the primary meta-analyses for this topic, we also sought to update the latter. We, therefore, reran our RE model only using the sources cited in Coelho et al. (2020), but with Foster et al. (2012) updated as two studies. Coelho et al. (2020) reported the RR of retention rates with circle hooks vs. J-hooks as 1.23 (95%, CI: 1.02 to 1.50). After updating Foster et al. (2012) into two studies, the RR dropped to 1.16 (95% CI: 0.98 to 1.38). The updated results, presented in **Figure 3**, demonstrate there is no significant difference in catchability between hook types.

Collectively, we provide three updates to the meta-analyses put forth by Reinhardt et al. (2018) and Coelho et al. (2020). These updates were made to ensure the correct effort was incorporated (**Figure 1**) and that Foster et al. (2012) was included as two separate studies to account for unequal effort of bait type between hook treatments (**Figures 2 and 3**). The results of these three meta-analyses demonstrate that there is no significant difference in shortfin mako catchability between circle hooks and J-hooks. These results represent strict updates to improve the resolution of previously published studies. Furthermore, Coelho et al. (2020) identified the high heterogeneity associated with their findings and this update lowers the I^2 from 84% to 79% (**Figure 3)**.

3.1.2 Updated results pursuant to the recommendations of the Sub-Committee

The Sub-Committee noted that Foster et al. (2012) included the use of tuna hooks. Since these hooks behave differently from J-hooks, it was requested that the lead author remove such hooks from the analysis. It was also suggested that in the meta-analyses, studies with small sample sizes should be removed.

After removing the tuna hooks from the Foster et al. (2012) data, the RR was reduced to 1.13 (95%CI 0.95 to 1.33) (**Figure 5**). Three experiments were included in the meta-analyses that captured less than 17 shortfin mako (Pacheco et al. 2011, 6 SMA; Afonso et al. 2011, 6 SMA; Domingo et al. 2012, 16 SMA). After removing the data from these studies (from the analysis which excluded the tuna hooks), the updated RR is 1.11 (95%CI 0.93 to 1.31) (**Figure 6**). These revised results also demonstrate that there is no significant difference in SMA catchability due to hook type.

3.2. At-haulback mortality

The same meta-analyses found at-haulback mortality rates were significantly lower for the shortfin mako while using circle hooks (Reinhardt et al. 2018: RR 0.89, 95% CI: 0.82 to 0.96; Rosa et al. 2020: RR 0.9, 95% CI: 0.83 to 0.97). In the updated paper, Coelho et al. 2020, however, concluded that the difference between hook treatments was not significant (RR: 0.82, 95% CI: 0.56 to 1.20). The variation that resulted in the loss of significance between Rosa et al. (2020) and Coelho et al. (2020) is not clear, as the same studies appear to be cited in both reports.

In Coelho et al. (2020) (and Rosa et al. 2020), there was one study, Yokota et al. (2006), not included in the analysis which was included in Reinhardt et al. (2018). Elsewhere in Coelho et al. (2020), this paper is listed as two experiments (due to separate sampling regimes, as in Reinhardt et al. (2018)). To account for the sampling effort and to maximize sample size, we included Yokota et al. (2006) as two experiments in an updated RE model. The updated RR of at-haulback mortality associated with circle hooks vs. J-hooks is 0.90 (95% CI: 0.83 to 0.96), which suggests a significant reduction of 10% in at-haulback mortality due circle hook use relative to J-hook use (**Figure 4**).

Overall, the updated model, which combines two previously accepted models, demonstrates that circle hook use significantly decreases the at-haulback mortality of shortfin mako. Given this, use of circle hooks has the potential to improve rates of survival for incidentally-caught shortfin mako sharks on longlines.

3.3 Anatomical hooking location

Four studies addressed anatomical hooking location; two studies lacked an adequate sample size to run statistics and two found a significant difference between hook types. Carruthers et al. (2009) and Epperly et al. (2012) found sharks caught on circle hooks (10° offset in one study) were approximately twice as likely to be mouth hooked as compared to gut or foul hooking **(Table 1)**. Epperly et al. (2012) also found that gut hooking (Odds ratio estimate: 0.214, p-value < 0.0001) and foul hooking (Odds ratio estimate: 0.218, p-value = 0.0009) are at least 4.5 times more lethal than mouth hooking. These data demonstrate that the use of J-hooks can cause increased injury to shortfin mako relative to circle hook use and have a negative effect on the body and release condition, both which likely contribute to increased post-release mortality rates.

4. Discussion

Meta-analyses are useful for summarizing findings from a number of studies, increasing the robustness of individual studies and carrying out statistical analyses when sample sizes may be low due to the rarity of a species. For these reasons, the use of meta-analyses to study the catchability and at-haulback mortality of the shortfin mako is valuable (see Keller et al. 2020 for review of individual studies on shortfin mako). While meta-analyses are, therefore, useful, source material should be carefully reviewed to ensure that no confounding variables skew interpretation of the results. We found two meta-analyses, Reinhardt et al. 2018 and Coelho et al. 2020, that assessed differences in catchability and at-haulback mortality for the shortfin mako. We subsequently reviewed the methodology of the cited source material and conducted our own analyses.

In Reinhardt et al. (2018), the RR for shortfin mako being captured on a circle hook was reported as 1.71, but this value was inflated due to a transcription error affecting circle hook effort (see section 3.1, paragraph 1 for explanation). Upon correction, the new RR value was 1.22, although the difference between hook types was not significant (**Figure 1**). For both meta-analyses, we found the interpretation of one study's catch rates attributed to hook type (Foster et al. 2012) was inclusive of a bait effect. We, therefore, considered this study separately in the aforementioned meta-analyses to control for bait type (**Figures 2 and 3**). With these updates, there was no significant difference in catchability between hook types, and the RR of a shortfin mako being captured on a circle hook vs. J-hook was reduced from 1.22 (Reinhardt et al. 2018) and 1.23 (Coelho et al. 2020) to 1.13 and 1.16, respectively.

Pursuant to the requests put forth by the Sub-Committee, a reanalysis was done to remove tuna hooks from the Foster et al. (2012) data. Upon completion, the RR was reduced to 1.13 (95%CI 0.95 to 1.33) (**Figure 5**), demonstrating no significant difference in SMA catchability due to hook type. We also removed three experiments from the reanalysis that had less than 17 specimens (Pacheco et al. 2011, 6 SMA; Afonso et al. 2011, 6 SMA; Domingo et al. 2012, 16 SMA) and found that after removing these studies (from the analysis which excluded the tuna hooks), the updated RR is 1.11 (95%CI 0.93 to 1.31) (**Figure 6**). These revised results also demonstrate that there is no significant difference in SMA catchability due to hook type.

Reinhardt et al. 2018 and Coelho et al. 2020 had different studies cited for analysis on at-haulback mortality. We combined these sources to maximize sample size and documented a significant decrease in at-haulback mortality attributable to hook type, with circle hooks resulting in a 10% reduction in at-haulback mortality (RR: 0.90, 95% CI: 0.83 to 0.96) relative to J-hooks. Finally, shortfin mako caught on circle hooks were twice as likely to be mouth hooked vs. those caught on J-hooks, which is significant because foul and gut hooking (which both occur significantly more on J-hooks) are at least 4.5 times more lethal than mouth hooking (Carruthers et al. 2009; Epperly et al. 2012).

In consideration of modifications to terminal gear to reduce total mortality, an alleged increase in catchability associated with circle hooks has been highlighted. Semba et al. (2018) used a RR from Reinhardt et al. (2018) to suggest that total mortality is higher when using circle hooks due to increased catch rates. However, as described above, the updates demonstrated that there is no significant difference in catchability between hook types (see **Figures 1-3**). Furthermore, the original argument by Semba et al. (2018) fails to address three key tenets. Firstly, the use of circle hooks results in significantly more mouth hooking of shortfin mako than J-hooks (Carruthers et al. 2009; Epperly et al. 2012). The decreased rate of mouth hooking associated with the use of J-hooks has been hypothesized to allow hooked animals to more easily bite off the gangion. Therefore, the perceived higher catch rates associated with circle hooks are likely not due to hooking efficiency, but decreased bite offs and increased retention (Afonso et al. 2012). The minor, non-significant differences in catchability may be attributable to bite offs as described in the literature. Secondly, sharks that bite off the leaders and swim away with a trailing leader while gut hooked may experience elevated levels of mortality. This cryptic mortality is unlikely to be zero and should be addressed in any total mortality estimates comparing hook types (Afonso et al. 2012).

Thirdly, the increase of 10% in at-haulback mortality due to J-hook use relative to circle hook use is due to anatomical hooking location. This is evident as foul and gut hooking have been shown to be at least 4.5 times more lethal than mouth hooking in the shortfin mako (Epperly et al. 2012). We assume that the difference in survival between hook types is due to interactions that occur after hooking; this has been similarly assumed in studies assessing catchability between the two hook types (Afonso et al. 2011). The direct relationship between anatomical hooking location and mortality is intuitive and supported by the data: J-hooks result in significantly less mouth hooking (Carruthers et al. 2009; Epperly et al. 2012) and hooking outside the mouth (either gut or foul-hooking) is significantly more lethal for this species (Epperly et al. 2012). The significant increase in at-haulback mortality associated with J-hooks is, therefore, due to the physiological effects resulting from the anatomical hooking location imposed by hook type. Given this relationship, it is clear that the overall release condition of the species must also be affected by hooking location and hook type; the latter due to the significantly increased likelihood of gut or foul hooking associated with J-hooks. To assume there is no difference in release condition due to hooking location and hook type would indicate that sharks injured from hooking location and/or hook type are not at higher risk of post-release mortality than those hooked in the mouth. For these reasons, it is not scientifically sound to assume that post-release mortality rates are the same between hook types, as calculated in Semba et al. (2018). In other pelagic shark species, such as the blue shark, *Prionace glauca,* gut-hooked individuals were shown to have higher post-release mortality rates due to internal damage (Campana et al. 2009). French et al. (2015) compared the effects of hook type on post-release mortality of the shortfin mako in a recreational fishery and found hooking location and physical injuries associated with J-hooks likely contributed to increased levels of mortality, further lending support to the conservation value of circle hook use.

These findings collectively resulted in updating two meta-analyses that have been discussed by the Sub-Committee on Ecosystems. In previous intersessional meetings, these meta-analyses have been used as support for assessing the effect of hook type on catchability and at-haulback mortality. As we have updated these meta-analyses to be more comprehensive, by adding studies and decreasing heterogeneity, we expect these results will be readily accepted.

In conclusion, the findings from this analysis are clear:

1. Based upon the review and updating of two meta-analyses, there is no significant difference in the catchability of the shortfin mako sharks attributable to circle hooks.
2. Based upon the review and updating of two meta-analyses, the at-haulback mortality of shortfin mako significantly decreases by at least 10% due to circle hook use relative to J-hook use.
3. The use of circle hooks vs. J-hooks significantly increases the likelihood of mouth hooking, with gut hooking and foul hooking being at least 4.5 times more lethal than mouth hooking.
4. Based on the best available science presented here, there is no evidence to indicate that total mortality associated with circle hook use is higher than J-hooks. When the additional factors described in this paper (reduced injury severity and at-haulback mortality with circle hooks, cryptic mortalities and injuries due to increased bite-offs with J-hooks), the total mortality associated with circle hooks is expected to be lower than that associated with J-hooks.

Literature Cited

Afonso, A.S., Hazin, F.H.V., Carvalho, F., Pacheco, J.C., Hazin, H., Kerstetter, D.W., Murie, D., Burgess, G.H. (2011). 'Fishing Gear Modifications to Reduce Elasmobranch Mortality in Pelagic and Bottom Longline Fisheries off Northeast Brazil', *Fisheries Research*, 108 (011), 336–43

Afonso, A.S., Santiago, R., Hazin, H., Hazin, F.H.V. (2012). 'Shark Bycatch and Mortality and Hook Bite-Offs in Pelagic Longlines: Interactions between Hook Types and Leader Materials', *Fisheries Research*, 131–133, 9–14

Amorim, S., Santos, M.N., Coelho, R., Fernandez-Carvalho, J. (2015). 'Effects of 17/0 Circle Hooks and Bait on Fish Catches in a Southern Atlantic Swordfish Longline Fishery', *Aquatic Conservation: Marine and Freshwater Ecosystems*, 25, 518–33

Andraka, S., Mug, M., Hall, M., Pons, M., Pacheco, L., Parrales, M. and others. (2013). 'Circle Hooks: Developing Better Fishing Practices in the Artisanal Longline Fisheries of the Eastern Pacific Ocean', *Biological Conservation*, 160, 214–24

Anonymous. (2019). Report of the 2019 shortfin mako shark stock assessment update meeting (Madrid, Spain 20-24 May 2019). *Collective Volume of. Scientific Papers.* ICCAT, 76(10): 1-77.

Campana, S.E., Joyce, W., Manning, M.J. (2009). 'Bycatch and Discard Mortality in Commercially Caught Blue Sharks Prionace Glauca Assessed Using Archival Satellite Pop-up Tags', *Marine Ecology Progress Series*, 387, 241–53

Carruthers, E.H., Schneider, D.C., Neilson, J.D. (2009). 'Estimating the Odds of Survival and Identifying Mitigation Opportunities for Common Bycatch in Pelagic Longline Fisheries', *Biological Conservation*, 142, 2620–30

Campagno, L.J.V., 1984. FAO species catalogue. Vol 4. Sharks of the world. An annotated and illustrated catalogue of shark species known to date. Part 1 - Hexanchiformes to Lamniformes. FAO. Fish. Synop. Vol. 4, Pt. 1: 1-250.

Coelho, R., Bach, P., Santos, C.C., Rosa, D., Romanov, E., Infante, P., Massey, Y., Mees, C., Arrizabalaga, H. (2020). Evaluation of the effects of hooks' shape & size on the catchability, yields and mortality of target and bycatch species, in the Atlantic Ocean and adjacent seas surface longline fisheries. Final Report. European Commission. Specific Contract No. 16 under Framework Contract No.EASME/EMFF/2016/008. 143 pp + XI Appendices.

Coelho, R., Santos, M.N., Amorim, S. (2012). 'Effects of Hook and Bait on Targeted and Bycatch Fisheries in an Equatorial Atlantic Pelagic Longline Fishery', *Bulletin of Marine Science*, 88, 449–467

Domingo, A., Pons, M., Jiménez, S., Miller, P., Barceló, C., Swimmer, Y. (2012). 'Circle Hook Performance in the Uruguayan Pelagic Longline Fishery', *Bulletin of Marine Science*, 88, 499–511

Epperly, S.P., Watson, J.W., Foster, D.G, Shah, A.K. (2012). 'Anatomical Hooking Location and Condition of Animals Captured with Pelagic Longlines: The Grand Banks Experiments 2002-2003', *Bulletin of Marine Science*, 88, 513–27

Fernandez-Carvalho, J., Coelho, R., Santos, M.N., Amorim, S. (2015). 'Effects of Hook and Bait in a Tropical Northeast Atlantic Pelagic Longline Fishery: Part II-Target, Bycatch and Discard Fishes', *Fisheries Research*, 164, 312–21

Foster, D. G., Epperly, S.P., Shah, A.K., Watson, J.W. (2012). 'Evaluation of Hook and Bait Type on the Catch Rates in the Western North Atlantic Ocean Pelagic Longline Fishery', *Bulletin of Marine Science*, 88, 529–45

French, R. P., Lyle, J., Tracey, S., Currie, S., Semmens, J. M. (2015). 'High survivorship after catch-and-release fishing suggests physiological resilience in the endothermic shortfin mako shark (*Isurus oxyrinchus*)', *Conservation physiology*, *3*(1), cov044

Keller, B.A., Swimmer, Y., Brown, C. (2020). Review of the effect of hook type on the catchability, hooking location, and post-capture mortality of the shortfin mako, *Isurus oxyrinchus. Collective Volume of Scientific Papers, ICCAT*, 77, 240–51

Kerstetter, D. W., Graves, J.E. (2006). 'Effects of Circle versus J-Style Hooks on Target and Non-Target Species in a Pelagic Longline Fishery', *Fisheries Research*, 80, 239–50

Kim, S., Moon, D., Boggs, C., Koh, J., An, D. (2006) 'Comparison of Circle Hook and J Hook Catch Rate for Target and Bycatch Species Taken in the Korean Tuna Longline Fishery', *Journal of the Korean Society of Fisheries Technology*, 42, 210–16

Mejuto, J., García-Cortés, B., Ramos-Cartelle, A. (2008). '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', *Collective Volume of Scientific Papers, ICCAT*, 62, 1793–1830

Natanson, L. J., Kohler, N.E., Ardizzone, D., Cailliet, G.M., Wintner, S.P., Mollet, H.F. (2006). 'Validated age and growth estimates for the shortfin mako, *Isurus oxyrinchus*, in the North Atlantic Ocean', *Environmental Biology of Fishes,* 77: 367–383

Natanson, L.J., Winton, M., Bowlby, H., Joyce, W., Deacy, B., Coelho, R., Rosa. D. (2020). 'Updated reproductive parameters for the shortfin mako (*Isurus oxyrinchus*) in the North Atlantic Ocean with inferences of distribution by sex and reproductive stage', *Fishery Bulletin* 118: 21–36

NMFS (2011). Southeast fisheries science center pelagic observer program data. Miami, FL: Southeast Fisheries Science Center. Unpublished raw data

Pacheco, J. C., Kerstetter, D.W., Hazin, F.H., Hazin, H., Segundo, R.S.S.L., Graves, J.E. and others. (2011). 'A Comparison of Circle Hook and J Hook Performance in a Western Equatorial Atlantic Ocean Pelagic Longline Fishery', *Fisheries Research*, 107 (2011), 39–45

Reinhardt, J.F., Weaver, J., Latham, P.J., Dell'Apa, A., Serafy, J.E., Browder, J.A. and others. (2018). 'Catch Rate and At-Vessel Mortality of Circle Hooks versus J-Hooks in Pelagic Longline Fisheries: A Global Meta-Analysis', *Fish and Fisheries*, 19, 413–30

Rosa, D., Mas, F., Mathers, A., Natanson, L.J., Domingo, A., Carlson, J., Coelho, R. (2017). 'Age and growth of shortfin mako in the north Atlantic, with revised parameters for con- sideration to use in the stock assessment'. *Int. Comm. Conserv. Atlantic Tunas*, ICCAT SCRS/2017/111, 22p.

Rosa, D, Santos, C.C., Coelho, R. (2020). 'Assessing the Effects of Hook , Bait and Leader Type As Potential Mitigation Measures To Reduce Bycatch and Mortality Rates of Shortfin Mako : A Meta-Analysis With Comparisons for Target , Bycatch and Vulnerable Fauna Interactions', *Collective Volume of Scientific Papers, ICCAT*, 76, 247–78

Sales, G., Giffoni, B.B., Fiedler, F.N., Azevedo, V.G., Kotas, J.E., Swimmer, Y., Bugonia, L. (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 and Freshwater Ecosystems*, 20, 428–36

Santos, M. N., Coelho, R., Fernandez-Carvalho, J. & Amorim, S. (2012). Effects of hook and bait on sea turtle catches in an equatorial Atlantic pelagic longline fishery. *Bulletin of Marine Science*, 88:683-701.

Ward, P., Epe, S., Kreutz, D., Lawrence, E., Robins, C., Annette, S. (2009). 'The Effects of Circle Hooks on Bycatch and Target Catches in Australia's Pelagic Longline Fishery', *Fisheries Research*, 97, 253–62

Yokota, K., Kiyota, M., Minami, H. (2006). 'Shark Catch in a Pelagic Longline Fishery: Comparison of Circle and Tuna Hooks', *Fisheries Research*, 81, 337–41

Table 1 – Summary table of details for each paper related to hooking location. Any significant differences are in boldface. Sample size relates to the number of shortfin mako used for any statistical tests.

Paper	Type	Region	Study period	Tests	# of hooks	# of hooks per treatment	Sample size	Results	Comments
Carruthers et al. 2009	Research	Northwest Atlantic	2001-2004, 2005-2006	16/0 (0° offset) circle v. 8/0 or 9/0 (20-30° offset) J-style v. 8/0 or 9/0 (0° offset) J-style	950000	596 v. 70 v. 193 sets per treatment	1189 (additional samples from observer data 2001-2006)	**Significant difference**	Twice as likely to be mouth-hooked on circle hooks (95% CI: 1.1-3.7).
Epperly et al. 2012	Research	Western North Atlantic	2002-2003	18/0 (0° and 10° offset) circle v. 9/0 (10-30° offset) J-style	813157	N/A	550	**Significant difference**	Odds of mouth hooking were significantly less with J-hooks compared to 10° offset circle hook (odds ratio 0.428, CI: 0.246-0.746). Non-offset circle hooks were not significant (p=0.0593). Foul hooking is 4.58 times more lethal than mouth hooking (Odds ratio estimate: 0.218, p-value = 0.0009). Gut hooking 4.67 times more lethal than mouth hooking (Odds ratio estimate: 0.214, p-value < 0.0001).
Kerstetter & Graves 2006	Research	Gulf of Mexico and Northwest Atlantic	2003-2004	16/0 (0° offset) circle v. 9/0 (10° offset) J-style	30600	15300	8	Lack of sample size	
Pacheco et al. 2011	Research	Equatorial South Atlantic	2006-2007	18/0 (0° offset) circle v. 9/0 (10° offset) J-style	50170	25085	6	Lack of sample size	

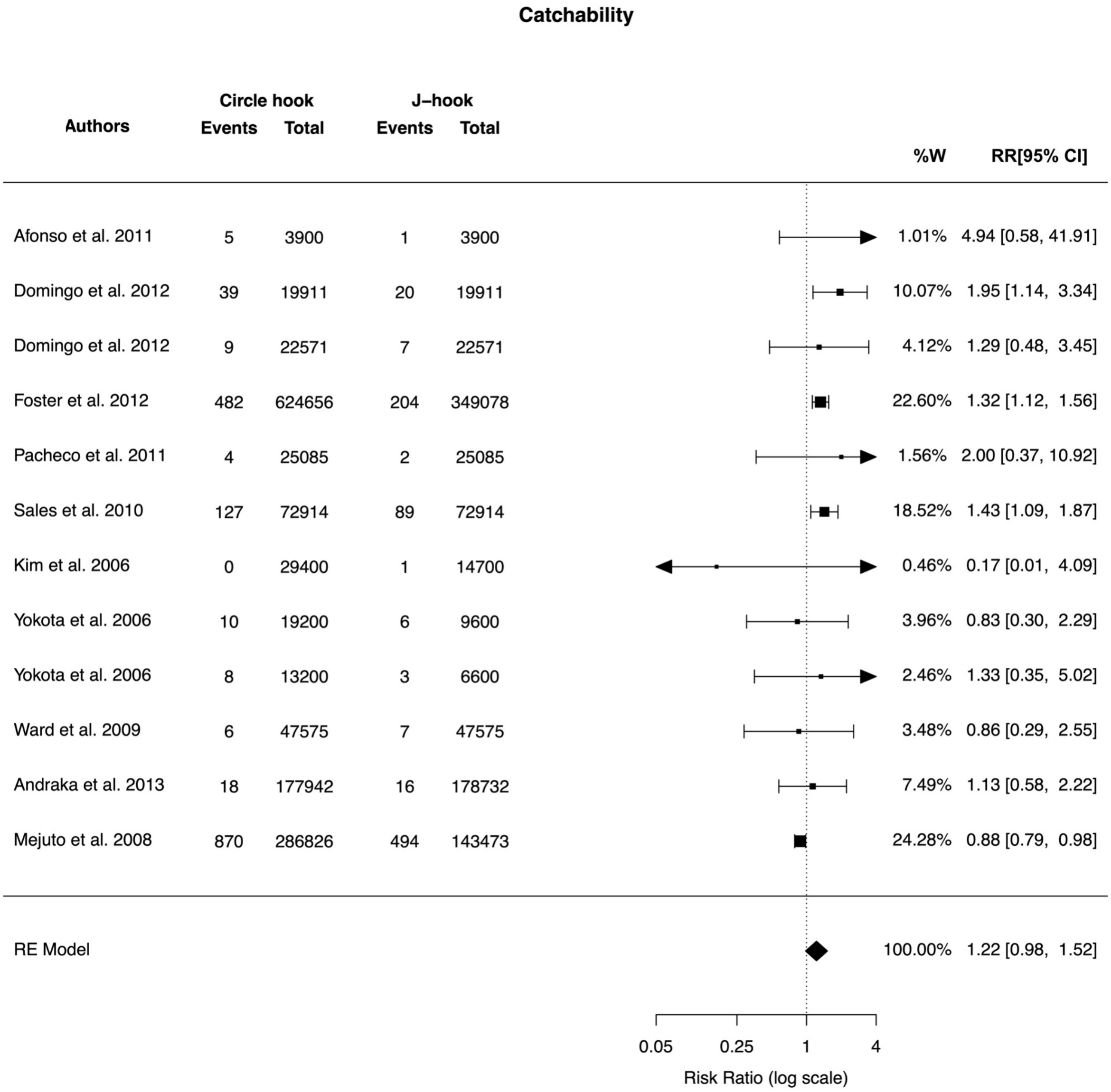

Figure 1. Effect size of hook type on catch rate for shortfin mako, updated from Reinhardt et al. (2018) to account for the correct effort associated with hook type. A RR > 1 indicates a higher catch was calculated on circle hooks compared to J-hooks. Weighting (%W) and the 95% confidence interval (CI) is shown for each study. These results demonstrate there is no significant difference between catch rates based upon hook type. Heterogeneity: I^2: 65.37%. p=0.08 (for RE model).

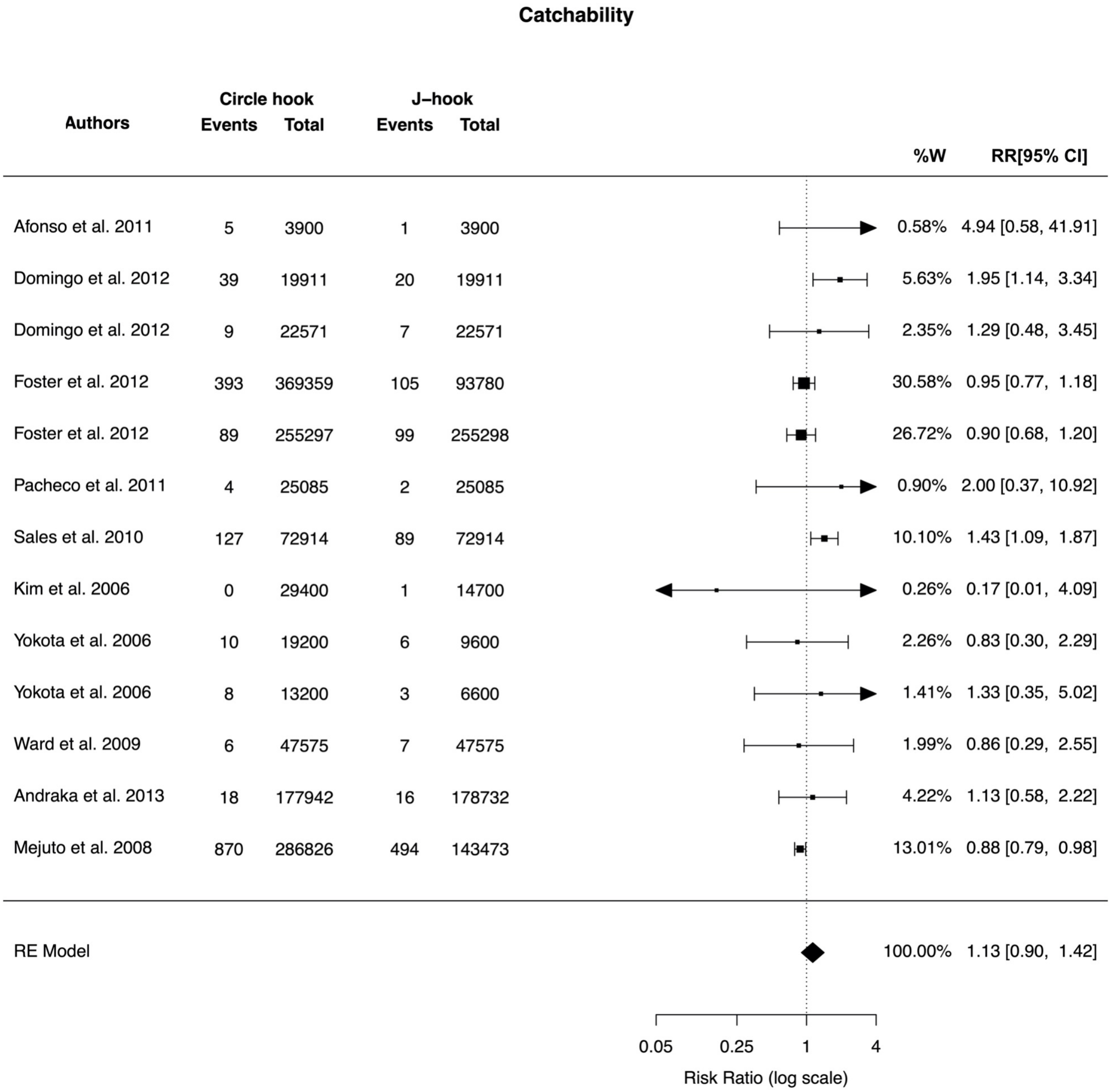

Figure 2. Effect size of hook type on catch rate for shortfin mako, updated from Reinhardt et al. (2018) to account for the correct effort associated with hook type and to include Foster at al. (2012) as two studies. A RR > 1 indicates a higher catch was calculated on circle hooks compared to J-hooks. Weighting (%W) and the 95% confidence interval (CI) is shown for each study. These results demonstrate there is no significant difference between catch rates based upon hook type. Heterogeneity: I^2: 68.59%. p =0.07 (for RE model).

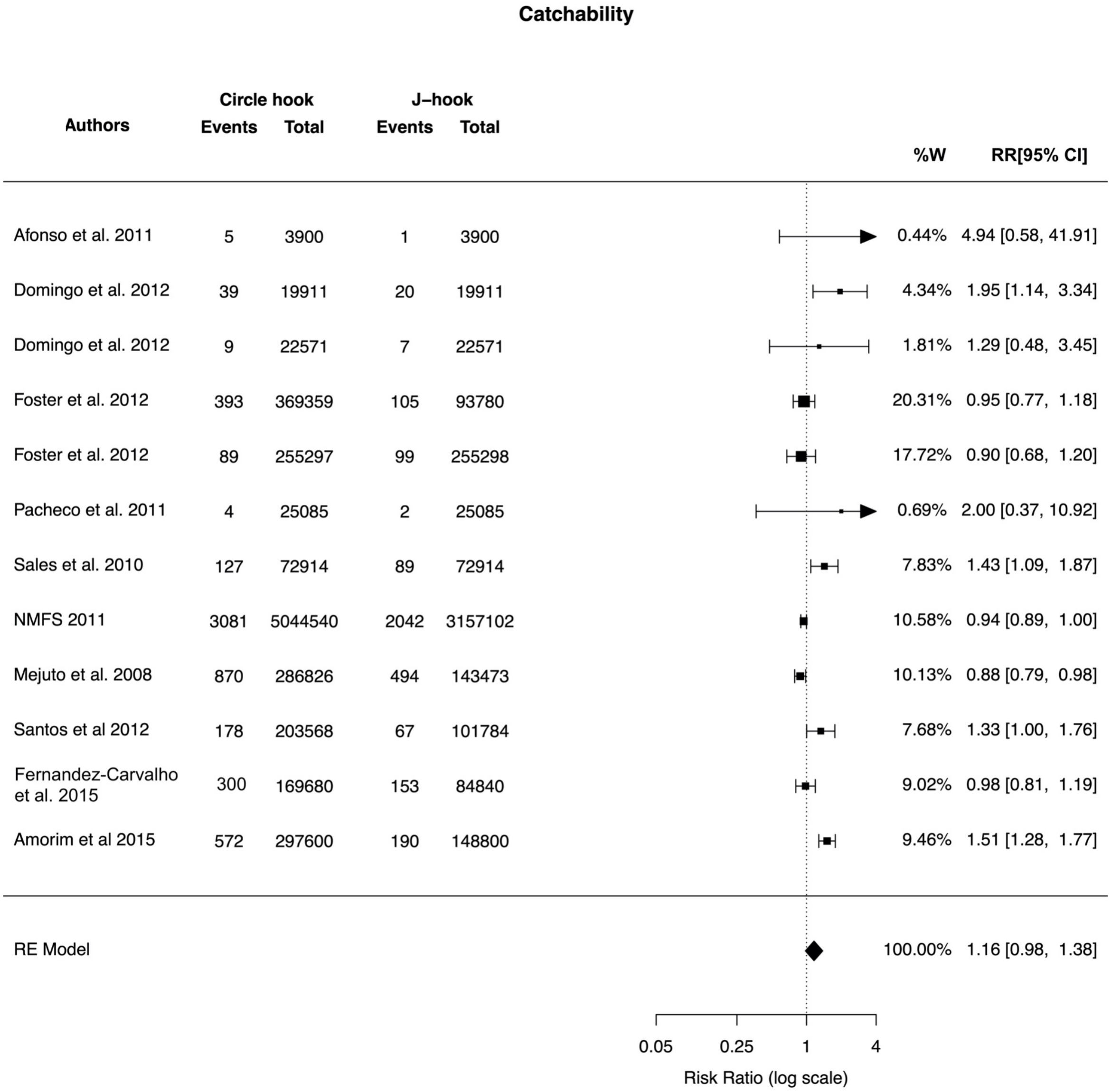

Figure 3. Effect size of hook type on catch rate for shortfin mako, updated from Coelho et al. (2020) to include Foster at al. (2012) as two studies. A RR > 1 indicates a higher catch was calculated on circle hooks compared to J-hooks. Weighting (%W) and the 95% confidence interval (CI) is shown for each study. These results demonstrate there is no significant difference between catch rates based upon hook type. Heterogeneity: I^2: 79.26%. $p = 0.09$ (for RE model).

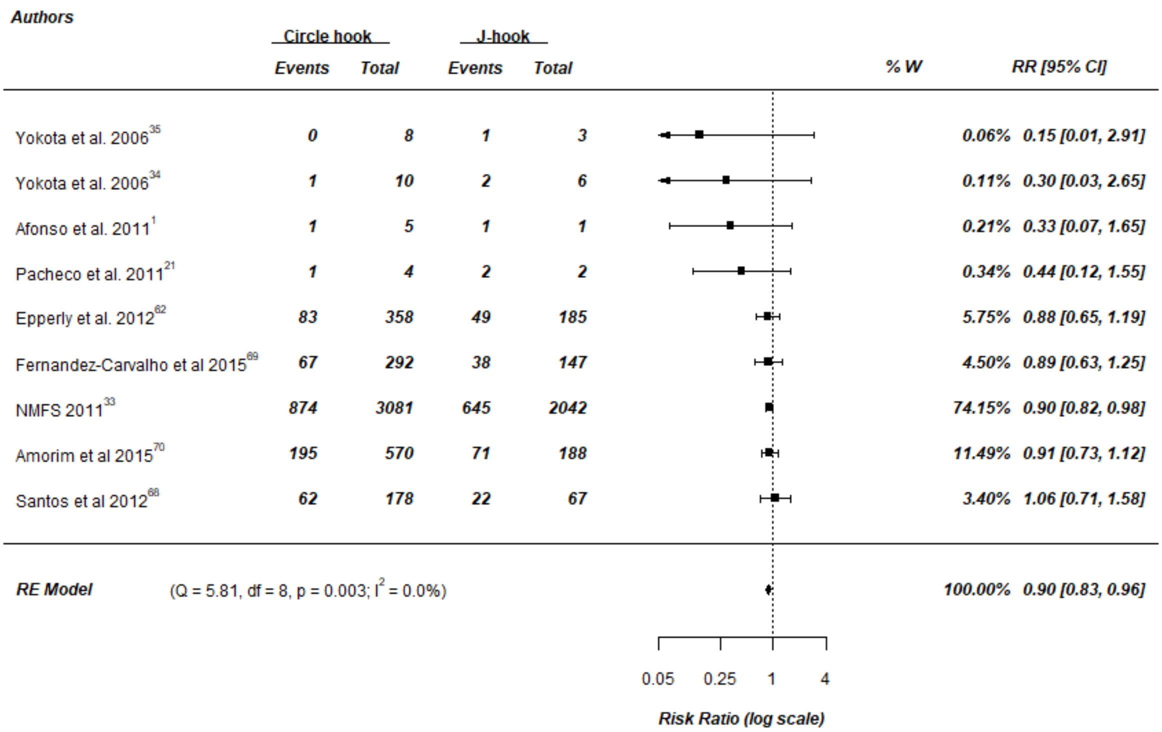

Figure 4. Effect size of hook type on at-haulback mortality rates for shortfin mako, updated from Coelho et al. (2020) to include Yokota at al. (2006) as two studies. A RR > 1 indicates at-haulback mortality rate was calculated on circle hooks compared to J-hooks. Weighting (%W) and the 95% confidence interval (CI) is shown for each study. These results demonstrate there is a significant decrease in at-haulback mortality attributable to circle hook use.

Authors	Circle hook Events	Circle hook Total	J-hook Events	J-hook Total	% W	RR [95% CI]
Foster et al. 2012[9]	393	369359	88	70990	10.84%	0.86 [0.68, 1.08]
Mejuto et al. 2008[59]	870	286826	494	143473	12.98%	0.88 [0.79, 0.98]
Foster et al. 2012[71]	89	255297	99	255298	9.73%	0.90 [0.68, 1.20]
NMFS 2011[33]	3081	5044540	2042	3157102	13.57%	0.94 [0.89, 1.00]
Fernandez-Carvalho et al 2015[69]	300	169680	153	84840	11.56%	0.98 [0.81, 1.19]
Domingo et al. 2012[8]	9	22571	7	22571	2.31%	1.29 [0.48, 3.45]
Santos et al 2012[68]	178	203568	67	101784	9.84%	1.33 [1.00, 1.76]
Sales et al. 2010[27]	127	72914	89	72914	10.04%	1.43 [1.09, 1.87]
Amorim et al 2015[70]	572	297600	190	148800	12.12%	1.51 [1.28, 1.77]
Domingo et al. 2012[7]	39	19911	20	19911	5.57%	1.95 [1.14, 3.34]
Pacheco et al. 2011[21]	4	25085	2	25085	0.88%	2.00 [0.37, 10.92]
Afonso et al. 2011[1]	5	3900	1	3900	0.57%	4.94 [0.58, 41.91]
RE Model (Q = 54.43, df = 11, p = 0.160; I^2 = 84.9%)					100.00%	1.13 [0.95, 1.33]

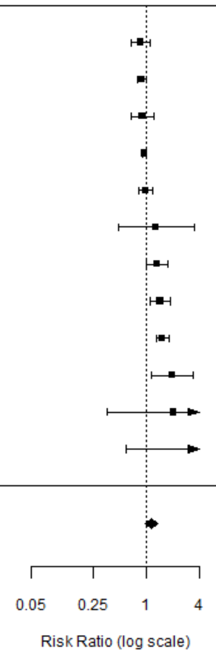

Figure 5. Effect size of hook type on catch rate for shortfin mako, updated from Coelho et al. (2020) to include Foster at al. (2012) as two studies with tuna hooks being removed from analysis. A RR > 1 indicates a higher catch was calculated on circle hooks compared to J-hooks. Weighting (%W) and the 95% confidence interval (CI) is shown for each study. These results demonstrate there is no significant difference between catch rates based upon hook type.

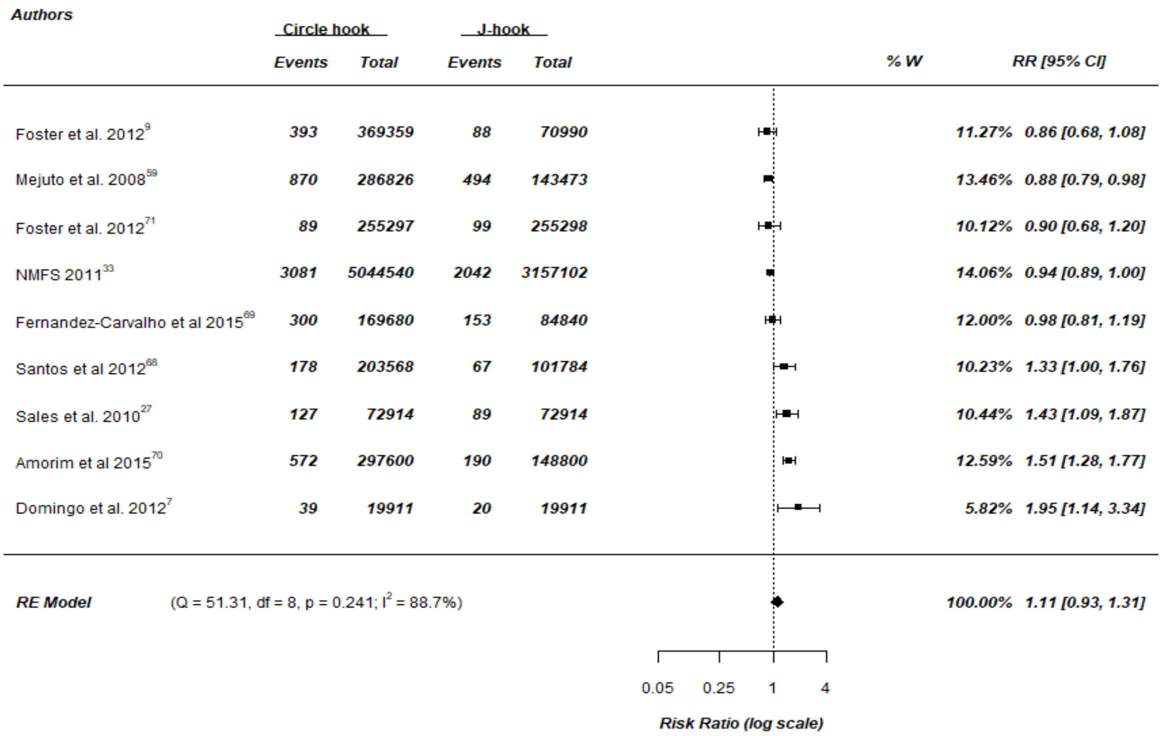

Figure 6. Effect size of hook type on catch rate for shortfin mako, updated from Coelho et al. (2020) to include Foster at al. (2012) as two studies with tuna hooks being removed from analysis. Studies with less than 17 specimens were removed from analysis. A RR > 1 indicates a higher catch was calculated on circle hooks compared to J-hooks. Weighting (%W) and the 95% confidence interval (CI) is shown for each study. These results demonstrate there is no significant difference between catch rates based upon hook type.