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Testing of hook sizes and appendages to reduce yelloweye rockfish bycatch in a Pacific halibut longline fishery

Mark J.M. Lomeli[1,2], W. Waldo Wakefield[2,3], Meagan Abele[2], Claude L. Dykstra[4], Bent Herrmann[5,6,7], Ian J. Stewart[4], and Gregory C. Christie[2]

[1] Pacific States Marine Fisheries Commission, 2032 SE OSU Drive, Newport, OR 97365, USA

[2] Oregon State University, Marine Resource Management Program, 318 Strand Hall, Corvallis, OR 97331, USA

[3] Oregon State University, Cooperative Institute for Marine Ecosystems and Resources Studies, 2030 SE Marine Science Drive, Newport, OR 97365, USA

[4]International Pacific Halibut Commission, 2320 W. Commodore Way, Ste 100, Seattle, WA 98199, USA

[5]SINTEF Ocean, Willemoesvej, DK-9850, Hirtshals, Denmark

[6]University of Tromsø, Breivika, N-9037, Tromsø, Norway

[7]DTU Aqua, Technical University of Denmark, Hirtshals, Denmark

Abstract

In U.S. Pacific halibut (*Hippoglossus stenolepis*) longline fisheries off the West Coast and Alaska, bycatch of yelloweye rockfish (*Sebastes ruberrimus*) is a concern as their stock status along the West Coast is "rebuilding" from being overfished, while the SE Alaskan stock has shown a ~60% decline since at least 1994 and through 2015 where it stabilized. In this study, we evaluated how size 16/0 and 18/0 circle hooks (QiHook brand) affect the catch efficiency of Pacific halibut and yelloweye rockfish. Further, we examined the catch efficiency of these hooks modified with a 3.1 mm stainless-steel wire appendage extending 7.6 cm from their shank at either a 45^{o} or 90^{o} angle. We also wanted to estimate probabilities for modes of capture (hooking locations) for Pacific halibut and yelloweye rockfish for the hooks tested, and determine by using hook timers if there is a temporal component in the catch between Pacific halibut and yelloweye rockfish. Results showed hook size did not significantly affect catch efficiency of Pacific halibut or yelloweye rockfish. However, hooks with a 45^{o} appendage angle caught significantly fewer yelloweye rockfish than hooks without an appendage, irrespective of hook size. Appendage angle did not affect the catch efficiency of Pacific halibut. For both Pacific halibut and yelloweye rockfish, the most frequent mode of capture was the *hook through cheek*, both with and without an appendage. Catches of Pacific halibut and yelloweye rockfish did not differ temporally; however, most individuals were caught within 3 hours of gear deployment. Results from our study suggest that hook appendages could have potential use in reducing catch rates on yelloweye rockfish in Pacific halibut longline fisheries.

1. Introduction

The Pacific halibut (*Hippoglossus stenolepis*) resource in U.S. waters is managed by the International Pacific Halibut Commission (IPHC) in collaboration with regional councils and NOAA Fisheries (Keith et al., 2014). Using longline gear, commercial fishers target Pacific halibut in the north Pacific Ocean and Bering Sea. Across this region, the fishery is divided into eight regulatory areas with each area having a specific annual harvest level of Pacific halibut. Off Alaska and Canada, the fishery operates under an individual quota system, while a derby fishery occurs off Washington, Oregon, and California for the sector's quota.

In U.S. West Coast and Alaska Pacific halibut longline fisheries, yelloweye rockfish (*Sebastes ruberrimus*) bycatch is an issue as their stock status along the West Coast is "rebuilding" from being overfished (NMFS, 2019), while the SE Alaskan stock has shown a ~60% decline since at least 1994 and through 2015 where it stabilized (ADFG, 2020). The retention of yelloweye rockfish is prohibited in some Pacific halibut fisheries and conservation zones have been established off the West Coast to protect yelloweye rockfish stocks (NOAA, 2021). In IPHC Regulatory Area 2A (Washington-Oregon-California), recent (2019-2021) non-treaty directed commercial longline catches of Pacific halibut have ranged from approximately 110-114 MT (IPHC, 2019-2021). Over these years, yelloweye rockfish bycatch in this fishery has been approximately 7.42, 2.2, and 1.1 MT, respectively (Somers et al., 2021; West Coast Groundfish Observer Program [WCGOP] database, 2022). For all commercial fisheries along the West Coast (fixed and mobile fishing gears), the yelloweye rockfish annual catch limit from 2019 to 2021 has ranged from approximately 47-51 MT (NOAA, 2019-2022). The potential impacts of yelloweye rockfish bycatch in IPHC Regulatory Area 2A has raised some management concerns. As the rebuilding plan for yelloweye rockfish predicts the stock will not be rebuilt until 2029 (NMFS, 2018), their bycatch will likely continue to be an issue in the directed Pacific halibut fishery and other fisheries where their bycatch occurs (e.g., trawl).

In longline and hook-and-line fisheries, circle hooks modified with an appendage have shown to affect the catch efficiency of smaller-sized fish, sea turtles, and the mode of capture (e.g., deep hooking) to which these species are exposed (Willis and Millar, 2001; Swimmer et al., 2011; Bergmann et al., 2014). These hook appendages consist of a stiff gauge wire which extends outward from the shank of the hook. This novel technique increases the overall dimension of the hook without altering its specified length, width, bite, or gape. In a pelagic Costa Rican longline fishery, use of modified circle hooks with an appendage significantly reduced the bycatch of sea turtles compared to unmodified circle hooks (Swimmer et al., 2011). Willis and Millar (2001) tested hook appendages in the New Zealand snapper (*Pagrus auratus*) longline fishery and found they significantly reduced both the catch efficiency of smaller-sized snapper and the rate of deep hooking (i.e., throat, stomach) compared to hooks without appendages. In the U.S. West Coast Pacific halibut longline fishery, bycatch of yelloweye rockfish typically consist of fish smaller in size than Pacific halibut (avg. 52 cm vs 94 cm, respectively, [Source: WCGOP database, 2022]). The morphological differences between flatfishes and roundfishes and the size difference between Pacific halibut and yelloweye rockfish, suggest there may be potential to reduce the rate of yelloweye rockfish bycatch in the fishery using hook appendages. Further, as yelloweye rockfish are a prohibited species and all fish caught must be discarded, if hook appendages could reduce deep hooking (as has been observed in other hook appendage studies [Willis and Millar, 2001; Swimmer et al., 2011; Bergmann et al., 2014]) this outcome may reduce incidental mortality.

In the Pacific halibut longline fishery, size 16/0 circle hooks are the conventional hook. Research has evaluated the catch efficiency of size 13/0 – 16/0 circle hooks (Leaman et al., 2012), but has not examined the selectivity of circle hooks larger than 16/0. In the Pacific halibut recreational hook-and-line fishery, however, a much larger hook size and design known as the čibu·d has been tested (Scordino et al., 2017; Petersen et al., 2020; Stewart et al., 2021). The čibu·d is the traditional hook of the Makah Tribe and is approximately 14 cm long by 12.5 cm wide in dimension (See Figure 1 in Petersen et al. [2020]). Research has shown the čibu·d to be highly selective for Pacific halibut. However, when compared to circle hooks the čibu·d exhibits a lower catch rate for Pacific halibut (Sordino et al., 2017; Petersen et al., 2020). While the čibu·d is less effective at catching Pacific halibut than circle hooks, its ability to be highly selective for Pacific halibut suggest that larger-sized circle hooks could potentially be effective at reducing the catch rate of yelloweye rockfish while maintaining Pacific halibut catches. Thus, research examining the catch efficiency of larger-sized hooks would be beneficial to fishers, fishery managers, and gear development.

The objectives of this study were: (i) evaluate how hook appendages and hook size affects the catch efficiency of Pacific halibut and yelloweye rockfish, (ii) estimate the capture mode probabilities for Pacific halibut and yelloweye rockfish for the hooks tested, and (iii) determine if there is a temporal component in the timing of the catch between Pacific halibut and yelloweye rockfish.

2. Material and methods

2.1. Fishing gear and sampling

Size 16/0 and 18/0 circle hooks (QiHook, stainless-steel 400 series, model # Q-16 and Q-18, respectively) were tested. To evaluate if hook size has an effect on Pacific halibut and/or yelloweye rockfish catches both in the presence and absence of an appendage (herein referred to as “app.”), we incorporated the 18/0 hook size into our study design. The appendages consisted of a stiff stainless-steel (300 series) wire 3.1 mm in diameter welded to the hook shank near the eye that extend outward 7.6 cm in length at one of two angles (relative to the plane of native curve and point of the hook): 45º or 90º. Thus, the hooks evaluated were: (i) 16/0 control (H1), (ii) 16/0 45º app. (H2), (iii) 16/0 90º app. (H3), (iv) 18/0 no app. (H4), (v) 18/0 45º app. (H5), and (vi) 18/0 90º app. (H6) (Fig. 1).

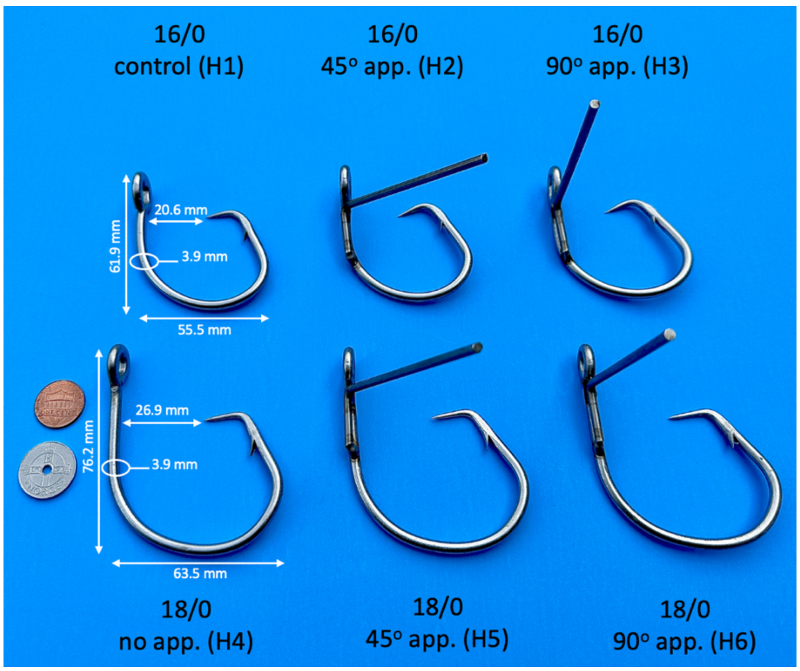

Figure 1. Image of the control hook (H1) and the five experimental hooks (H2-H6) examined. app. = appendage. Scale: Diameter of the Norwegian 1 krone displayed is 21 mm, diameter of the United States 1 cent displayed is 19 mm.

Gangions (short lengths of fishing gear, including a snap, line, and hook, connecting to the groundline) were built using hard lay gangen twine (Powers #72 braided nylon cover with a Dyneema® polyester core). From the tip of the snap to the bottom of the hook, the gangions ranged from 86.4-88.9 cm in total length. Color-coded markings were affixed to the snap on each gangion to uniquely identify each of the six hook types during setting and hauling the gear. Hooks were manually baited with 0.11 to 0.15 kg Chinook salmon (*Oncorhynchus tshawytshca*) and spaced 5.5 m apart along each groundline (9.5 mm diameter line). A single groundline of 549 m in length and outfitted with 100 hooks is referred to as a skate. As the hooks were baited the skates were coiled into tubs and subsequently deployed over a chute on the vessel stern. For each fishing day, two sets of gear (each set of gear consisting of three skates) were fished within a similar area to each other (Fig. 2). Per each skate, we planned to fish 100 hooks in a random pattern that consisted of groupings of four hooks per each hook type along the skate. Fishing occurred during daylight hours, and tori lines were used during setting to minimize the risk of seabird bycatch. Except for the experimental hooks (H2-H6), the fishing gear and configuration was intended to closely mimic common practice in the existing commercial fisheries for Pacific halibut.

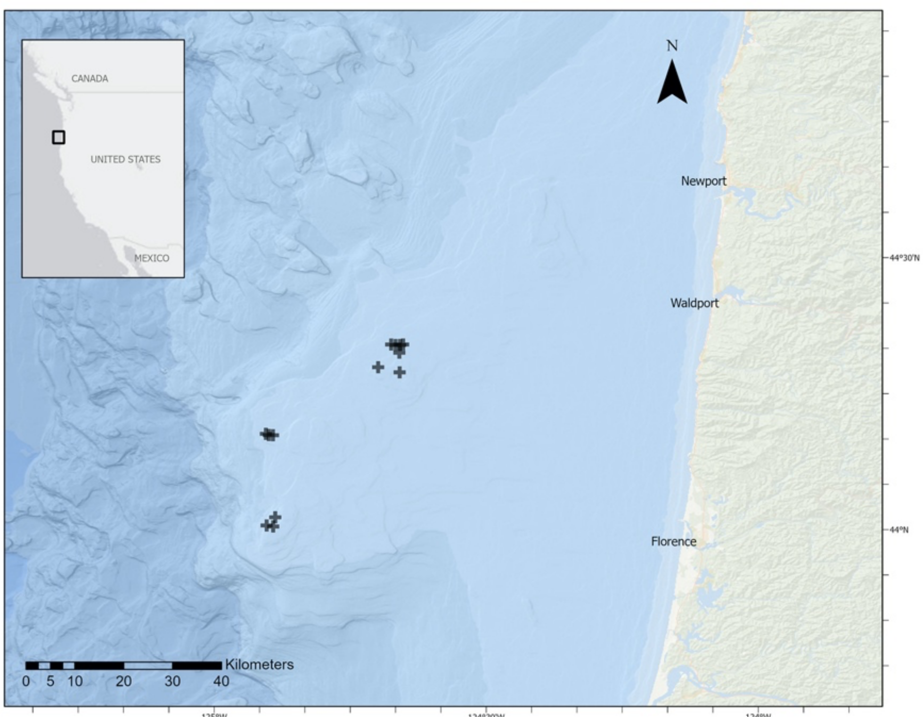

Figure 2. Map of the area off the Oregon coast where sea trials were conducted. Symbols represent set locations.

Length, weight, and capture mode were collected on all Pacific halibut and yelloweye rockfish caught per hook type. For each haul, yelloweye rockfish were placed into recovery tanks (after biological data was collected) to treat barotrauma, and then released to recompression depths at the end of the haul using SeaQualizer descending devices. For all other species caught, only species was recorded. To evaluate if there was a temporal component in the catch between Pacific halibut and yelloweye rockfish, Lindgren-Pitman hook timers (Fig. 3) set at 1kg of release tension were placed on a subset of the gangions fished. Approximately 25% of each hook typed fished each day included a hook timer. On some sets, a GoPro camera (placed in an aluminum housing and outfitted with two LED dive lights) was placed on the groundline in efforts to observe the behavior of fish as they interacted with the control (H1) and experimental hooks (H2-H6). This study occurred in IPHC Regulatory Area 2A off the central Oregon coast (Fig. 2) during August 2022 onboard the R/V *Pacific Surveyor* (17 m LOA, 380 hp). Our study site was selected as it is an area where Pacific halibut and yelloweye rockfish often co-occur.

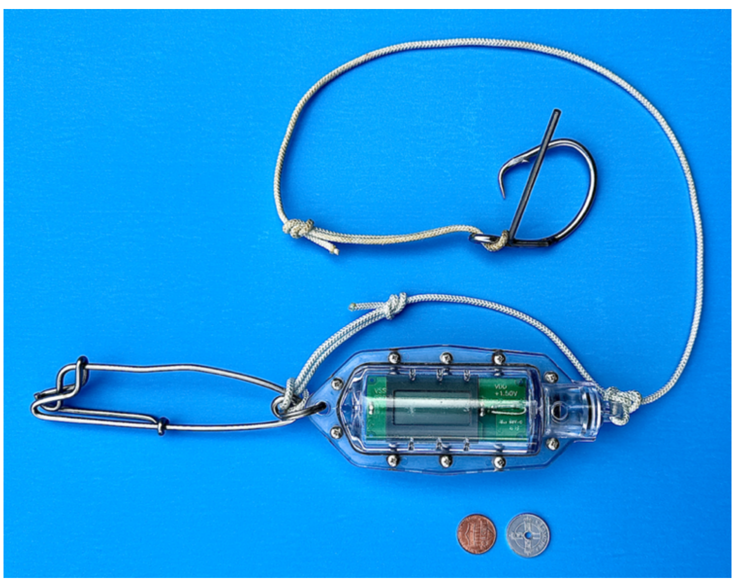

Figure 3. Hook timer rigged to a gangion with a 16/0 45^{o} app. hook (H2). Scale: Diameter of the Norwegian 1 krone displayed is 21 mm, diameter of the United States 1 cent displayed is 19 mm.

2.2. Estimating the catch efficiency between hook types

We compared the catch efficiency between hook types for Pacific halibut and yelloweye rockfish by conducting catch comparison and catch ratio analyses. Analysis was carried out for each species and pair of hook types compared separately following the description below using the statistical package SELNET (Herrmann et al., 2012), software version date 21 September 2022. Assessing the difference in relative length-dependent catch efficiency between a specific pair of hook types was done using the method described in Cerbule et al. (2022). This method models the length-dependent catch comparison rate (CC_l) summed over all longline deployments during the entire data collection period. CC_l is expressed by the following equation:

$$CC_l = \frac{\sum_{j=1}^{m}\{nt_{lj}\}}{\sum_{j=1}^{m}\{nt_{lj}+nc_{lj}\}} \quad (1)$$

where nt_{lj} and nc_{lj} are the numbers of the species analyzed caught in each length class (1 cm classes) l in deployment j of a longline with the hook type considered as respectively test hook (t) and control hook (c) in the specific analysis. m is the number of longline deployments carried out. The functional form for the catch comparison rate $CC(l,\boldsymbol{v})$ was obtained using maximum likelihood estimation by minimizing the following expression:

$$-\sum_l\{\sum_{j=1}^{m}\{nt_{lj} \times ln(CC(l,\boldsymbol{v})) + nc_{lj} \times ln(1.0 - CC(l,\boldsymbol{v}))\}\} \quad (2)$$

where $\boldsymbol{v}$ represents the parameters describing the catch comparison curve defined by $CC(l,\boldsymbol{v})$. The outer summation in Expression 2 is the summation over length classes l. If the two hook types compared have the same catch efficiency, the value for the summed catch comparison rate is 0.5, which acts as a baseline. The experimental CC_l (Eq. 1) was modeled by the function $CC(l,\boldsymbol{v})$ using the following equation (Krag et al., 2014):

$$CC(l,\boldsymbol{v}) = \frac{exp(f(l,v_0,\ldots,v_k))}{1+exp(f(l,v_0,\ldots,v_k))} \quad (3)$$

where f is a polynomial of order k with coefficients v_0 to v_k, were order k was set to 4. The values of the parameters v describing $CC(l,\mathbf{v})$ were estimated by minimizing Expression (2) and multi-model inference was used to obtain a combined model (Burnham & Anderson, 2002; Herrmann et al., 2017). The ability of the combined model to describe the experimental data was evaluated based on the p-value. This was calculated based on the model deviance and the degrees of freedom. For the combined model to adequately describe the experimental data the p-value should not be < 0.05, except for cases experiencing overdispersion in the data (Wileman et al., 1996; Herrmann et al., 2017).

Based on the estimated catch comparison function $CC(l,\mathbf{v})$, we obtained the relative catch ratio $CR(l,\mathbf{v})$ between the two hook types using the following equation (Cerbule et al., 2022):

$$CR(l,\boldsymbol{v}) = \frac{CC(l,\boldsymbol{v})}{(1-CC(l,\boldsymbol{v}))} \quad (4).$$

If the two hook types have an identical catch efficiency, then this value will be 1.0. If $CR(l,\mathbf{v})$ = 1.3 the test hook is catching 30 % more fish with length l than the control hook. On the other hand, if $CR(l,\mathbf{v})$= 0.6 the test hook is catching only 60 % of the fish with length l compared to the control hook.

The confidence limits (CLs) for $CC(l,\mathbf{v})$ and $CR(l,\mathbf{v})$ were estimated using the double bootstrapping method described by Cerbule et al. (2022). We conducted 1,000 bootstrap repetions in the analysis. To identify the sizes of the species analyzed with significant differences in catch efficiency between hook types, we checked for length classes in which the 95 % CLs for the catch ratio curve did not contain 1.0.

The length-integrated average catch ratio ($CR_{average}$) value was estimated directly from the experimental catch data using the following equation:

$$CR_{average} = \frac{\sum_l \sum_{j=1}^{m} \{nt_{lj}\}}{\sum_l \sum_{j=1}^{m} \{nc_{lj}\}} \quad (5)$$

where the outer summation covers the length classes in the catch during the experimental fishing period. In contrast to the length-dependent evaluation of the relative capture efficiency $CR(l, \boldsymbol{v})$, $CR_{average}$ is specific for the population structure encountered during the experimental trials. Therefore, this information cannot be extrapolated to other scenarios in which the size structure of the fish species may be different.

Based on Eq. 5, we estimated the percent change in average catch efficiency of changing between hook type using Eq. 6:

$$\Delta CR_{average} = 100 \times \left(CR_{average} - 1.0\right) \quad (6).$$

Eq. 6 was used to provide an overall value for the effect of changing from one hook type (i.e., hook *A*) to another hook type (i.e., hook *B*) on the catch efficiency. If hook *A* has an increase in catch efficiency, then the $\Delta CR_{average}$ value will be above zero. On the contrary, if hook *B* has a decrease in catch efficiency, then the $\Delta CR_{average}$ value will be below zero. A value of zero depicts equal catch efficiency between the two hooks.

2.3. Estimating the mode of capture probability

To determine the length-dependent probability to capture fish with each of the 15 capture modes considered, we followed the method outlined in Savina et al. (2022). Specifically, we used numbers of observed fish that were captured by each of the capture modes and the corresponding length measurements with each of the hook types and species caught separately. The analysis was carried out for each mode of capture independently. The expected probability for the capture mode q for fish length l can be estimated using the following equation (Savina et al., 2022):

$$CPq_l = \frac{\sum_{j=1}^{h} n_{qlj}}{\sum_{j=1}^{h} \sum_{i=1}^{Q} n_{ilj}} \tag{7}$$

where n_{qlj} is the number n of fish caught per length class l with capture mode q for longline deployment j. Q is the number of capture modes considered. h is the total number of longline deployments. The functional description of the capture mode probability $CPq(l, \boldsymbol{v})$ was obtained using maximum likelihood estimation by minimizing Expression 8 (Savina et al., 2022):

$$-\sum_{j=1}^{h} \sum_{l} \left\{ n_{qlj} \times ln\left[CPq(l, \boldsymbol{v})\right] + \left[-n_{qlj} + \sum_{i=1}^{Q} n_{ilj}\right] \times ln[1.0 - CPq\ (l, \boldsymbol{v})] \right\} \tag{8}$$

In Expression 8, $\boldsymbol{v}$ represents the parameters describing the capture mode probability curve defined by $CPq(l, \boldsymbol{v})$. Eq. 7 and Expression 8 are similar in form to what is often used for modeling and estimating the length-dependent catch comparison rate between two fishing gears (Krag et al., 2014). We adapted the same approach for modeling $CPq(l, \boldsymbol{v})$ as is often applied for catch comparison studies based on binominal count data (Herrmann et al., 2017):

$$CPq(l, \boldsymbol{v}) = \frac{exp[f(l, v_0, \ldots, v_k)]}{1 + exp[f(l, v_0, \ldots, v_k)]} \tag{9}$$

In Eq. 9, f is a polynomial of order k with coefficients v_0 to v_k, such that $\boldsymbol{v}=(v_0, \ldots v_k)$. The values of the parameter v describing $CPq(l, \boldsymbol{v})$ are estimated by minimizing Expression 8. For the catch comparison analysis described above, we considered f of up to an order of 4 with parameters $v0$, $v1$, $v2$, $v3$ and $v4$. Leaving out one or more of the parameters $v0 \ldots v4$ at a time resulted in 31 additional candidate models that were considered as potential models for the catch comparison $CC(l, \boldsymbol{v})$. Among these models, the catch comparison rate was estimated using multi-model inference to obtain a combined model (Burnham and Anderson, 2002; Herrmann et al., 2017). The CLs for $CPq(l, \boldsymbol{v})$ were estimated using the double bootstrapping method applied for the catch comparison analysis described above.

Length-integrated average value for the capture mode probability ($CPq_{average}$) was directly estimated from the experimental data using the following equation (Savina et al., 2022):

$$CPq_{average} = \frac{\sum_l \sum_{j=1}^{h} n_{qlj}}{\sum_l \sum_{j=1}^{h} \sum_{i=1}^{Q} n_{qlj}} \quad (10)$$

where the outer summations include the size classes in the catch during the experimental fishing period. In contrast to the length-dependent evaluation of the capture mode probability $CPq(l, \boldsymbol{v})$, $CPq_{average}$ is specific for the population structure encountered during the experimental trials. Therefore, this result cannot be extrapolated to other scenarios in which the size structure of the fish species may be different.

2.4 Inference of the difference in the length-dependent probability for capture modes between hook types

To investigate the effect of changing from hook type *Y* to hook type *Z* on the capture mode probability curve $CP_{q,hook}(l, \boldsymbol{v}_{hook})$ for mode q the length-dependent change $\Delta CPq(l)$ in the values was estimated using the following equation:

$$\Delta CPq(l) = CP_{q,Z}(l) - CP_{q,Y}(l) \quad (11).$$

In Eq. 11, $CP_{q,Y}(l)$ represents the probability for hook type *Y* and $CP_{q,Z}(l)$ represents the probability for hook type *Z*. The bootstrap populations (both containing 1,000 repetitions with replacement) of results for both $CP_{q,Y}(l)$ and $CP_{q,Z}(l)$ were used to estimate 95% percentile CLs for $\Delta CPq(l)$. Because these were obtained independently, a new bootstrap population of results was created for $\Delta CPq(l)$ by:

$$\Delta CP_q(l)_i = CP_{q,Z}(l)_i - CP_{q,Y}(l)_i \quad i \in [1 \ldots 1000] \quad (12).$$

In Eq. 12, i denotes the bootstrap repetition index. As the bootstrap resampling was random and independent for the two groups of results, it is valid to generate the bootstrap population of results for the difference based on using the two independently generated bootstrap files (Herrmann et al., 2018). Based on the bootstrap population, Efron 95% percentile CLs were obtained for $\Delta CPq(l)$ as described above.

The methodology applied in this section for difference in capture mode probability is similar to the one applied by Larsen et al. (2018) for inference for difference in size selectivity.

3. Results

3.1. Fishing effort

Overall, 14 sets were completed with a total of 4,189 hooks fished. By hook type, the number of hooks fished was 726, 706, 660, 738, 685, and 674 for the 16/0 control (H1), 16/0 45^o app. (H2), 16/0 90^o app. (H3), 18/0 no app. (H4), 18/0 45^o app. (H5), and 18/0 90^o app. (H6), respectively. The difference in the number of hooks fished per hook type was the result of hook loss due to either gangion/hook snagging causing bending or breaking, or manually being cut from the gangion at the vessel rail to release bycatch species too large to haul onboard such as bluntnose sixgill shark (*Hexanchus griseus*) and big skate (*Raja binoculata*). Due to budget constraints, we were limited to 100 appendage hooks manufactured for each of the four appendage hooks tested. This quantity provided four spare hooks for each appendage hook type. Quantities of 250 were available for the control 16/0 and 18/0 no app. hooks, providing 150 spares for each of these hooks. Hooks returning bent, broken, or missing did not differ between hooks with and without appendages. Further, the appendages did not interfere with the hook baiting process or the deployment of skates. Soak durations ranged from 5 to 6 hours before the gear was hauled. The hauling process of each set took approximately 1 hour to complete, resulting in some hooks near the end of the third skate of the second gear set being fished upwards to 7 hours. The mean fishing depth was 197 m and ranged from 150 to 247 m.

Pacific halibut (n=145) and yelloweye rockfish (n=188) were the only species caught in sufficient numbers for use in our statistical analyses.

3.2. Fit statistics

The combined *CC(l,v)* models described the observed data well for Pacific halibut and yelloweye rockfish for most hook comparisons as shown by the fit statistics p-value >0.05 and the deviances within two times of the degrees of freedom values. In the instances where the fit statistics p-value was <0.05, inspection of the observed data and mean modeled curve show the poor fit statistics were due to data overdispersion rather than the model's inability to describe the data.

3.3. Catch efficiency between hook types

The length-dependent catch efficiency results showed some instances where a significant catch efficiency effect occurred in yelloweye rockfish for some length classes between the 16/0 control (H1) and 16/0 45° app. (H2), the 16/0 control (H1) and the 18/0 90° app. (H4), and the 16/0 90° app. (H3) and the 18/0 45° app. (H5) (Fig. 4). For those length classes where a significant effect was noted, the results show the 16/0 control (H1) catching more yelloweye rockfish than the 16/0 45° app. (H2) and the 18/0 90° app. (H6). In the 16/0 90° app. (H3) vs the 18/0 45° app (H5) catch comparison, the results show the 16/0 catching more than the 18/0. However, these values were barely significant as their 95% lower CL catch ratio values are near the baseline value of 1.0 (Fig. 4). No significant length-dependent catch efficiency was noted for yelloweye rockfish between the other hooks. For Pacific halibut 60-150 cm in length, no significant length-dependent catch efficiencies were noted between the hooks tested. On some sets a video camera system was used in an effort to capture the behavior of fishes as they interacted with the hooks, but unfortunately, we were unable to gather any such footage.

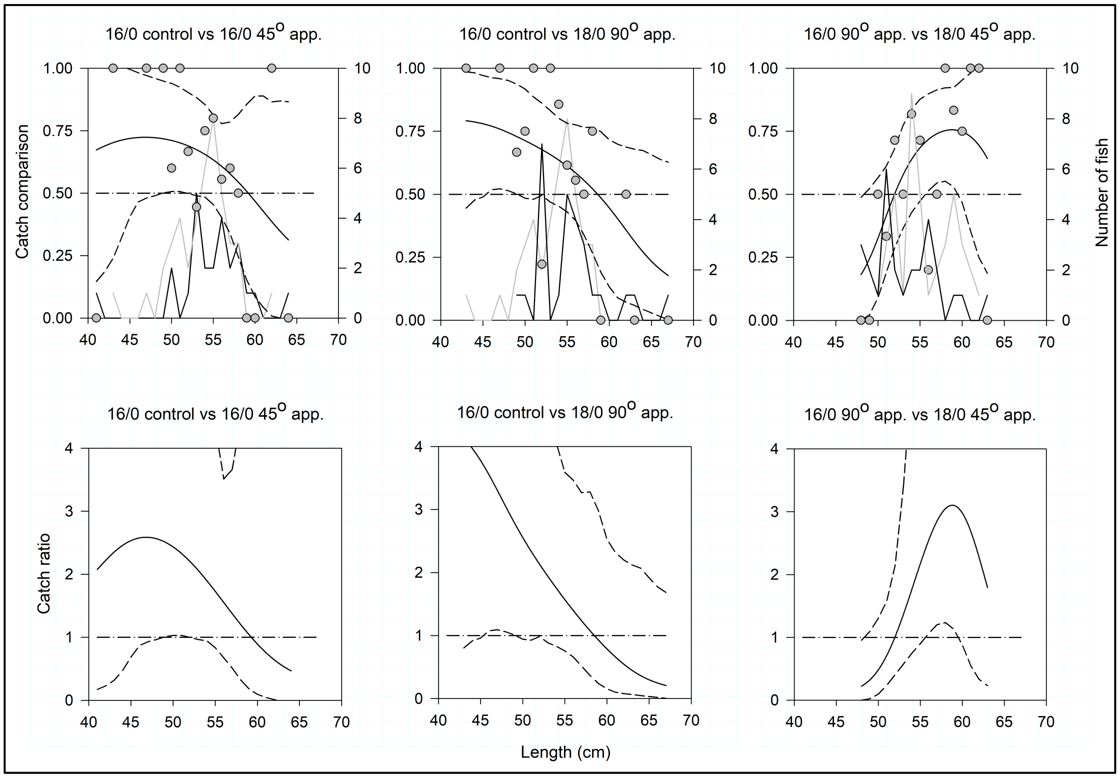

Figure 4. Mean catch comparison (upper) and catch ratio (lower) plots for yelloweye rockfish between the 16/0 control (H1) and 16/0 45° app. (H2), the 16/0 control (H1) and 18/0 90° app. (H6), and the 16/0 90° app. (H3) and 18/0 45° app. (H5). Shaded circles are the observed data; smooth fitted solid black lines are the modeled value; dashed lines are the 95% CLs; the vertical grey lines depict the number of fish caught by the hook type indicated first in the plot title, while the vertical black lines depict the number of fish caught by the subsequent hook type indicated in the plot title (e.g., in the upper left plot the grey line represents the 16/0 control hook, while the black line presents the 16/0 45° app. hook); the dash-dot-dash lines at 0.5 (upper) and 1.0 (lower) represent the baseline value at which both types of hooks have an equal catch efficiency.

The length-integrated average catch efficiency results showed the 16/0 control (H1) tended to catch more yelloweye rockfish than the five experimental hooks. However, this result was not significant as the 95% CLs for these hook comparisons extend above and below the baseline value of zero (Fig. 5). While not significant, the 16/0 45° app. (H2) tended to catch fewer yelloweye rockfish than the other experimental hooks, whereas the 16/0 90° app. (H3) tended to catch more yelloweye rockfish than the three 18/0 experimental hooks (Fig. 5). For Pacific halibut, no clear catch trends were observed between the hooks tested.

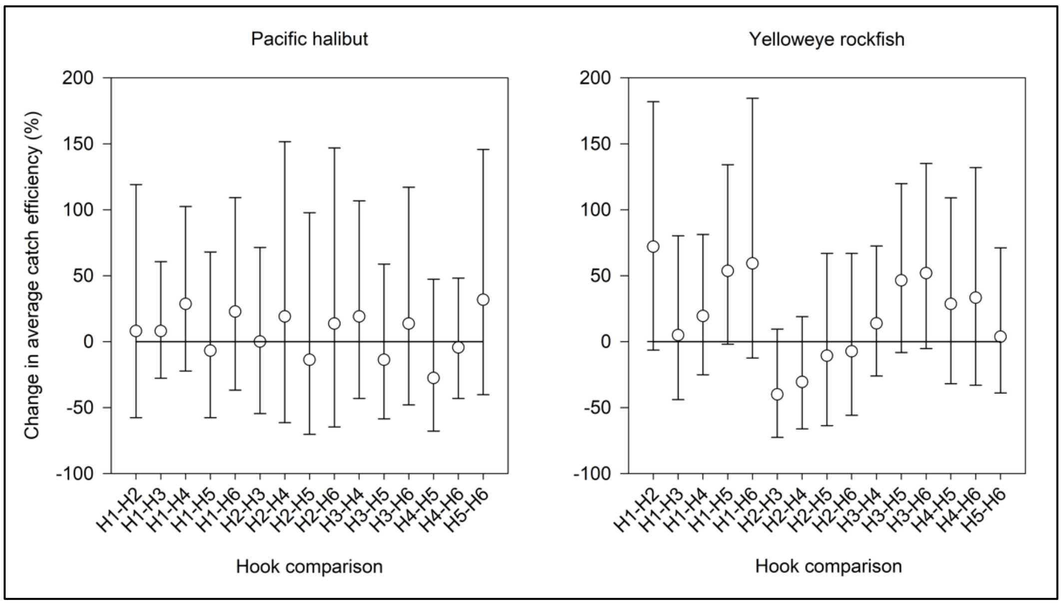

Figure 5. Change in average catch efficiency between hook comparisons. Open circles depict the mean value. Vertical lines are 95% CLs. H1 =16/0 control; H2 = 16/0 45° app.; H3 = 16/0 90° app.; H4 = 18/0 no app.; H5 = 18/0 45° app.; H6 = 18/0 90° app. app. = appendage.

Length-integrated average catch efficiency of Pacific halibut and/or yelloweye rockfish, irrespective of hook size, showed hooks without an appendage caught 52.9% (95% CLs: 9.8-107.2) more yelloweye rockfish than hooks with a 45° appendage (Fig. 6). This change in average catch efficiency was statistically significant as indicated by the 95% CLs not extending across the baseline value of zero. Hooks with a 45° appendage did not influence catch efficiency of Pacific halibut (Fig. 6). Hooks with a 90° appendage did not influence catch efficiency of either Pacific halibut or yelloweye rockfish when compared to hooks with a 45° appendage or hooks without an appendage present.

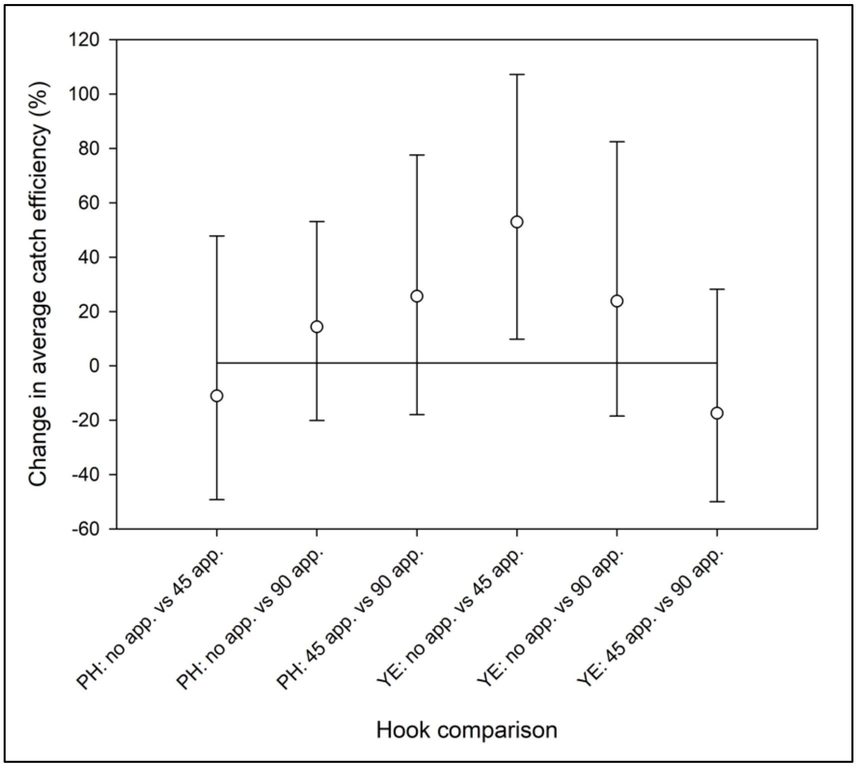

Figure 6. Change in average catch efficiency (%) between hooks with no appendage, 45° appendage, and 90° appendage. Open circles depict the mean value. Vertical lines are 95% CLs. PH = Pacific halibut; YE = yelloweye rockfish; app. = appendage.

3.4. Capture mode probability

For each hook type, the most dominant capture mode for Pacific halibut and yelloweye rockfish was *hook through cheek* (Fig. 7) followed by *hooked inside cheek* but not extending through (Tables 1 and 2). Combined, these two capture modes accounted for the majority of all Pacific halibut and yelloweye rockfish capture modes. Deep hooking was observed in three yelloweye rockfish (2 hooked in the throat, 1 hooked on a gill raker) and they occurred in the 18/0 no app. (H4). No Pacific halibut were deep hooked. The length-integrated average value for the probability of being captured by a specific hook and specific capture mode for Pacific halibut and yelloweye rockfish are shown in Tables 3 and 4, respectively. Length-dependent probability of capture for Pacific halibut and yelloweye rockfish by a certain hook type by the capture mode *hook through cheek* are presented in Figures 8 and 9, respectively.

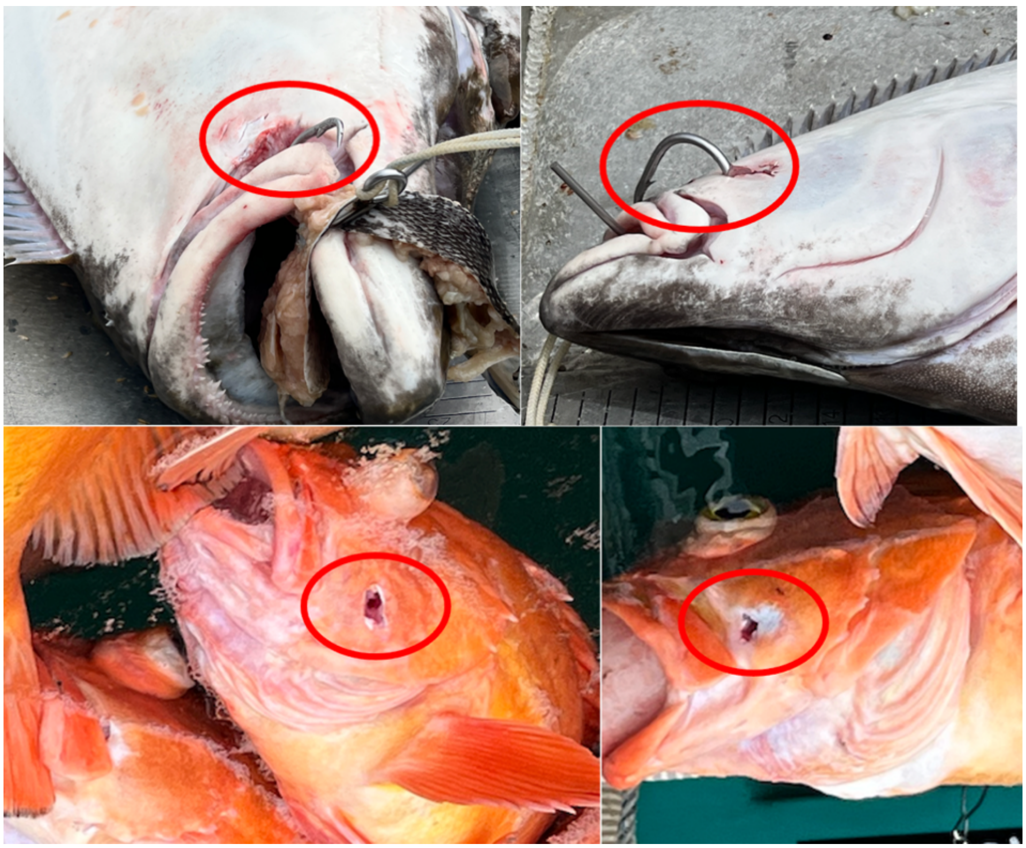

Figure 7. Images of Pacific halibut (top) and yelloweye rockfish (bottom) showing the capture mode *hook through cheek* (red circles).

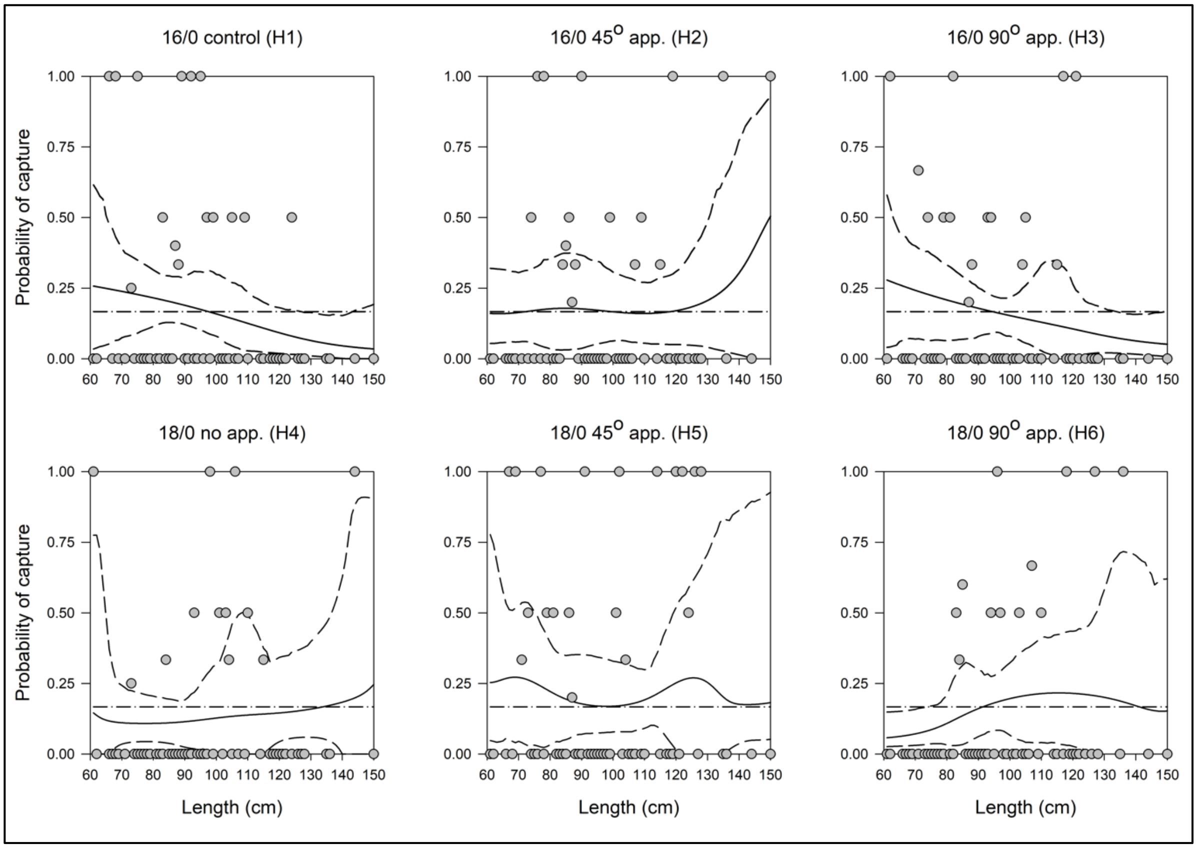

Figure 8. Length-dependent probability of capture for Pacific halibut by a certain hook type by the capture mode *hook through cheek*. Shaded circles are the observed data; fitted solid lines are the modeled value; dashed lines are 95% CLs; the dash-dot-dash line at 0.167 represents the baseline value for no difference in capture probability between the hooks.

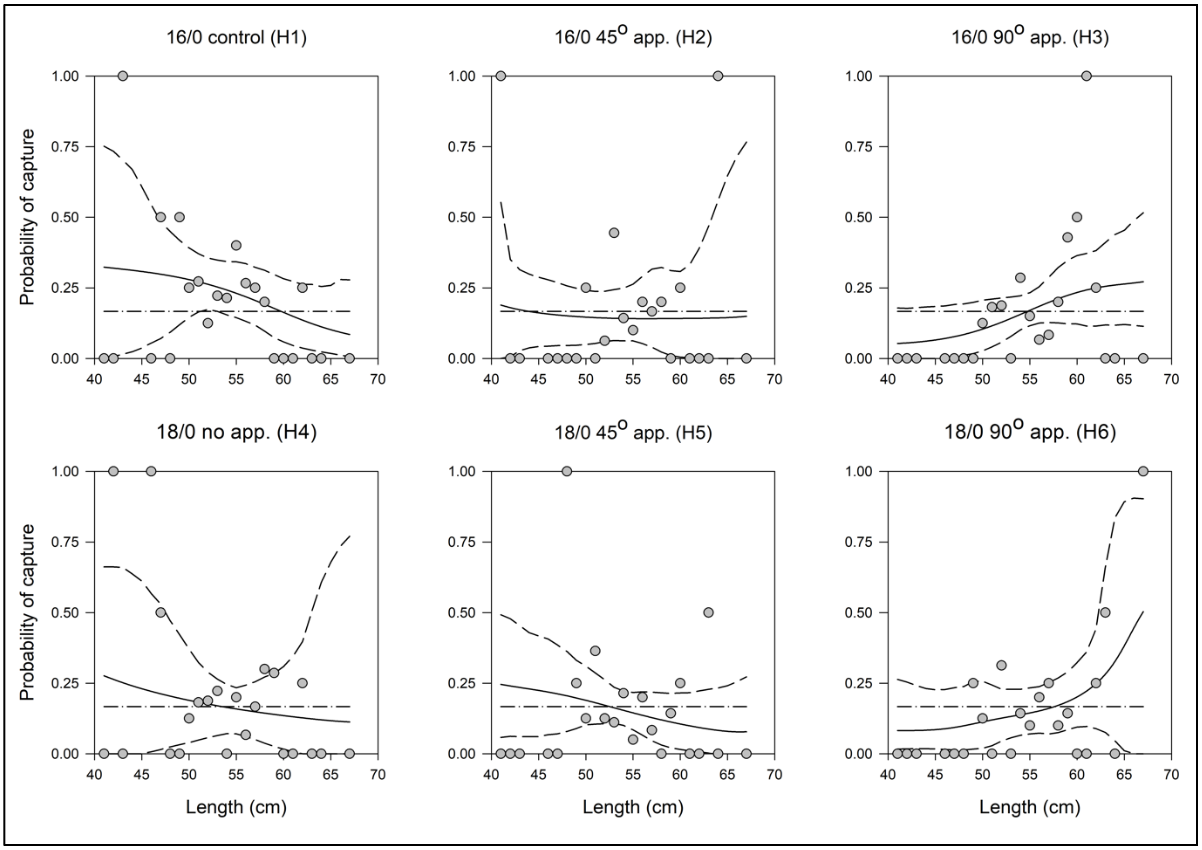

Figure 9. Length-dependent probability of capture for yelloweye rockfish by a certain hook type by the capture mode *hook through cheek*. Shaded circles are the observed data; fitted solid lines are the modeled value; dashed lines are 95% CLs; the dash-dot-dash line at 0.167 represents the baseline value for no difference in capture probability between the hooks.

Table 1. Length-integrated average value (%) for the capture mode for Pacific halibut by hook type. Values in parentheses represent 95% CLs. Other* = torn face (n=3), jig head (n=2), hooked on tongue (n=2), hooked under jaw (n=4). app. = appendage.

		Capture mode					
Hook type	# of fish	Hook through cheek	Hook inside cheek	Jaw only	Torn jaw	Hook penetrating eye	Other*
16/0 control (H1)	27	61.5 (43.7-80.9)	23.1 (5.4-41.8)	3.8 (0.1-10.8)	7.6 (0.3-15.1)	-	3.8 (0.0-13.4)
16/0 45º app. (H2)	25	70.8 (57.8-86.7)	12.5 (0.0-29.5)	-	4.2 (0.3-11.1)	4.1 (0.3-11.8)	8.3 (0.3-17.0)
16/0 90º app. (H3)	23	68.2 (37.1-92.4)	13.6 (0.0-32.7)	4.8 (0.0-16.5)	-	4.8 (0.0-17.1)	9.5 (0.0-23.5)
18/0 no app. (H4)	21	61.9 (38.0-84.9)	4.7 (0.2-13.2)	9.5 (0.0-29.0)	4.8 (0.3-13.3)	4.8 (0.0-17.8)	14.3 (0.9-34.2)
18/0 45º app. (H5)	29	76.9 (58.8-93.7)	3.8 (0.0-15.4)	3.9 (0.0-14.1)	-	11.5 (0.5-28.1)	3.8 (0.0-14.6)
18/0 90º app. (H6)	20	72.2 (52.3-92.2)	5.6 (0.0-15.8)	5.0 (0.0-19.9)	-	5.0 (0.0-17.5)	10.0 (0.2-21.0)

Table 2. Length-integrated average value (%) for the capture mode for yelloweye rockfish by hook type. Values in parentheses represent 95% CLs. Other* = hooked inside throat (n=2), hooked on gill raker (n=1). app. = appendage.

		Capture mode					
Hook type	# of fish	Hook through cheek	Hook inside cheek	Jaw only	Torn jaw	Hook penetrating eye	Other*
16/0 control (H1)	42	85.0 (69.0-95.5)	15.0 (3.6-28.7)	-	-	-	-
16/0 45º app. (H2)	25	87.5 (64.3-100)	12.5 (0.0-33.3)	-	-	-	-
16/0 90º app. (H3)	35	68.0 (53.1-82.3)	21.9 (8.3-33.6)	-	3.1 (0.0-11.8)	-	-
18/0 no app. (H4)	36	73.1 (53.3-87.6)	9.4 (0.0-28.6)	3.1 (0.4-7.7)	3.1 (0.4-7.9)	-	9.4 (0.0-23.2)
18/0 45º app. (H5)	26	90.9 (79.8-99.8)	4.0 (0.0-12.4)	-	-	4.0 (0.0-16.4)	4.0 (0.2-12.8)
18/0 90º app. (H6)	24	95.7 (83.9-99.7)	4.3 (0.5-14.9)	-	-	-	-

Table 3. Length-integrated average value (%) for the probability of being captured by a specific hook and specific capture mode for Pacific halibut. Values in parentheses represent 95% CLs. Other* = torn face (n=3), jig head (n=2), hooked on tongue (n=2), hooked under jaw (n=4). app. = appendage.

	Capture mode					
Hook type	Hook through cheek	Hook inside cheek	Jaw only	Torn jaw	Hook penetrating eye	Other*
16/0 control (H1)	16.7 (12.1-20.6)	40.0 (21.3-65.7)	16.7 (2.9-32.9)	50.0 (0.0-99.9)	-	9.1 (0.9-22.4)
16/0 45º app. (H2)	17.7 (8.1-29.0)	20.0 (7.4-43.5)	-	25.0 (0.0-73.4)	14.2 (0.0-50.0)	18.2 (0.0-43.8)
16/0 90º app. (H3)	16.7 (10.2-22.2)	20.0 (7.7-43.8)	16.7 (2.5-32.5)	-	14.3 (0.0-49.0)	18.2 (0.0-53.9)
18/0 no app. (H4)	12.5 (5.9-18.9)	6.7 (1.2-13.7)	33.3 (0.0-94.2)	25.0 (0.8-75.8)	14.3 (0.3-50.3)	27.3 (2.2-52.2)
18/0 45º app. (H5)	20.8 (12.3-30.4)	6.7 (0.0-20.0)	16.7 (3.2-33.2)	-	42.9 (2.8-85.4)	9.1 (0.0-32.6)
18/0 90º app. (H6)	15.6 (9.4-21.8)	6.7 (0.9-13.4)	16.7 (0.0-72.4)	-	14.3 (0.0-49.6)	18.2 (0.0-43.5)

Table 4. Length-integrated average value (%) for the probability of being captured by a specific hook and specific capture mode for yelloweye rockfish. Values in parentheses represent 95% CLs. Other* = hooked inside throat (n=2), hooked on gill raker (n=1). app. = appendage.

	Capture mode					
Hook type	Hook through cheek	Hook inside cheek	Jaw only	Torn jaw	Hook penetrating eye	Other*
16/0 control (H1)	23.1 (17.0-29.5)	28.5 (10.8-49.7)	-	-	-	-
16/0 45º app. (H2)	14.3 (8.0-21.0)	14.3 (0.6-32.4)	-	-	-	-
16/0 90º app. (H3)	16.3 (11.5-21.8)	38.1 (19.6-54.7)	-	50.0 (0.8-100)	-	-
18/0 no app. (H4)	16.3 (9.3-22.8)	9.5 (0.0-27.2)	100 (100-100)	50.0 (0.0-100)	-	66.7 (0.6-100)
18/0 45º app. (H5)	14.9 (10.4-20.4)	4.8 (0.3-17.7)	-	-	100 (100-100)	33.3 (0.0-99.5)
18/0 90º app. (H6)	14.9 (9.7-20.4)	4.7 (0.1-13.8)	-	-	-	-

3.5. Time of capture during the soak duration

Hook timers were deployed 907 times across the six hook types with 21 Pacific halibut and 32 yelloweye rockfish being caught on those hooks. For both Pacific halibut and yelloweye rockfish and each hook type, the majority of captures occurred within 3 hours of the gear being deployed (Fig. 10). Hook type did not appear to affect the temporal catchability of Pacific halibut or yelloweye rockfish. Across all hooks, the mean time of capture during the soak process for Pacific halibut and yelloweye rockfish was 3:56 hr:min (95% CLs: 3:15-4:37) and 4:01 hr:min (95% CLs: 3:33-4:31), respectively.

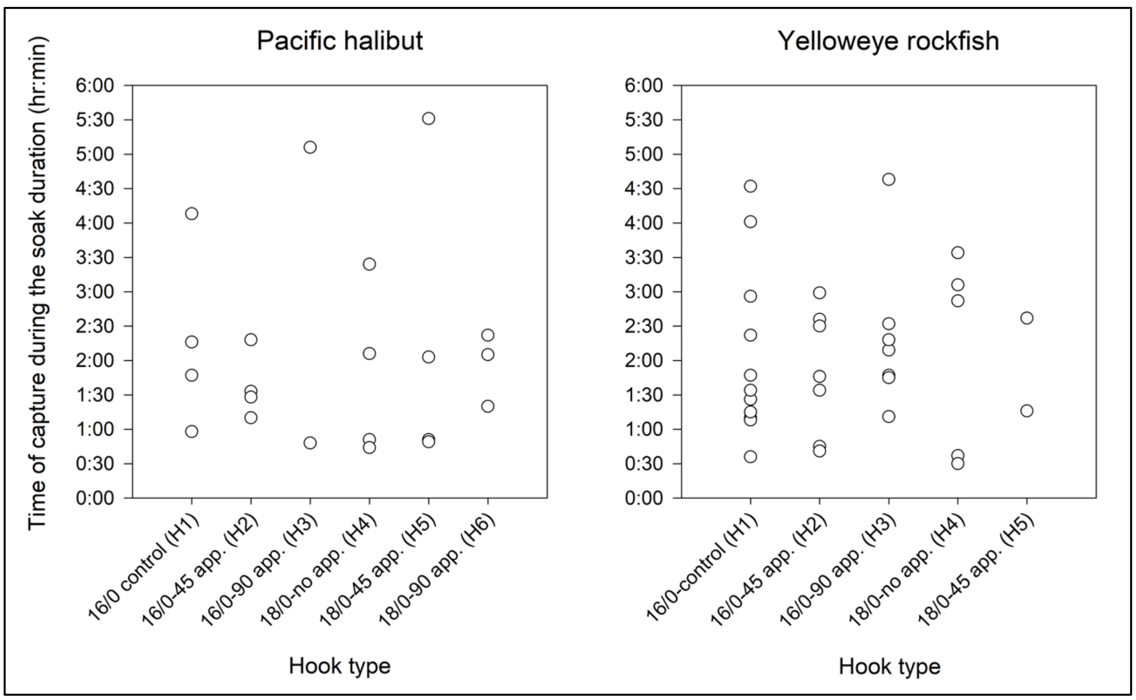

Figure 10. Time of capture during the soak duration per hook type for Pacific halibut and yelloweye rockfish caught on hook timers.

4. Discussion

We evaluated how size 16/0 and 18/0 circle hooks with and without hook appendages effected the catch efficiency of Pacific halibut and yelloweye rockfish. Hook size and appendage angle did not have a significant effect on the catch efficiency of Pacific halibut. For yelloweye rockfish, the 16/0 control (H1) tended to catch more individuals than the five experimental hooks (H2-H6) tested. However, this result was only a trend and was not significant. When examining the effect of appendage angle, irrespective of hook size, on the catch efficiency of yelloweye rockfish, hooks with a 45° app. caught significantly fewer individuals compared to hooks without an appendage. While the mechanism(s) causing this result are not exactly clear, it is plausible that given the differences in mouth orientation and morphology that occur between yelloweye rockfish and Pacific halibut, that the near proximity of the 45° app. wire to the hooks' point reduces the probability of the point contacting and engaging with the mouth compared to non-appendage hooks. Pertaining to 45° app. hooks for Pacific halibut, several fish were caught with the entire appendage pressed firmly down across their outer jaw and front cheek area while the capture mode was either *hook through cheek* or *hook inside cheek*. This appendage observation was not noted in yelloweye rockfish.

Prior to our research, the selectivity of an 18/0 circle hook size had not been evaluated in Pacific halibut longline fisheries. We found the catch efficiency of the 18/0 hook was similar to the 16/0 hook for both Pacific halibut and yelloweye rockfish. How circle hooks larger than 18/0 would affect the catch efficiency of Pacific halibut and yelloweye rockfish is unknown; however, research has shown a larger hook style known as the čibu·d to be highly selective against rockfishes (*Sebastes* spp.) and more selective for Pacific halibut (Scordino et al., 2017; Petersen et al., 2020; Stewart et al., 2021). While the čibu·d is more selective for Pacific halibut, it displays a decrease in Pacific halibut catches when compared to circle hooks. The known selectivity characteristics of circle hooks and the čibu·d, suggest that circle hooks larger than 18/0 (i.e., 20/0) could potentially be effective at reducing catch rates of yelloweye rockfish with minimal or no catch loss of Pacific halibut. Hooks larger than 18/0 with appendages could also potentially be effective at improving species selectivity. Research in this area of work would be beneficial to fishers, fisheries managers, and the resource of Pacific halibut and yelloweye rockfish.

In Northeast Atlantic cod (*Gadus morhua*) gillnet fisheries, recent studies are modeling the length-dependent and length-integrated probability of fish being captured by a specific gillnet type and by a specific mode of capture (i.e., lip, gills, body, etc.) (Brinkhof, 2022; Cerbule et al., 2022; Savina et al., 2022). This modeling is important in terms of improving gear performance and catch efficiency, but also from an incidental mortality standpoint where retention of a species and/or size range (e.g., minimum landing size) is prohibited. For example, in a gillnet fishery a prohibited species caught by the capture mode *gills* may exhibit a higher incidental mortality rate than a fish caught by the capture mode *lip*. In our study, we applied this novel technique and found the dominant mode of capture for Pacific halibut and yelloweye rockfish across each hook type was *hook through cheek*. For this capture mode, and when manual hook removal is applied as opposed to automated hook strippers (Kaimmer, 1994), released fish may experience a lower mortality rate. Previous research estimating post-release mortality of longline caught Pacific halibut with minor injuries exhibited a mortality rate of approximately 3.5-3.8% (Peltonen 1969; Loher et al., 2022).

Hooking location can affect post-release mortality of discarded fish. For fish with severe hook injuries (i.e., deep hooked, gill damage, torn jaw and/or face), their mortality rate is often higher than fish with minor hook injuries (Kaimmer and Trumble, 1998; Loher et al., 2022). In our research, we only observed deep hooking to occur three times and that occurred in the 18/0 no app. (H4) in yelloweye rockfish. Our result of not observing deep hooking in the appendage hooks is consistent to previous studies that have shown hook appendages to reduce deep hooking (Willis and Millar, 2001; Swimmer et al., 2011; Bergmann et al., 2014). In West Coast Pacific halibut recreational hook-and-line fisheries where fishers encounter yelloweye rockfish bycatch, which their take is prohibited in the fishery, hook appendages could potentially prove beneficial to reducing the catch rate of yelloweye rockfish, but also potentially reduce the severity of hook injuries and mortality of discarded fishes.

We used hook timers on a subset of hooks to explore if there was a temporal component in the catch rate between Pacific halibut and yelloweye rockfish. In the Pacific halibut fishery, historical research has used hook timers for the purpose of examining the effect of competition by spiny dogfish (*Squalus acanthias*) on the catch of Pacific halibut (IPHC, 1991; Kaimmer, 2011; Soderlund et al., 2012). However, these studies did not report temporal data on species time of capture during the soak duration. Our study is the first to present temporal data on the time of capture in the soak duration for Pacific halibut and yelloweye rockfish using hook timers. Our catch data did not show that a temporal difference between their respective catches occurred. However, the hook timer data did show that most Pacific halibut and yelloweye rockfish caught on hooks with hook timers were caught within the first 3 hours of gear saturation. As our gear deployments ranged from ~5-7 hours, and with most fish caught within 3 hours, this results in ~2-4 hours where the gear fished at a low catch efficiency. Thus, further research using hook timers would be valuable to better understand the relationship between soak duration and Pacific halibut catch efficiency.

In conclusion, our study (i) evaluated how hook size and hook appendages affect the catch efficiency of Pacific halibut and yelloweye rockfish, (ii) modeled the length-dependent and length-integrated capture mode probability for Pacific halibut and yelloweye rockfish by hook type, and (iii) investigated if a temporal effect occurs in the catch between Pacific halibut and yelloweye rockfish. Our findings indicate that hook appendages could be effective at reducing yelloweye rockfish bycatch while maintaining Pacific halibut catches. While we did not see a hook size effect on the catchability of Pacific halibut or yelloweye rockfish, it is worth investigating how circle hooks larger than 18/0 with and without appendages affect the catch efficiency of these species. Our modeling results showed the main mode of capture for Pacific halibut and yelloweye rockfish for each hook type tested was *hook through cheek* followed by *hook inside cheek* and that deep hooking was not a frequent capture mode. While a temporal catch effect between Pacific halibut and yelloweye rockfish was not noted, our hook timer data does provide new insights on soak duration and catchability of these two species. Further use of hook timers on Pacific halibut longline gear to explore relationships between soak durations and catch efficiencies would provide valuable information to fishers and fisheries managers. Lastly, while this research has applications to Pacific halibut longline fisheries, our findings may have potential applications in other commercial longline fisheries and recreational hook-and-line fisheries nationally and internationally.

Acknowledgments

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