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

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Abstract

In Pacific halibut (*Hippoglossus stenolepis*) longline fisheries in the eastern North Pacific Ocean bycatch of yelloweye rockfish (*Sebastes ruberrimus*) is a concern as their stock status along the U.S. West Coast is “rebuilding” from being “overfished”, the southeast Alaska stock has shown a ~60% decline since at least 1994 and through 2015 where it stabilized, and the Canadian stock has been recently declared “threatened”. In this study, we evaluated how size 16/0 and 18/0 circle hooks 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 estimated hooking location probabilities for Pacific halibut and yelloweye rockfish for the hooks tested, and tested for a difference in the time of capture between Pacific halibut and yelloweye rockfish. Results showed that hook size did not significantly affect the 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 hooking location was *hook through cheek*, both with and without an appendage. Time of capture of Pacific halibut and yelloweye rockfish did not differ over the duration of a set; however, the majority (75%) of individuals were caught within 2.5 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, which could lead to increased fishing opportunities, more efficient Pacific halibut fisheries and less effect of fluctuations in the more productive Pacific halibut stock on fisheries that may be constrained by yelloweye rockfish.

1. Introduction

The Pacific halibut (*Hippoglossus stenolepis*) resource 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 eastern North Pacific Ocean, including the 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 (IPHC, 2023). Off Alaska and Canada, the fishery operates under an individual quota system, while a derby fishery occurs off Washington, Oregon, and California.

In U.S. and Canada Pacific halibut longline fisheries, yelloweye rockfish (*Sebastes ruberrimus*) bycatch is a management issue due to the species' low stock abundance. Along the U.S. West Coast the yelloweye rockfish stock is "rebuilding" from being "overfished" (NMFS, 2019), the southeast (SE) Alaska stock has shown a ~60% decline since at least 1994 and through 2015 where it stabilized (ADFG, 2020), and the Canadian stock (both inside and outside waters) has recently been changed from a "species of concern" to "threatened" by the COSEWIC assessment committee (COSEWIC, 2020). The retention of yelloweye rockfish is prohibited in some Pacific halibut fisheries and management conservation zones have been established off the U.S. West Coast to protect the yelloweye rockfish stock (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 metric tons (MTs) (IPHC, 2020, 2021a, 2022a). Over these years, yelloweye rockfish bycatch in this fishery has been approximately 7.4, 2.2, and 1.1 MTs, respectively (Somers et al., 2021; West Coast Groundfish Observer Program [WCGOP] database, 2022). For all commercial fisheries along the U.S. West Coast (fixed and mobile fishing gears), the yelloweye rockfish annual catch limit for the years

2019 to 2021 has ranged from approximately 48-51 MTs (NOAA, 2018, 2020, 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 (Gertseva and Cope, 2017, 2018; NMFS, 2018), management measures such as restrictive commercial harvest guidelines (NOAA, 2022), prohibited take and long-leader gear restrictions in the recreational groundfish hook-and-line fishery (NMFS, 2017; NOAA, 2022; PFMC, 2022a), and conservation areas (PFMC, 2020) will likely continue to be implemented for several years to come. Thus, identifying, developing, and testing techniques (including gear modifications) to reduce yelloweye rockfish bycatch in commercial and recreational fisheries would be beneficial to the conservation of yelloweye rockfish, support management objectives (Gertseva and Cope, 2017, 2018; NMFS, 2018; PFMC, 2022a), and contribute to sustainable fishery practices.

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 hooking location (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 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, using 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 consists 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 fishery regulations prohibit the take of yelloweye rockfish in U.S. West Coast longline and hook-and-line fisheries 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 would likely reduce discard mortality and support management measures designed to conserve and rebuild the yelloweye rockfish stock (NMFS, 2017; PFMC, 2020, 2022b; NOAA, 2022).

In the Pacific halibut longline fishery, size 16/0 circle hooks are the conventional hook. The IPHC has evaluated the catch efficiency of size 13/0-16/0 circle hooks for management and stock assessment purposes (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 (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 suggests that larger-sized circle hooks could potentially reduce the catch rate of yelloweye rockfish while maintaining Pacific halibut catches. Thus, research examining the catch efficiency of larger-sized hooks would provide beneficial information to fishers, fisheries managers, stock assessors, and gear designers.

In addition to evaluating the effect of hook appendages and larger-sized circle hooks on the catchability of Pacific halibut and yelloweye rockfish, understanding their time of capture over the duration of a given longline set is of importance to managers and stock assessors (IPHC, 2021b). If catch timing were to differ significantly between Pacific halibut and yelloweye rockfish, changes in the timing of gear soaking could be identified as a technique to alter species selectivity and fishers' catch efficiency. Further, if gear soak duration had a considerable effect on Pacific halibut catches, this result could affect the IPHC setline survey data collection and subsequent estimates of Pacific halibut abundances. To date, research has not examined the time of capture between catches of Pacific halibut and yelloweye rockfish in Pacific halibut or other longline fisheries. Thus, the collection of this data may help to improve the standardization of catch rates in the IPHC's fishery-independent setline survey (IPHC, 2021b), and strengthen the coastwide management of the resource.

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) document the hooking location probabilities for Pacific halibut and yelloweye rockfish for the hooks tested, and (iii) test if there is a difference in the time of capture between Pacific halibut and yelloweye rockfish.

2. Material and methods

2.1. Study area, fishing gear, and sampling

We conducted our study in IPHC Regulatory Area 2A off the central Oregon coast (Fig. 1) in July 2022 onboard the R/V *Pacific Surveyor* (17 m LOA, 380 hp) over seven fishing days. Our study site is an area where Pacific halibut and yelloweye rockfish often co-occur. Fishing occurred during daylight hours, and tori lines were used during setting to minimize the risk of seabird bycatch.

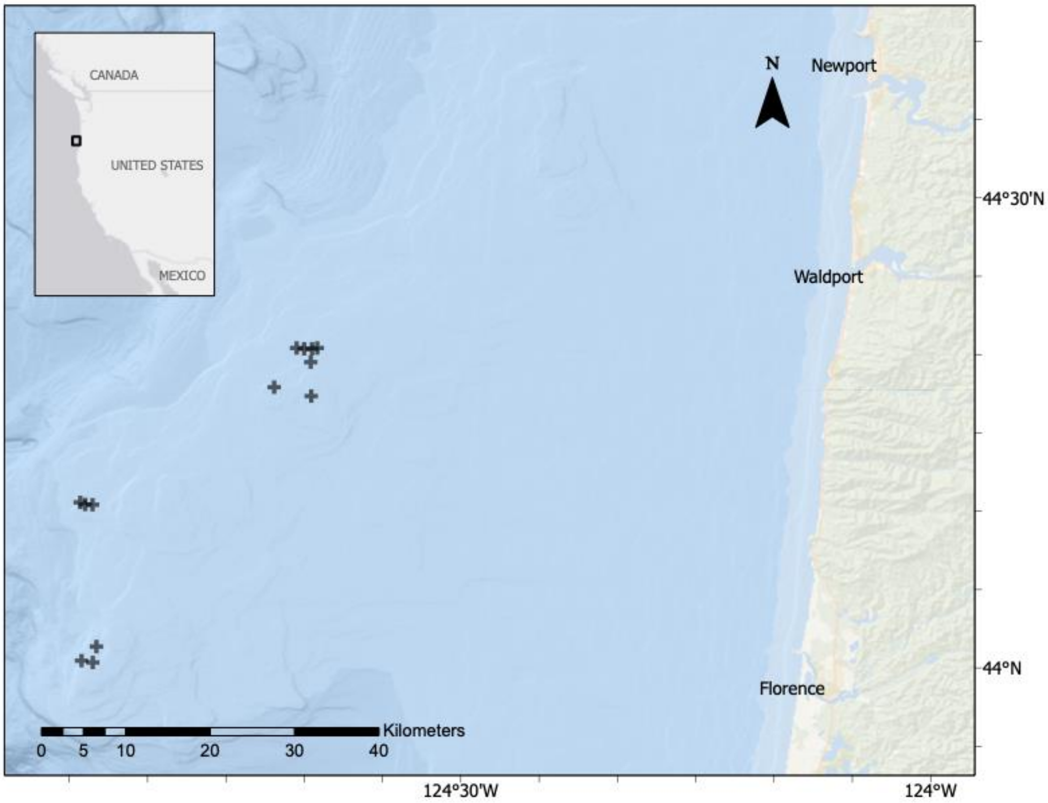

Figure 1. Map of the area off the Oregon coast where sea trials were conducted. Symbols represent set locations.

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 influences 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: 45° or 90° (relative to the plane of native curve and point of the hook). Thus, the hooks evaluated were: (i) 16/0 control (H1), (ii) 16/0 45° app. (H2), (iii) 16/0 90° app. (H3), (iv) 18/0 no app. (H4), (v) 18/0 45° app. (H5), and (vi) 18/0 90° app. (H6) (Fig. 2, Supplementary video 1).

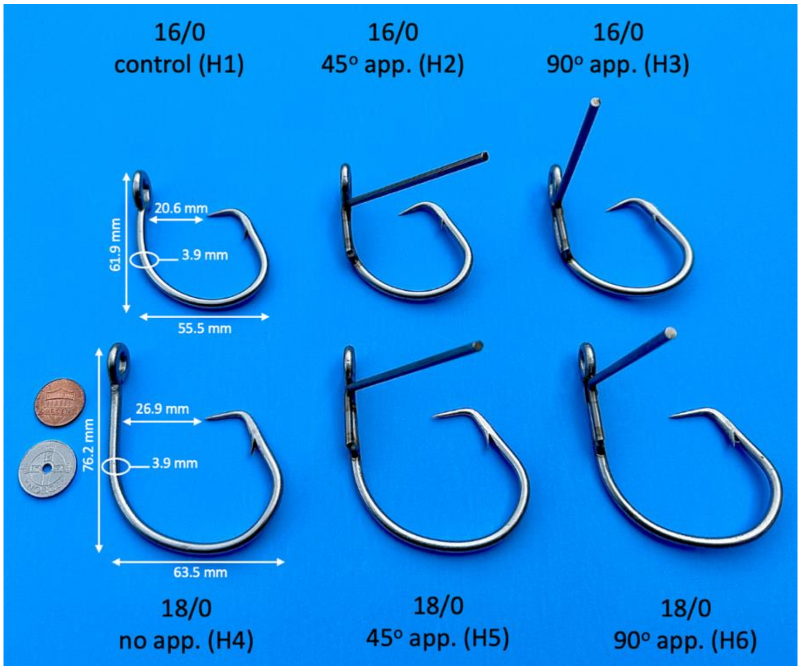

Figure 2. Image of the control hook (H1) and the five experimental hooks (H2-H6) tested. app. = appendage. Scale: Diameter of the Norwegian 1 krone coin displayed is 21 mm, diameter of the United States 1 cent coin displayed is 19 mm.

Gangions (short lengths of fishing line, connecting a snap with hook to the groundline) were built using hard-lay 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 of 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). For our study, 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 (Supplementary Video 2). 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. Per each skate, we planned to fish 100 hooks in a random pattern consisting of groupings of four hooks per each hook type along the skate (see Supplementary Table S1 for an example of a hook pattern). To evaluate if there was a difference in the time of capture between Pacific halibut and yelloweye rockfish, Lindgren-Pitman hook timers (Fig. 3) set at 1 kg of release tension were placed on a subset of the gangions fished. Approximately 25% of each hook typed fished daily included a hook timer. On some sets, a GoPro^{TM} video camera (placed in an aluminum housing and outfitted with two LED dive lights) was placed on the groundline in an effort to observe the behavior of fish as they interacted with the control (H1) and experimental hooks (H2-H6). Except for the experimental hooks (H2-H6), the fishing gear and configuration were intended to closely mimic common practice in the existing commercial fisheries for Pacific halibut.

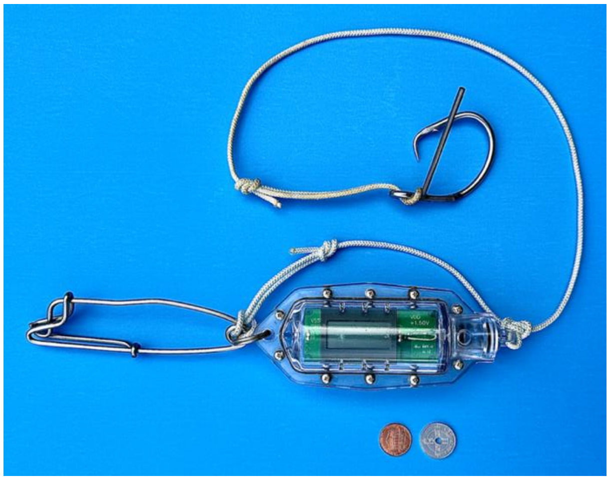

Figure 3. Hook timer rigged to a gangion with a 16/0 45^{o} app. hook (H2). Scale: Diameter of the Norwegian 1 krone coin displayed is 21 mm, diameter of the United States 1 cent coin displayed is 19 mm.

Length, weight, and hooking location (Table 1) were collected on all Pacific halibut and yelloweye rockfish caught per hook type. Hooks were manually removed from captured fish following commercial practices. 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.

Table 1. Hooking locations considered and their definitions.

Hooking location	Definition
Hook inside cheek	Cheek only, but not through the skin
Jaw only	Jaw only, but not clear through the jaw
Torn lip	Torn skin covering the external part of the jaw, cheek not punctured
Hook through cheek	Small hole through cheek only (includes in mesentery around the jaw and cheek)
Torn jaw	Either side, with little or no tearing in the cheek
Cheek and jaw	Tear in cheek extending through the jaw
Hook penetrating eye	Hook penetrated the eye (not just the socket)
Torn face	Torn through cheek and jaw, like above, but large flap of side of head is ripped/missing
Split jaw	Lower jaw is split laterally
Torn snout	Upper jaw is split laterally, usually tearing through the snout as well
Jig body	Fish snagged by hook somewhere on body other than the head
Jig head	Fish snagged by hook in the head (not through the mouth)
Tongue	Hooked on tongue
Throat	Hooked inside throat
Gill raker	Hook on gill raker

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. The analyses were 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:

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

where nt_{lj} and nc_{lj} are the number n of fish 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:

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

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):

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

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

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

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

The confidence limits (CLs) for $CC(l,\boldsymbol{v})$ and $CR(l,\boldsymbol{v})$ were estimated using the double bootstrapping method described by Cerbule et al. (2022). We conducted 1,000 bootstrap repetitions 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:

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

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 hooking location probabilities

To determine the length-dependent probability to capture fish with each of the 15 hooking locations considered (Table 1), we followed the method outlined in Savina et al. (2021). Specifically, we used numbers of observed fish that were captured by each of the hooking locations and the corresponding length measurements with each of the hook types and species caught separately. The analysis was carried out for each hooking location independently. The expected probability for the hooking location *q* for fish length *l* can be estimated using the following equation (Savina et al., 2021):

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

where n_{qlj} is the number of fish caught per length class *l* with capture location *q* for longline deployment *j*. *Q* is the number of hooking locations considered. *h* is the total number of longline deployments. The functional description of the hooking location probability *CPq*(*l*, ***v***) was obtained using maximum likelihood estimation by minimizing Expression 8 (Savina et al., 2021):

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

In Expression 8, ***v*** represents the parameters describing the hooking location probability curve defined by *CPq*(*l*, ***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*, ***v***) as is often applied for catch comparison studies based on binominal count data (Herrmann et al., 2017):

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

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*, ***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*...*v4* at a time resulted in 31 additional candidate models that were considered as potential models for the catch comparison *CC(l,**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 hooking location probability ($CPq_{average}$) was directly estimated from the experimental data using the following equation (Savina et al., 2021):

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

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 hooking location probability *CPq*(*l*, ***v***), $CPq_{average}$ is specific for the population structure encountered during the experimental trials.

2.4 Inference of the difference in the length-dependent probability for hooking location between hook types

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

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

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:

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

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.

3. Results

3.1. Fishing effort

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.

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 specimens of 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 modified 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 (e.g., broken gangion) we not common as over 98.7% of all hooks deployed returned in normal condition. Further, the appendages did not interfere with the manual hook baiting process or the deployment of skates.

Pacific halibut (n=145) and yelloweye rockfish (n=188) were the only species caught in sufficient numbers for use in our statistical analyses. The next most frequent species caught was Pacific spiny dogfish (*Squalus suckleyi*, n=17).

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 (Supplementary Table S2). 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^o app. (H2), the 16/0 control (H1) and the 18/0 90^o app. (H4), and the 16/0 90^o app. (H3) and the 18/0 45^o app. (H5) (Fig. 4). For those length classes where a significant affect was noted, the results show the 16/0 control (H1) catching more yelloweye rockfish than the 16/0 45^o app. (H2) and the 18/0 90^o app. (H6). In the 16/0 90^o app. (H3) vs the 18/0 45^o app. (H5) catch comparison, the results show the 16/0 90^o app. (H3) catching more than the 18/0 45^o app. (H5). 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 (Supplementary *CC(l,***v***)* Figs. S1-S2). For Pacific halibut 60-150 cm in length, no significant length-dependent catch efficiencies were noted between the hooks tested (Supplementary *CC(l,***v***)* Figs. S3-S5). On some sets a video camera system was used to capture the behavior of fishes as they interacted with the hooks, but unfortunately, we were unable to gather any such footage.

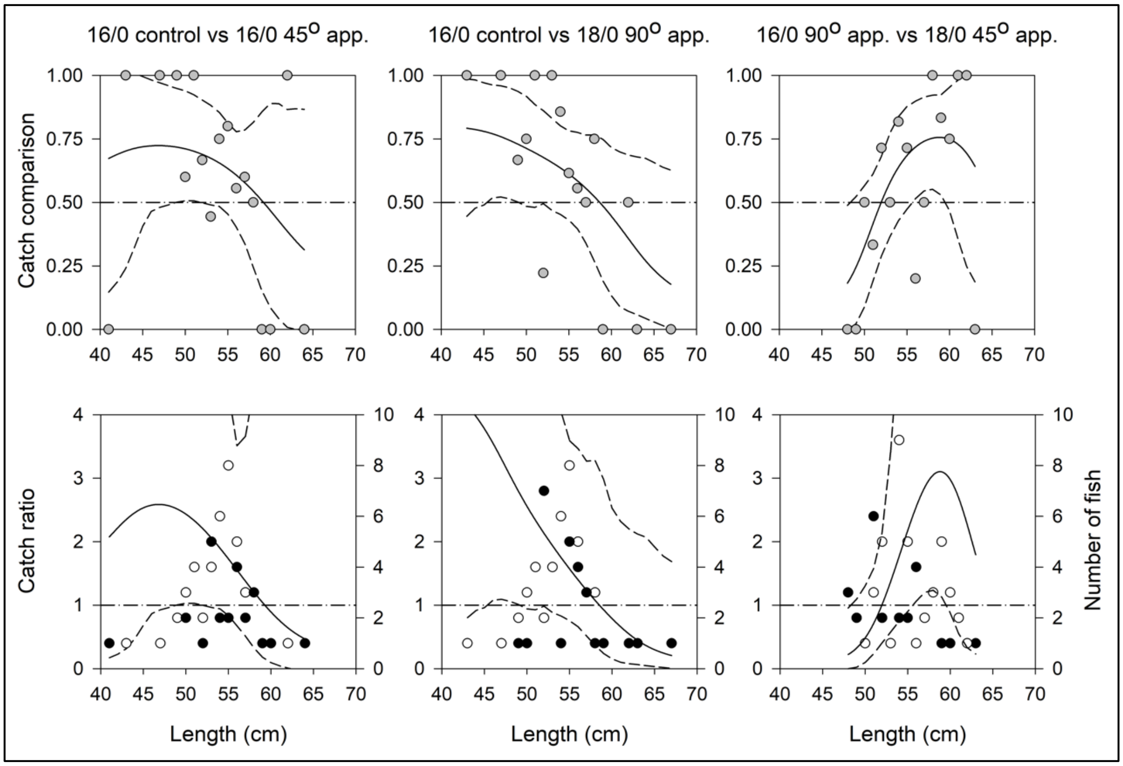

Figure 4. Mean catch comparison (upper) and catch ratio (lower) plots for yelloweye rockfish between the 16/0 control (H1) and 16/0 45^{o} app. (H2), the 16/0 control (H1) and 18/0 90^{o} app. (H6), and the 16/0 90^{o} app. (H3) and 18/0 45^{o} app. (H5). Shaded circles are the observed data; smooth fitted solid black lines are the modeled value; dashed lines are the 95% CLs; the open circles depict the number of fish caught by the hook type indicated first in the plot title, while the black circles depict the number of fish caught by the subsequent hook type indicated in the plot title (e.g., in the upper left plot the open circles represent the 16/0 control hook, while the black circles present the 16/0 45^{o} 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.

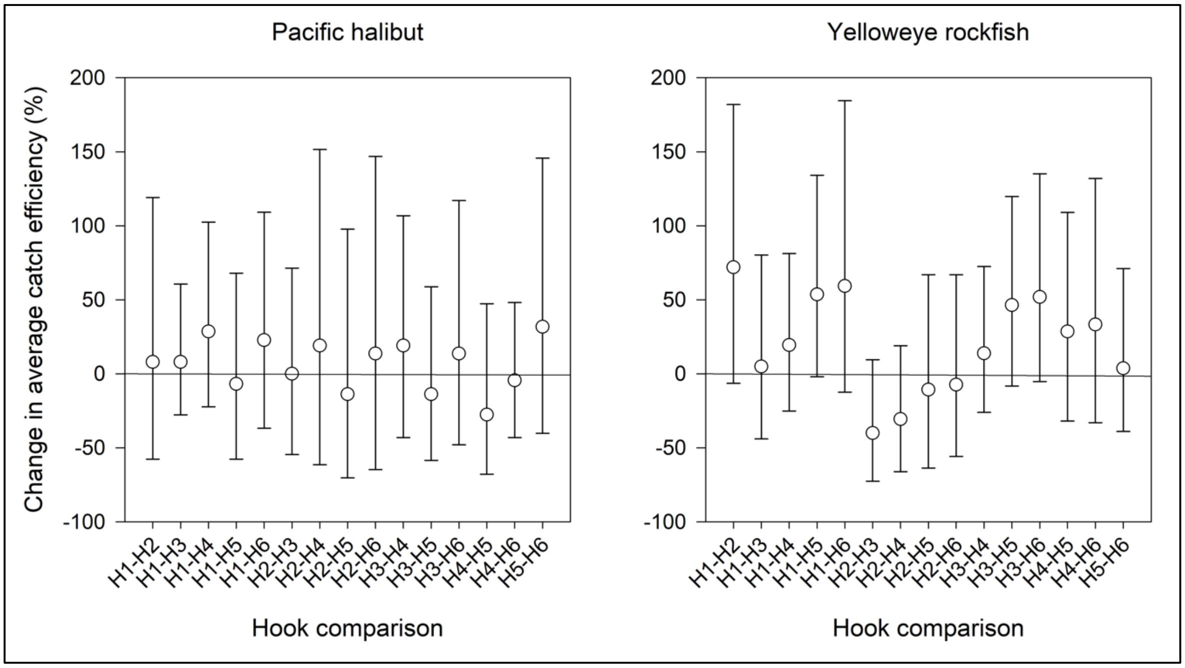

Figure 5. Change in length-integrated average catch efficiency between hook comparisons. Open circles depict the mean value. Vertical lines are 95% CLs. H1 =16/0 control; H2 = 16/0 45° app.; H3 = 16/0 90° app.; H4 = 18/0 no app.; H5 = 18/0 45° app.; H6 = 18/0 90° app. app. = appendage.

Length-integrated average catch efficiency of Pacific halibut and 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° app. (Fig. 6, Supplementary *CC(l,**v**)* and *CR(l,**v**)* Fig. S6). 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° app. did not influence catch efficiency of Pacific halibut (Fig. 6). Hooks with a 90° app. did not influence catch efficiency of either Pacific halibut or yelloweye rockfish when compared to hooks with a 45^{o} app. or hooks without an appendage present. When examining if hook size had a catch effect, irrespective of appendage presence or absence, results showed the 16/0 hook size tended to catch more Pacific halibut and yelloweye rockfish. However, this result was not significant as the CLs for these hook comparisons extend above and below the baseline value of zero (Fig. 6).

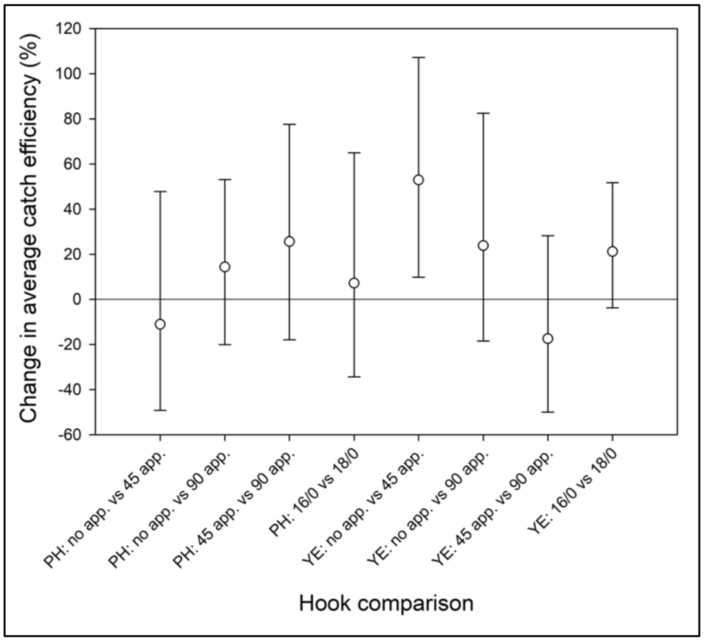

Figure 6. Change in average catch efficiency (%) between hooks with no appendage, 45^{o} appendage, and 90^{o} appendage. Open circles depict the mean value. Vertical lines are 95% CLs. PH = Pacific halibut; YE = yelloweye rockfish; app. = appendage.

3.4. Hooking location probability

For both the control (H1) and modified hooks (H2-H6), the most dominant hooking location for Pacific halibut and yelloweye rockfish was *hook through cheek* (Fig. 7) followed by *hooked inside cheek* but not extending through (Supplementary Tables S3 and S4). Combined, these two hooking locations accounted for 76.6% and 88.8% of all Pacific halibut and yelloweye rockfish capture locations, respectively. 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 hooking location for Pacific halibut and yelloweye rockfish are presented in Supplementary Tables S5 and S6, respectively. Length-dependent probability of capture for Pacific halibut and yelloweye rockfish by a certain hook type by the hooking location *hook through cheek* are presented in Supplementary Figure S7.

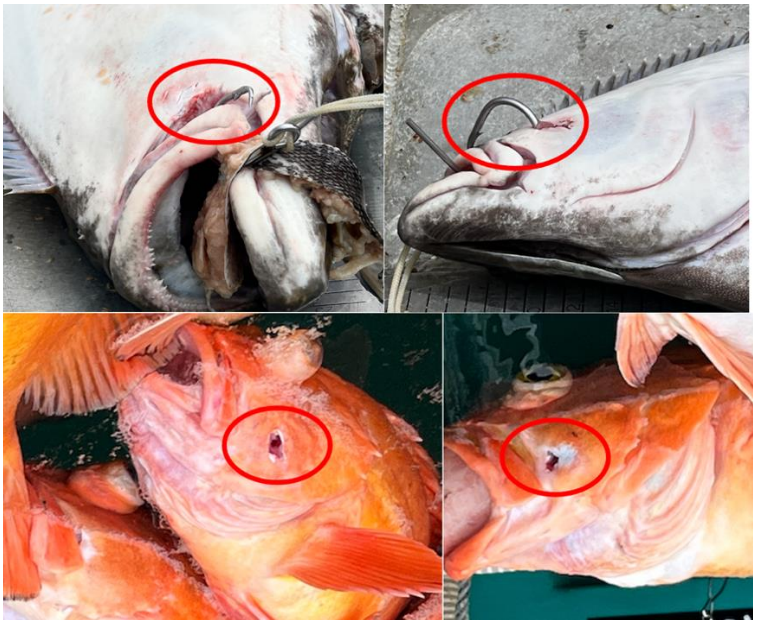

Figure 7. Images of Pacific halibut (top) and yelloweye rockfish (bottom) showing the hooking location *hook through cheek* (red circles).

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 (75% of all captures) occurred within 2.5 hours of the gear being deployed (Supplementary Fig. S8). Across all hooks, the range in time of capture during the soak process for Pacific halibut and yelloweye rockfish was 0:30-4:38 hr:min and 0:44-5:31 hr:min, respectively. However, it is important to note that a larger sample size could potentially show different results for time of capture overall and by hook type.

4. Discussion

We evaluated how size 16/0 and 18/0 circle hooks with and without hook appendages affected the catch efficiency of Pacific halibut and yelloweye rockfish in a Pacific halibut longline fishery. Irrespective of appendage presence or absence, the 16/0 hook size tended to catch more Pacific halibut and yelloweye rockfish than the 18/0 hook size. This result was not significant and may have been affected by our study sample size. When examining the effect of appendage angle, irrespective of hook size, on the catch efficiency of yelloweye rockfish, hooks with a 45^o app. caught significantly fewer individuals compared to hooks without an appendage. While the mechanism(s) causing this result are not entirely clear, it is plausible that given the differences in mouth orientation and morphology that exist between yelloweye rockfish and Pacific halibut, that the near proximity of the 45^o app. wire to the hooks' point reduces the probability of the point contacting and engaging with the mouth compared to non-appendage hooks. For hooks with a 90^o app., the appendage position in relation to the hook's point did not hinder the hook's point from contacting and engaging the mouth, which was also noted for non-appendage hooks. Pertaining to 45^o app. hooks for Pacific halibut, some fish were caught with the appendage pressed firmly down across their outer jaw and front cheek area while the hooking location was either *hook through cheek* or *hook inside cheek*. This observation of the appendage was not noted in yelloweye rockfish.

Along the U.S. West Coast, the yelloweye rockfish stock spawning biomass (SB) is “rebuilding” from being “overfished” and their stock SB mean value of 28.4% is still below the management target level of SB40% (Gertseva and Cope, 2017, 2018; NMFS, 2018). As a result of their low SB% abundance, restrictive commercial harvest guidelines, prohibited take and long-leader gear restrictions in the recreational groundfish hook-and-line fishery, and marine conservation areas have been implemented by fisheries management to help conserve and rebuild the stock (NMFS, 2017; PFMC, 2020, 2022a; NOAA, 2022). In our research, a total of 188 yelloweye rockfish were caught in our study area off central Oregon. While this sample size and our research area are both relatively small, our study was fortunate to encounter this number of yelloweye rockfish (given their low SB% abundance and potential encounter rates) and explore how hook size and appendage angle may affect their catchability in a Pacific halibut longline fishery. We observed encouraging results in those hooks with a 45^{o} app. caught significantly fewer yelloweye rockfish than hooks without an appendage, irrespective of hook size. For the current study, we acknowledge our small sample size, but contend that our research provides international, federal, and state managers (e.g., IPHC, Fisheries and Oceans Canada, NOAA, Pacific Fishery Management Council, Washington- and Oregon- Department of Fish and Wildlife) with valuable information and insights on a simple technique that may reduce yelloweye rockfish bycatch in Pacific halibut longline fisheries. However, further data collection across broader temporal and spatial coverage is needed before management actions regarding hook size and/or appendages are recommended.

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 statistically 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 considerable 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 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. If larger-sized hooks can reduce yelloweye rockfish bycatch without affecting Pacific halibut catches, implementing hook size and/or design restrictions would be a simple management measure to implement and regulate by law enforcement.

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 type of capture (i.e., lip, gills, body, etc.) (Brinkhof, 2023; Cerbule et al., 2022; Savina et al., 2021). This modeling is important in terms of improving gear performance, but also from a fisheries management and 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 captured by the *gills* may exhibit a higher incidental mortality rate than a fish captured by the *lip*. In our study, we applied this novel technique (and to our best knowledge this research is the first to apply the technique to hook data) and found the dominant hooking location for both the control (H1) and modified hooks (H2-H6) for Pacific halibut and yelloweye rockfish was *hook through cheek* followed by *hook inside cheek*. These findings are similar to results reported by Dykstra (2022) which found the most common hook injury for Pacific halibut where the hook was manually removed was a small hole through the cheek. Further, Pacific halibut hooked and removed under these scenarios were most frequently categorized as being in excellent viable condition (Dykstra, 2022). For fish hooked in the cheek, and when manual hook removal is applied as opposed to automated hook strippers (Kaimmer, 1994), released fish are likely to experience a lower mortality rate, for example, post-release mortality of longline-caught Pacific halibut with minor hook injuries exhibit a mortality rate of approximately 3.5-3.8% (Peltonen 1969; Loher et al., 2022). Prior to our research, estimating hooking location probabilities for Pacific halibut and yelloweye rockfish exposed to conventional (e.g., 16/0 control [H1]) and experimental hooks (e.g., hooks H2-H6) had not been performed.

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). As yelloweye rockfish suffer barotrauma when brought to the surface, and with hook injuries known as a factor to affect post-release survivorship, it is critical for management applications that any modified hook design to be considered for fisheries use (whether commercial or recreational) does not increase hooking injures and post-release mortality. For the control (H1) and modified (H2-H6) hooks we evaluated, the dominant hooking locations of *hook through cheek* and *hook inside cheek* are likely to have a lower post-release mortality impact than fish with hooking locations such as gills, throat, and stomach where bleeding, organ damage, and increased handling times and air exposure can occur. 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 the U.S. West Coast Pacific halibut recreational hook-and-line fishery where fishers encounter yelloweye rockfish bycatch, which their take is prohibited, hook appendages could potentially prove beneficial as a management technique to reduce the catch rate of yelloweye rockfish, but also potentially reduce the severity of hook injuries and mortality of discarded fishes. In our study, we did not experience difficulties removing the control or modified hooks from yelloweye rockfish. For the appendage hooks a crew member commented was made that the appendages provided leverage, making it easier to remove the hook compared to non-appendage hooks. While removing the hook from the fish's mouth is common practice in commercial and recreational fisheries, there are instances in recreational fisheries where some fishers unhook halibut and rockfishes hooked in locations such as the eye socket or cheek by releasing their leader and running the hook out externally through the hole/injury. As we did not practice this unhooking procedure, it is uncertain if hooks with appendages can effectively be removed by this method. While further research examining post-release survivorship in yelloweye rockfish caught with modified hooks would provide beneficial information on the efficacy of hook appendages to reduce bycatch while minimizing injuries, our results suggest that hook appendages (as tested in our study) do not increase injuries, unhooking times, or post-release mortality compared to conventional circle hooks used in commercial and recreational fisheries.

We used hook timers on a subset of hooks to explore if there was a difference in the time of capture 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 Pacific spiny dogfish on the catch of Pacific halibut (IPHC, 1991; Kaimmer, 2011; Soderlund et al., 2012).

However, these studies did not report on species' time of capture during the soak duration. Our study is the first to present 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 difference in time of capture occurred. However, the hook timer data did show the majority of Pacific halibut and yelloweye rockfish caught on hooks with hook timers were caught within 2.5 hours of the gear being deployed. As our gear deployments ranged from approximately 5-7 hours, and with most fish caught within 2.5 hours, this results in approximately 2.5-4.5 hours where the gear fished at a lower catch efficiency. In addition to fishing at a lower catch efficiency, this also extends the period of time where hooked fish are vulnerable to "sand flea" (a term applied by fishers to scavenging amphipods) predation. In our research, we noted one yelloweye rockfish mortality from sand flea scavenging and a few instances in Pacific halibut where sand flea scavenging had begun. While our study was limited in temporal and spatial coverage, our hook timer data still provides new insights to IPHC stock assessors and managers on their standardization assumptions of catch-rates in the IPHC's fishery-independent setline survey and their Pacific halibut population estimates.

In the eastern North Pacific Ocean, marine mammal depredation has been recognized as a significant issue affecting longline hook fisheries for Pacific halibut and sablefish (*Anoplopoma fimbria*) (Peterson and Carothers, 2013; Peterson and Hanselman, 2017; Hanselman et al., 2018) and has resulted in fishers seeking alternative gear designs (e.g., shrouded branchline, cod coil, Sago Extreme) to protect their catch from depredation (IPHC, 2022b). During our study, we did not observe any marine mammal depredation events.

5. Conclusion

Minimizing yelloweye rockfish bycatch and discard mortality is a high priority to international, federal, and state fisheries managers (NMFS, 2017; COSEWIC, 2020; NOAA, 2022). On the U.S. West Coast, the yelloweye rockfish stock is “rebuilding” (Gertseva and Cope, 2017, 2018) and individual yelloweye rockfish quotas remain small. In response, managers have closed large areas (e.g., the entire coast of Washington north of 46°53.30 North latitude) to the directed Pacific halibut fishery to reduce yelloweye rockfish encounters and have thereby reduced fishery efficiency (PFMC, 2022b). Further, in the Oregon recreational groundfish hook-and-line fishery, fishes are required to use long-leader gear (NMFS, 2017) to minimize yelloweye rockfish bycatch when targeting midwater schooling species such as widow rockfish (*S. entomelas*) and yellowtail rockfish (*S. flavidus*). In Canadian waters, the yelloweye rockfish stock has been recently declared “threatened” (COSEWIC, 2020), and the Pacific halibut fishery has moved away from yelloweye rockfish ‘hotspots’ to reduce incidental catch, again leading to reduced catch rates for the target species (Forrest et al., 2020). In SE Alaska, the yelloweye rockfish stock has shown a ~60% decline since at least 1994 and through 2015 where it stabilized (ADFG, 2020). The recreational fishery there has been prohibited from retaining yelloweye rockfish since 2020 (Joy et al., 2022). Fishery managers have closed directed commercial fishing for yelloweye rockfish in variable areas since 1995, and closed all areas in 2020 (Joy et al., 2022). At present, much of the fishing mortality on the yelloweye rockfish stock occurs incidental to commercial longline fisheries in the area. Thus, across the range where Pacific halibut and yelloweye rockfish co-occur fisheries managers are seeking tools to reduce the mortality of yelloweye rockfish, while maintaining efficient fisheries for Pacific halibut and other species.

Conservation engineering research designed to reduce bycatch, including reducing post-release mortality, is a management priority area of the Magnuson-Stevens Fishery Conservation and Management Reauthorization Act of 2006 (*Section 318(c)(iii)*). In our study, we looked to support these management priorities and performed research evaluating how hook size (16/0 vs 18/0) and hook appendage angle (45° vs 90°) affect the catch efficiency of yelloweye rockfish in a Pacific halibut longline fishery. Our findings showed hooks with a 45° app. caught significantly less yelloweye rockfish than hooks without an appendage, irrespective of hook size, without impacting Pacific halibut catches. This reduction in yelloweye rockfish catches not only reduces their level of post-release mortality as fewer individuals are hauled to the surface and then subsequently released, but also improves fishers' catch efficiency of Pacific halibut. Although we encountered a relatively small sample size, these encouraging results suggest that hook appendages could have potential use in reducing catch and discard mortality rates of yelloweye rockfish in Pacific halibut longline fisheries. However, continued research examining hook size and appendage angle over a broader region is strongly encouraged before recommending changes to fisheries management regulations.

While our research occurred off the central Oregon coast within IPHC Regulatory Area 2A, our study findings could very well have applications to IPHC Regulatory Areas 2B (Canadian waters), and 2C and 3A (SE Alaskan waters) where bycatch of yelloweye rockfish stocks are of management concern (ADFG, 2020; COSEWIC, 2020). Except for the experimental hooks (H2-H6) fished, our study used fishing gear configurations and gear deployment/retrieval procedures that are common practice in existing Pacific halibut commercial fisheries. As we found, the modified hooks did not interfere with the hook baiting process, deployment/retrieval of skates, manual hook removal of captured fish, or create safety handling issues. Our study presents practicable procedures that can be replicated under most commercial fishing practices. From a fisheries management perspective, if changes in hook designs were to be implemented this would only result in the replacement of existing hooks and would not require other gear changes for fishers' use. In the event fisheries managers were to implement the use of hook appendages (as presented in our study), this would result in manufacturing costs to fishers that include purchasing stainless steel wire and cutting it into appendage lengths, and welding the appendages to the hook. For our study, the average cost to manufacture a single modified hook was $0.13 (USD) for the wire appendage and $7.43 (USD) for research development and welding services. However, as most fishers have welding equipment and experience, it is likely that the average cost for a fisher to manufacturer a modified hook, specifically the welding component, would be much lower than the cost we incurred. Further, if modified hooks were to be widely used it is possible that a company could begin manufacturing these hooks at a substantially lower cost.

In conclusion, in IPHC Regulatory Area 2A 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 hooking location probability for Pacific halibut and yelloweye rockfish by hook type, and (iii) examined if a difference in the time of capture occurred between Pacific halibut and yelloweye rockfish. Our work provides fisheries managers, fishers, and gear developers information on a simple technique that shows encouraging results for reducing catch rates of yelloweye rockfish without affecting Pacific halibut catches. Further, our study produces probabilities for hooking location for yelloweye rockfish and Pacific halibut (which had not been studied prior to our research) that managers and stock assessors may use in their statistical models for estimating injuries and post-release mortality for discarded fish. Data from our hook timers may also provide new insights for IPHC stock assessors and managers on their standardization assumptions of catch-rates in the IPHC's fishery-independent setline survey and their Pacific halibut population estimates. While further research is obviously needed to better understand the effect of hook sizes and appendages over broader temporal and spatial coverages, our study provides fisheries managers and fishers with the necessary information to inform future research and data needs pertaining to hook sizes and appendages in Pacific halibut fisheries. As yelloweye rockfish remain a management concern in eastern North Pacific Ocean fisheries, developing and testing techniques to reduce yelloweye rockfish encounter rates and management measures such as restrictive commercial harvest guidelines, prohibited take in recreational hook-and-line fisheries, and conservation areas will likely be implemented for several years to come to help conserve their stocks.

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On behalf of all the authors on our submission, as the corresponding author I (Mark J.M. Lomeli) can confirm that we do not have any conflicts of interest as defined by *Ocean & Coastal Management* in their “Guide for Authors”.

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Declaration Statement

Figure S1

Figure S2

Figure S3

Figure S4

Figure S5

Figure S6

Figure S7

Figure S8

Table S2

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Table S3

Table S4

Table S5

Table S6