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Faculty of Biosciences, Fisheries and Economy
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Bycatch Reduction in Eastern North Pacific Trawl Fisheries

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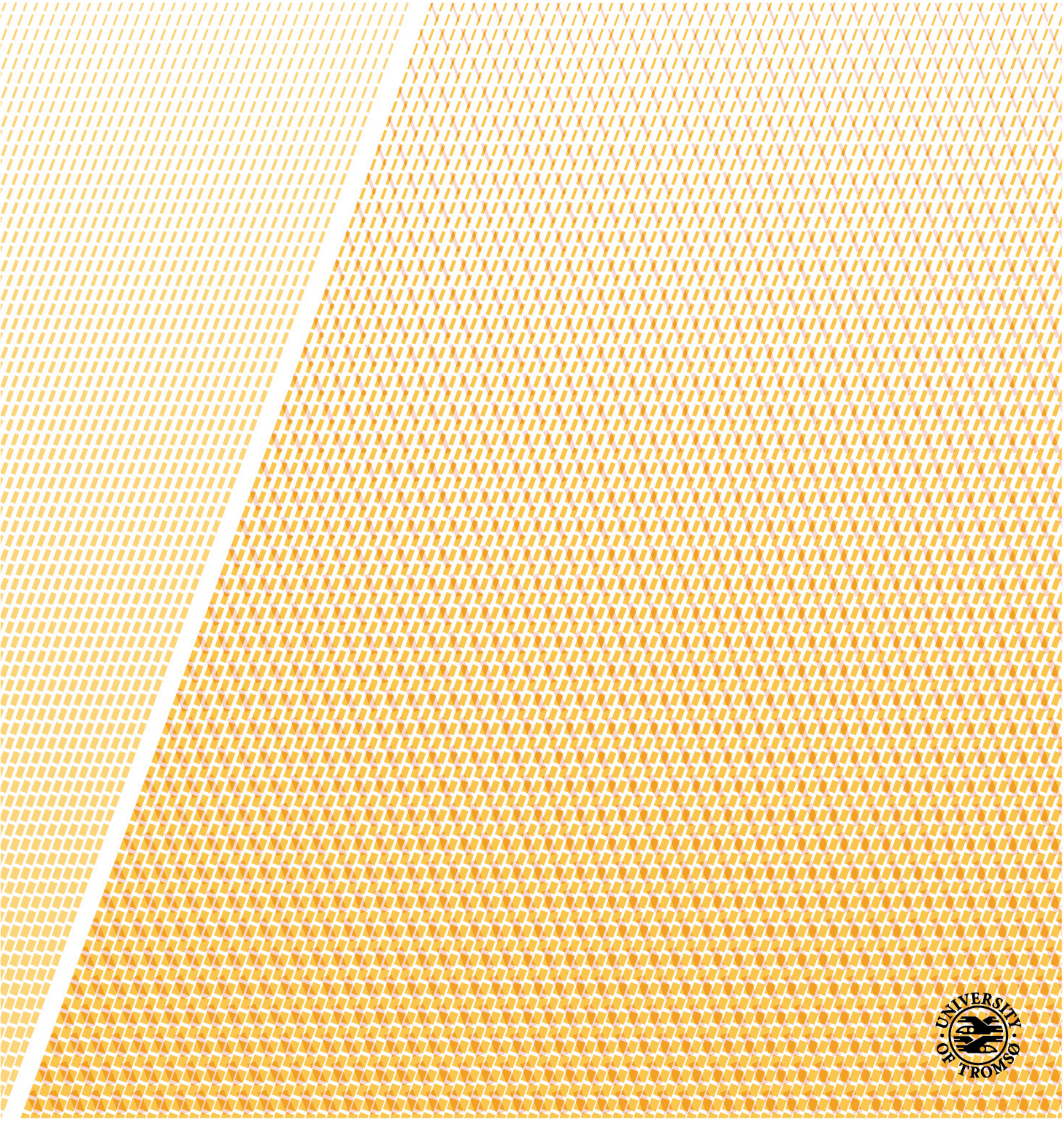
Mark J.M. Lomeli

A dissertation for the degree of Doctor Philosophiae – December 2019



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Abstract

This thesis provides an overview of recent selectivity studies conducted in eastern North Pacific trawl fisheries (e.g., West Coast groundfish bottom trawl fishery, Pacific hake [*Merluccius productus*] fishery, and ocean shrimp [*Pandalus jordani*] fishery). Collectively, these fisheries play a significant role in supporting fishing jobs, income, and coastal communities. However, bycatch can impact fishers ability to fully utilize the fisheries resource. Thus, developing gear modifications to reduce bycatch are increasingly important. In this thesis, results from VIII selectivity research papers addressing bycatch issues in eastern North Pacific trawl fisheries are presented.

In the U.S. West Coast groundfish bottom trawl fishery, constraining species such as darkblotched rockfish (*Sebastes crameri*), sablefish (*Anoplopoma fimbria*), and Pacific halibut (*Hippoglossus stenolepis*) bycatch can impact fishers ability to maximize their quota shares of healthier groundfish stocks. In Papers I-III, results from sea trials evaluating sorting grid bycatch reduction devices (BRDs) to reduce catches of these species are presented. Results from these papers demonstrate the ability of sorting grid devices to reduce bycatch while retaining a relatively high proportion of the targeted species. In Paper IV, the efficacy of T90 mesh codends to improve catch composition in the Dover sole-thornyhead-sablefish complex fishery were examined. In this fishery, where catches of juvenile and sub-adult sablefish are affecting fishers ability to achieve a higher ex-vessel value (e.g., landed value) of the sablefish resource, and higher attainment rates of Dover sole (*Microstomus pacificus*), results presented in Paper IV demonstrates that T90 mesh codends have potential to increase fishers opportunities to capitalize on their Dover sole individual fishing quota and enhance their net economic benefits while more effectively attaining their quota shares of sablefish.

In Papers V-VIII, results are presented from studies testing the efficacy of artificial illumination (e.g., light-emitting diodes [LEDs]) to reduce fish bycatch. In Paper V, research tested if simple enhancements to the visibility of a low-rise selective flatfish trawl headrope could improve bycatch reduction for darkblotched rockfish, sablefish and Pacific halibut. Findings from Paper V suggest that use of illumination could have potential applications for reducing bycatch under particular situations. For example, fishers seeking to reduce sablefish catches and/or Pacific halibut bycatch when targeting English sole (*Parophrys vetulus*) and petrale sole (*Eopsetta jordani*) could potentially benefit from illuminating the trawl headrope, whereas fishers seeking to target Dover sole and/or sablefish but avoid darkblotched rockfish, would likely not benefit from using illumination. In Papers VI-VII, studies evaluating the

efficacy of LEDs to reduce eulachon (*Thaleichthys pacificus*) and groundfish bycatch were examined. For eulachon, an anadromous smelt species endemic to the eastern North Pacific, their bycatch is an issue facing the ocean shrimp fishery as the species' southern Distinct Population Segment was listed as "threatened" under the U.S. Endangered Species Act (ESA) in 2010. Results presented in Papers VI and VII continue to support the hypothesis that there is a significant reduction in eulachon bycatch when artificial illumination is present. For rockfishes and flatfishes, findings suggest their ability to escape trawl entrainment in response to illumination along the fishing line is not as strong as previously indicated. As conservation of ESA-listed eulachon is an ongoing management priority, Papers VI and VII contribute new data on the efficacy of footrope illumination to reduce their bycatch. Lastly, Paper VIII conducted two separate experiments evaluating the influence of artificial illumination on Chinook salmon (*Oncorhynchus tshawytscha*, a species with ESA listings) behavior and escapement out of a BRD in a Pacific hake midwater trawl. Findings from Paper VIII demonstrate that artificial illumination can influence where Chinook salmon exit out the BRD tested, but also that illumination can be used to enhance their escapement overall. Because ocean distributions of Chinook salmon and Pacific hake often overlap, interactions between Pacific hake trawl gear and Chinook salmon are likely to continue to be an issue facing the fishery. Findings from Paper VIII provides data on a gear modification that can minimize Chinook salmon bycatch.

Lastly, the collective work presented within this thesis has contributed substantially to the development and advancements of gear modifications for reducing bycatch in eastern North Pacific trawl fisheries and the conservation of ESA-listed species.

Papers I, II, and VIII are published in *Fisheries Research*, Papers III, IV, and V are published in *Marine and Coastal Fisheries*, Paper VI is published in the *International Council for the Exploration of the Sea Journal of Marine Science*, and Paper VII is published in the *Canadian Journal of Fisheries and Aquatic Sciences*.

List of papers

Paper I: Lomeli, M.J.M., Wakefield, W.W., 2013. A flexible sorting grid to reduce Pacific halibut (*Hippoglossus stenolepis*) bycatch in the U.S. West Coast groundfish bottom trawl fishery. Fisheries Research, 143: 102-108.

Paper II: Lomeli, M.J.M., Wakefield, W.W., 2016. Evaluation of a selective flatfish sorting grid bycatch reduction device in the U.S. West Coast bottom trawl fishery. Fisheries Research, 183: 294-303.

Paper III: Lomeli, M.J.M., Wakefield, W.W., Herrmann, B., 2017. Testing of two selective flatfish sorting-grid bycatch reduction devices in the U.S. West Coast groundfish bottom trawl fishery. Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science, 9: 597-611.

Paper IV: Lomeli, M.J.M., Hamel, O.S., Wakefield, W.W., Erickson, D.L., 2017. Improving catch utilization in the U.S. West Coast groundfish bottom trawl fishery: An evaluation of T90-mesh and diamond-mesh cod ends. Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science, 9: 149-160.

Paper V: Lomeli, M.J.M., Wakefield, W.W., Herrmann, B., 2018. Illuminating the headrope of a selective flatfish trawl: Effect on catches of groundfishes, including Pacific halibut. Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science, 10: 118-131.

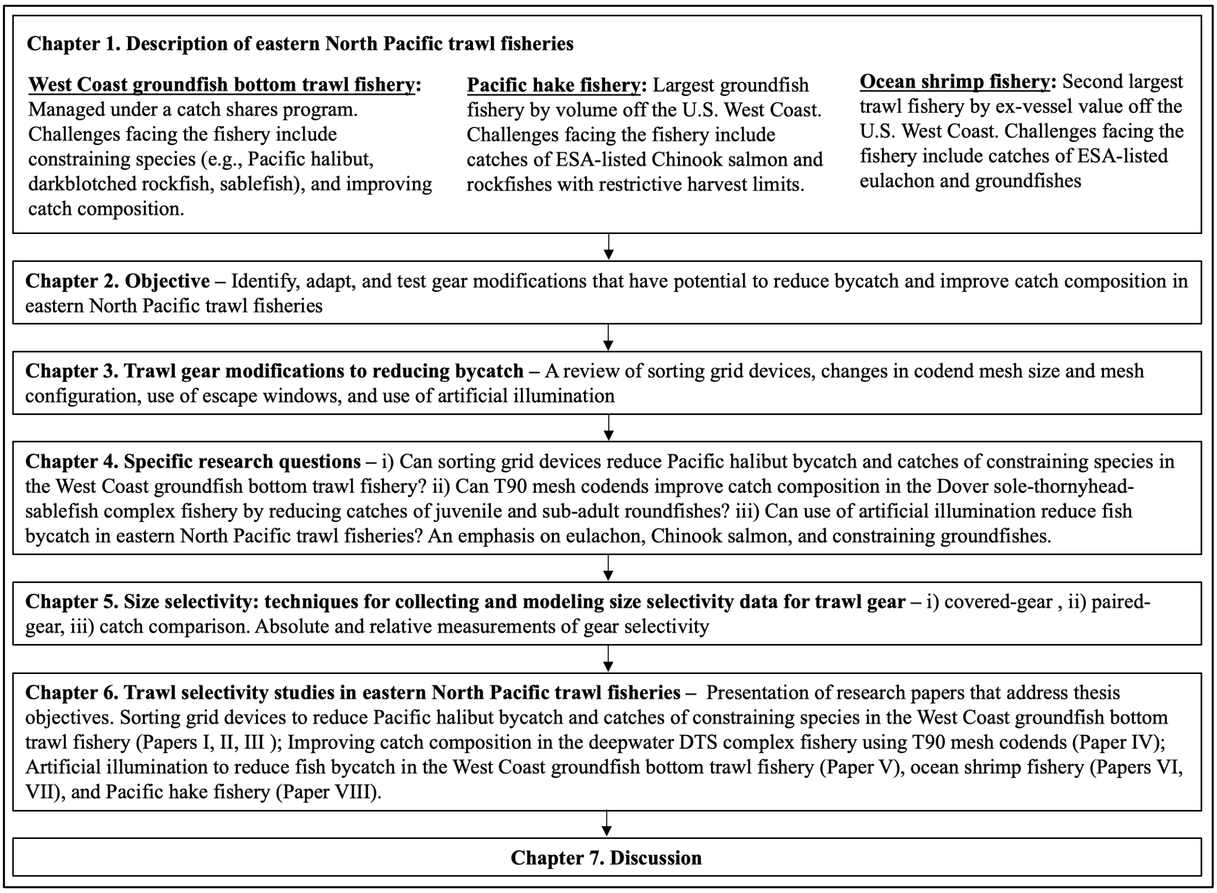
Paper VI: Lomeli, M. J. M., Groth, S. D., Blume, M. T. O., Herrmann, B., and Wakefield, W. W., 2018. Effects on the bycatch of eulachon and juvenile groundfish by altering the level of artificial illumination along an ocean shrimp trawl fishing line. ICES Journal of Marine Science, 75: 2,224-2,234.

Paper VII: Lomeli, M. J. M., Groth, S. D., Blume, M. T. O., Herrmann, B., and Wakefield, W. W. 2019. The Efficacy of illumination to reduce bycatch of eulachon and groundfishes before trawl capture in the eastern North Pacific ocean shrimp fishery. Canadian Journal of Fisheries and Aquatic Sciences, Published on the web 24 May 2019, https://doi.org/10.1139/cjfas-2018-0497.

Paper VIII: Lomeli, M.J.M., Wakefield, W.W., 2019. The effect of artificial illumination on Chinook salmon behavior and their escapement out of a midwater trawl bycatch reduction device. Fisheries Research, 218: 112-119.

Thesis structure

In Chapter 1 of this thesis, a description of eastern North Pacific trawl fisheries (e.g., West Coast groundfish bottom trawl fishery, Pacific hake fishery, and ocean shrimp fishery) is presented along with bycatch challenges facing the fisheries in this region. This leads to Chapter 2 where the overall thesis objective to "*identify, adapt, and test gear modifications that have potential to reduce bycatch and improve catch composition in eastern North Pacific trawl fisheries*" is developed. In Chapter 3, a review of trawl gear modifications that potentially could be used to reduce bycatch in these fisheries is provided. Following this review, Chapter 4 formulates specific research questions that include potential trawl gear modifications that can address the thesis objective. In Chapter 5, techniques for collecting and modeling selectivity data that can be used to test the thesis specific research questions is presented. In Chapter 6, the specific research papers that address the thesis objective are presented (Papers I-VIII). In the final chapter, the thesis research papers are discussed, future research directions are identified, and final remarks are made. See Figure 1 for a schematic diagram depicting the structural layout of this thesis.



Chapter 1. Description of eastern North Pacific trawl fisheries

West Coast groundfish bottom trawl fishery: Managed under a catch shares program. Challenges facing the fishery include constraining species (e.g., Pacific halibut, darkblotched rockfish, sablefish), and improving catch composition.

Pacific hake fishery: Largest groundfish fishery by volume off the U.S. West Coast. Challenges facing the fishery include catches of ESA-listed Chinook salmon and rockfishes with restrictive harvest limits.

Ocean shrimp fishery: Second largest trawl fishery by ex-vessel value off the U.S. West Coast. Challenges facing the fishery include catches of ESA-listed eulachon and groundfishes

Chapter 2. Objective – Identify, adapt, and test gear modifications that have potential to reduce bycatch and improve catch composition in eastern North Pacific trawl fisheries

Chapter 3. Trawl gear modifications to reducing bycatch – A review of sorting grid devices, changes in codend mesh size and mesh configuration, use of escape windows, and use of artificial illumination

Chapter 4. Specific research questions – i) Can sorting grid devices reduce Pacific halibut bycatch and catches of constraining species in the West Coast groundfish bottom trawl fishery? ii) Can T90 mesh codends improve catch composition in the Dover sole-thornyhead-sablefish complex fishery by reducing catches of juvenile and sub-adult roundfishes? iii) Can use of artificial illumination reduce fish bycatch in eastern North Pacific trawl fisheries? An emphasis on eulachon, Chinook salmon, and constraining groundfishes.

Chapter 5. Size selectivity: techniques for collecting and modeling size selectivity data for trawl gear – i) covered-gear , ii) paired-gear, iii) catch comparison. Absolute and relative measurements of gear selectivity

Chapter 6. Trawl selectivity studies in eastern North Pacific trawl fisheries – Presentation of research papers that address thesis objectives. Sorting grid devices to reduce Pacific halibut bycatch and catches of constraining species in the West Coast groundfish bottom trawl fishery (Papers I, II, III); Improving catch composition in the deepwater DTS complex fishery using T90 mesh codends (Paper IV); Artificial illumination to reduce fish bycatch in the West Coast groundfish bottom trawl fishery (Paper V), ocean shrimp fishery (Papers VI, VII), and Pacific hake fishery (Paper VIII).

Chapter 7. Discussion

Figure 1. Schematic diagram illustrating the structural organization of this thesis.

Chapter 1. Description of eastern North Pacific trawl fisheries

Along the eastern North Pacific (Figure 2), the U.S. West Coast groundfish bottom trawl fishery, Pacific hake (*Merluccius productus*) midwater trawl fishery, and ocean shrimp (*Pandalus jordani*) otter trawl fishery represent the largest trawl fisheries by volume and ex-vessel value (e.g., landed value) (PacFIN, 2019). From 2011 to 2018, these fisheries combined annual landings have averaged 291,933 MT resulting in an average annual ex-vessel value of $118.4 million USD. The Pacific hake fishery is the largest fishery in the eastern North Pacific in terms of annual landings and ex-vessel value. Throughout the course of the year, many fishers participate in each fishery. For the Pacific hake and ocean shrimp trawl fisheries, the Marine Stewardship Council (MSC) has identified these fisheries as sustainably managed (MSC, 2014, 2018). In the groundfish bottom trawl fishery, 13 species to date have received MSC certification (MSC, 2019). Collectively, the West Coast groundfish bottom trawl fishery, Pacific hake fishery, and ocean shrimp fishery play a critical role in supporting fishing jobs, income, and coastal communities along the eastern North Pacific.

In the following chapter, a detailed description of the West Coast groundfish bottom trawl fishery, Pacific hake fishery, and ocean shrimp fishery are presented along with bycatch challenges facing each fishery. Note: State and Federal trawl fishing regulations described in this thesis are reflective of the regulations implemented in the West Coast groundfish bottom trawl fishery, Pacific hake fishery, and ocean shrimp fishery at the time this thesis was written.

1.1. West Coast groundfish bottom trawl fishery

The West Coast groundfish bottom trawl fishery ranges from the USA-Mexico border to the USA-Canada border (Figure 2) and seaward to depths upwards to 1,280 m. Catcher vessels primarily ranging from 15.2 to 24.4 m in length deliver to shore-side processing plants. Prior to 2011, the fishery was principally managed by two-month cumulative landing limits to control catches, and area closures to minimize bycatch of overfished species. This management regime, however, was marked by biological and social concerns and viewed as economically unsustainable. Thus, in 2011, the fishery began management under a catch share program that allocates individual fishing quotas (IFQs) and establishes annual catch limits (ACLs) for over 30 groundfish managed units (stocks, stock complexes, and geographical subdivisions of stocks), and individual bycatch quotas (IBQ) for Pacific halibut (*Hippoglossus stenolepis*) (PFMC and NMFS, 2011, 2015). In this program, fishers are allocated a proportion of the fishery ACL (based on catches during a catch history qualifying period, 1994 to 2003) with the

Figure 2. Region of the eastern North Pacific where research presented in this thesis occurred. Map created by Kirsten Lomeli.

option to transfer, lease, or permanently sell their quota to another shareholder. Since implementation of the catch share program, annual groundfish landings (excluding Pacific hake) have averaged 22,357 MT resulting in an average annual ex-vessel value of $28.2 million USD (Figure 3). The catch share program was intended to improve the economic efficiency of the fishery, allow full utilization of the species allocations, encourage practices that maximize bycatch, discards, and biological impacts, and hold fishers accountable for their catch impacts

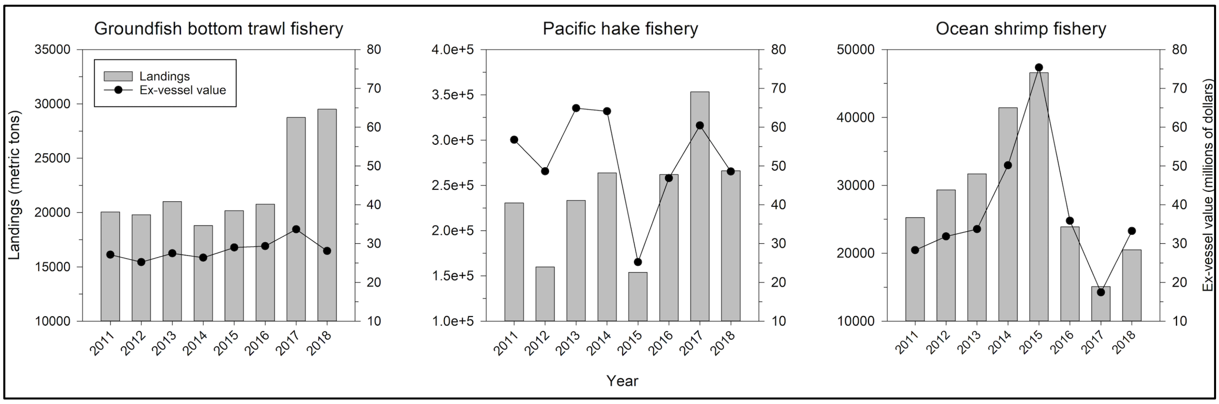


Figure 3. Landings and ex-vessel value (USD) for the groundfish bottom trawl fishery, Pacific hake fishery, and ocean shrimp fishery from 2011 to 2018. Data source: PacFIN (2019).

on bycatch species. Catch accountability has encouraged fishers to fish more selectively to improve the composition of their catches of IFQ species. However, catches of stocks with restrictive harvest limits, prohibited species, and juvenile fishes continue to impact fishers ability to maximize their quota shares of healthier groundfish stocks. This fishery operates year around.

The groundfish bottom trawl fishery can be categorized into two fishery components: 1) a nearshore fishery that occurs over the inner continental shelf (<183 m [100 fathom] bottom contour depth) where fishers target Dover sole (*Microstomus pacificus*), petrale sole (*Eopsetta jordani)*, English sole (*Parophrys vetulus*), Pacific sanddab (*Citharichthys sordidus*), and rex sole (*Glyptocephalus zachirus*), and 2) a fishery that occurs over the continental shelf break and upper slope (>365 m [200 fathom] bottom contour depth) where fishers target Dover sole, shortspine thornyhead (*Sebastolobus alascanus*), longspine thornyhead (*Sebastolobus altivelis*), and sablefish (*Anoplopoma fimbria*, also known as black cod). This fishery is referred to as the Dover sole-thornyhead-sablefish (DTS) complex fishery. In the groundfish bottom trawl fishery, gear modifications such as development of a selective flatfish trawl design (King et al., 2004; Hannah et al., 2005), elevated trawl sweeps (Lomeli et al., 2019), and size-selection characteristics of diamond mesh codends and square mesh codends (Wallace et al., 1996; Perez-Comas et al., 1998) have been tested.

Over the inner continental shelf of the U.S. West Coast, fishers trawling north of 40^{o}10’N latitude and shoreward of 183 m bottom depth have been required to use a two-seam low-rise selective flatfish trawl with a cutback headrope and footrope rubber discs diameter no larger than 20.3 cm (King et al., 2004; Hannah et al., 2005; NOAA, 2014). This trawl design is intended to reduce bycatch of rockfishes (*Sebastes* spp.). The “small footrope” requirement is to deter fishers from trawling over high-relief substrates where overfished and rebuilding rockfishes occur, as trawling over these grounds would damage the footrope. The selective flatfish trawl has shown success at reducing catches of some benthopelagic rockfishes (notably canary rockfish *S. pinniger*, a previously overfished stock recently rebuilt) (King et al., 2004; Hannah et al., 2005; Thorson and Wetzel, 2016). However, catches of rockfishes with restrictive harvest limits (e.g., darkblotched rockfish, *S. crameri*), sablefish, and Pacific halibut often occur that restrict many fishers from fully utilizing their flatfish IFQs. For Pacific halibut, their bycatch is of concern as they are a prohibited trawl species and limited bycatch quota is available to the groundfish fishery. Fishers could reach their Pacific halibut IBQ before reaching their groundfish catch share quotas, thereby ending their fishing season with allowable harvest still left in the ocean unless additional Pacific halibut bycatch quota can be leased or purchased from another quota share permit holder. Acquiring additional quota, however, can be costly and/or difficult to obtain given certain circumstances (i.e. amount of quota needed, time of year, etc.). For sablefish, their quota is needed to harvest Dover sole and thornyheads in the DTS fishery. These complex fishery interactions have affected fishers efforts and opportunities to increase the utilization of their quota shares.

In the DTS complex fishery over the continental shelf break and upper slope, fishers use high-rise trawls outfitted with rockhopper footropes. In this fishery, sablefish are the most economically important species harvested. However, they have become a constraining species in this fishery as their shore-side trawl allocation (3,415 MT) is relatively low when compared to the Dover sole allocation (50,000 MT) (NOAA, 2018). Recent catches of Dover sole (ca. 7,456 MT; PacFIN, 2019) represent only 14.9% attainment of the shore-side trawl allocation, with constraining species such as sablefish as the primary cause. Further, economic utilization of the sablefish ACL has been impacted by catches of juvenile and sub-adult sized sablefish (e.g., sablefish ≤ 1.4 kg and 45 cm in length, which are of lesser economic value). Because most size classes of sablefish are marketable, and fishers are held fully accountable for all IFQ catches whether retained or discarded, fishers retain all sablefish catches regardless of size. These catch constraints have affected fishers ability to achieve: 1) a higher ex-vessel value for sablefish, 2) higher attainment rates of Dover sole, and 3) increased net economic benefits.

1.2. Pacific hake (Merluccius productus) fishery

The Pacific hake (also referred to as Pacific whiting or whiting) midwater trawl fishery is governed through a bilateral agreement between the U.S. and Canada under the Pacific Whiting Treaty. Under this Treaty, 73.88% and 26.12% of the Pacific hake total allowable catch goes to the U.S. and Canada, respectively. The Pacific hake fishery is the largest groundfish fishery by volume off the U.S. West Coast. From 2011-2018, annual landings of Pacific hake have averaged 240,353 MT resulting in an average annual ex-vessel value of $51.9 million USD (Figure 3). Pacific hake are harvested across three sectors: 1) catcher vessels delivering to shore-side processing plants, 2) catcher vessels delivering to at-sea mothership processors, and 3) catcher processor vessels. Each sector receives a proportion of the Pacific hake ACL with the shore-side, mothership, and catcher-processors receiving 42, 24, and 34% of the ACL, respectively. Spatially, this fishery ranges from the Oregon-California border to the USA-Canada border and seaward to depths exceeding 500 m. The fishery operates from 15 May to 31 December.

In this fishery, catches comprise mainly Pacific hake (typically >95% by volume). However, bycatch of Chinook salmon (*Oncorhynchus tshawytscha*) can be an issue affecting the fishery as U.S. Endangered Species Act (ESA) listed Chinook salmon represent a portion of the total Chinook salmon bycatch. Currently, an ESA biological opinion is issued in the West Coast groundfish fishery addressing the potential effects of Chinook salmon bycatch in the Pacific hake fishery (NMFS WCR, 2017). The biological opinion restricts the annual bycatch of Chinook salmon to 11,000 individuals. This number of Chinook salmon is shared across all sectors of the fishery. If this bycatch threshold is exceeded, then conservation measures such as implementing the Ocean Salmon Conservation Zone (OSCZ) may be implemented to protect ESA-listed Chinook salmon. The OSCZ is a zone prohibiting Pacific hake vessels from fishing shoreward of the 183 m depth contour line where increased Chinook salmon bycatch rates typically occur. In 2014, the fishery exceeded the 11,000 Chinook salmon bycatch threshold resulting in the implementation of the OSCZ (NMFS WCR, 2014), which affected the fleet's access to the Pacific hake stock.

In addition to Chinook salmon, bycatch of rockfishes with restrictive harvest limits such as rougheye (*S. aleutianus*), darkblotched, widow (*S. entomelas*), and canary rockfishes, and Pacific ocean perch (*S. alutus*) have often affected fishers access to the Pacific hake resource over fishing grounds where these species co-occur. When rockfishes are present in considerable numbers, fishers are often forced to move to different fishing grounds to avoid exceeding their IFQs for these rockfishes. While moving to different fishing grounds may minimize rockfish bycatch, it can potentially affect fishers catch per unit effort if abundances of Pacific hake are lower and/or are of sizes of lesser marketable value. As ocean distributions of Chinook salmon, rockfishes, and Pacific hake can overlap, interactions between the Pacific hake trawl fishery and Chinook salmon and rockfishes are likely to continue and remain an issue for the fishery.

Hence, developing techniques that minimize bycatch in the Pacific hake fishery are important to fishers, management, and the conservation of ESA-listed Chinook salmon.

1.3. Ocean shrimp (Pandalus jordani) fishery

The ocean shrimp fishery is the second largest trawl fishery by ex-vessel value off the U.S. West Coast (PacFIN, 2019). From 2011 to 2018, annual landings of ocean shrimp averaged 29,222 MT resulting in an average annual ex-vessel value of $38.2 million USD (Figure 3). Otter trawls equipped with small mesh codends (35 mm between knots [BK]) are used to harvest ocean shrimp over soft bottom habitats (Hannah et al., 2013). Spatially, this fishery ranges from central California to the USA-Canada border at depths typically between 75 - 275 m. The fishery operates from 01 April to 31 October. This fishery is managed by the states of California, Oregon, and Washington with each state having jurisdiction of fishing operations for catches delivered to their ports. The mandatory use of rigid sorting grid bycatch reduction devices (BRDs), similar to the Nordmøre grid, with 19.1 mm maximum bar spacings are required off Oregon and Washington to minimize fish bycatch (WDFW, 2017; ODFW, 2018). Prior to this regulation, fishers were using sorting grids with bar spacing ranging from 22.2 to 28.6 mm. Off California, fishers are required to use either a rigid sorting grid BRD with 50.8 mm maximum bar spacings, a soft-panel BRD made of netting no larger than 15.2 cm BK, or a fisheye excluder (CDFW, 2017).

Fish bycatch in the ocean shrimp trawl fishery has been significantly reduced by using sorting grid BRDs (Hannah and Jones, 2007; Hannah et al., 2011). However, bycatch of juvenile groundfishes, such as Pacific hake, rockfishes, and flatfishes, and eulachon (*Thaleichthys pacificus*) and whitebait smelt (*Allosmerus elongatus*) can still occur at considerable levels as these fish can pass through the bar spacings of the BRDs. For eulachon, an anadromous smelt species endemic to the eastern North Pacific, bycatch is of special concern, as the species' southern Distinct Population Segment (DPS) is listed as "threatened" under the U.S. ESA (DOC, 2011; Gustafson et al., 2012). An ESA recovery plan has been implemented to protect and recover the southern DPS of eulachon; however, there are many uncertainties in forecasting their recovery (NMFS, 2017). For Pacific hake, rockfishes, and flatfishes (e.g., Dove sole, English sole), these fishes are of economic importance to the groundfish bottom trawl fishery during their adult life phase. As ocean distributions of eulachon, groundfishes, and ocean shrimp often overlap, interactions between the ocean shrimp fishery and eulachon and groundfishes are likely to continue to be an issue facing the fishery and the conservation of ESA-listed eulachon.

Chapter 2. Objective

Reducing bycatch of constraining species, ESA-listed species, and improving catch composition in eastern North Pacific trawl fisheries is a management priority (PFMC and NMFS, 2011, 2015). Developing techniques that can improve trawl selectivity would be beneficial to fishers (e.g., increase their net economic benefits, and improve their fishing efficiency), coastal communities, and the resource. Thus, the overall objective of this thesis is to *identify, adapt, and test gear modifications that have potential to reduce bycatch and improve catch composition in eastern North Pacific trawl fisheries*.

Chapter 3. Trawl gear modifications to reducing bycatch

In the West Coast groundfish bottom trawl fishery and Pacific hake fishery, fishers are allocated a proportion of the fishery ACL based on their catches during a catch history qualifying period prior to the catch share program, 1994 to 2003. Thus, the proportion of the available ACL for IFQ species is not allocated equally across permit holders. This has resulted in many fishers seeking the use of selective fishing devices (e.g., light-emitting diodes [LEDs], sorting grids, escape windows, etc.) to reduce catches of species with restrictive harvest limits to allow for fuller utilization of their IFQ of target species. In the ocean shrimp fishery, although fishers are required to use sorting grids, bycatch of juvenile groundfishes (e.g., Pacific hake, rockfishes, flatfishes), and eulachon and whitebait smelt can occur at considerable levels as these fish can pass through the bar spacings of the grids. As many fishers participate in each the groundfish bottom trawl fishery, Pacific hake fishery, and ocean shrimp fishery throughout the course of a year, identifying gear modifications that could allow fishers to fish more selectivity would allow fishers to more effectively utilize the fisheries resource and increase their economic benefits.

In the following chapter, trawl gear modifications that could potentially reduce bycatch in eastern North Pacific trawl fisheries are reviewed.

3.1. Sorting grids

Sorting grids (Figure 4) can be effective at reducing bycatch in trawl fisheries when morphological differences occur between the target and bycatch species (Rose and Gauvin, 2000; Sistiaga et al., 2010; Hannah et al., 2011; Lomeli and Wakefield, 2015; Santos et al., 2016a; Larsen et al., 2017). In a bottom trawl targeting aggregated deepwater flatfishes off Alaska, Rose and Gauvin (2000) examined a rigid sorting grid with 15 cm × 15 cm openings and observed a 94% reduction in the incidental catch of Pacific halibut. The overall retention of the targeted species was 68%. In the Barents Sea cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) fishery, Sistiaga et al. (2010) tested a sort-V sorting grid device with 55 mm bar spacings designed to reduce catches of juvenile cod and haddock. Findings demonstrated the sorting device functioned well for both species as over 75% of cod and 94% of haddock were estimated to attempt to exit out the device. In the Baltic cod directed fishery, Santos et al. (2016a) tested a sorting grid device with 38 mm horizontal bar spacing designed to reduce flatfish bycatch (e.g., plaice [*Pleuronectes platessa*], flounder [*Platichthys flesus*]). Results showed bycatch of flatfishes was reduced by ca. 68%, with only a minimal loss of

Figure 4. Example of sorting grid BRDs designed to reduce bycatch of Pacific halibut (top left image) and roundfishes (top right image) in the West Coast groundfish bottom trawl fishery, rockfishes in the Pacific hake fishery (bottom left image), and fish in the ocean shrimp fishery (bottom right image).

marketable-sized cod, 7%. In the West Coast groundfish bottom trawl fishery, where Pacific halibut are typically larger in size than the primary target species (King et al., 2004; Hannah et al., 2005), sorting grid devices could prove effective at reducing their bycatch in both the nearshore and DTS complex fishery. Further, a device similar to the one developed and tested by Santos et al. (2016a), but designed to retain flatfishes and exclude larger-sized roundfishes, could prove effective at reducing darkblotched rockfish and sablefish bycatch in the nearshore flatfish fishery over the inner continental shelf of the eastern North Pacific. Lastly, as most vessels in the West Coast groundfish bottom trawl fishery and Pacific hake fishery are less than 30 m in overall length (except catcher processor vessels in the Pacific hake fishery), have limited deck space, and use net drums, flexible sorting grid devices are likely to be more suitable for use in these fisheries (as opposed to rigid sorting grids which can provide handling difficulties on vessels with restricted deck space or that use net drums for setting and hauling their net).

3.2. Codend mesh size and mesh orientation

Research has demonstrated that diamond mesh configured codends become distorted into a bulbous shape (Figure 5) as tension on the netting increases and catch levels accumulate (Stewart and Robertson, 1985; Wileman et al., 1996). Most fish escapement occurs just ahead of the accumulating catch bulge where a few rows of meshes are more open and unblocked by fishes. Further ahead in the codend the netting is stretched under tension and the meshes tend to be closed or reduced in opening. Thus, reducing the probability that a fish has of escaping out an open mesh. A technique shown to reduce catches of smaller-sized fish is through modifying the mesh size and mesh orientation of the codend (Perez-Comas et al., 1998; He, 2007; Madsen and Valentinsson, 2010). In recent years, use of T90 mesh codends to improve trawl selectivity has increased (Wienbeck et al., 2011, 2014; Madsen et al., 2012; Herrmann et al., 2013a; Tokaç et al., 2014). T90 mesh is conventional diamond mesh that has been turned 90° in configuration (Figure 6). In diamond mesh configuration, the meshes resistance to opening tends to close when the meshes are stretched under longitudinal tension (Herrmann et al., 2007; Madsen et al., 2012). However, rotating the mesh 90° in configuration hinders this mechanism and creates a mesh more open and resistant to closing. Thus, creating increased opportunities for fish escapement (particularly roundfishes) through the meshes. The simple construction of a T90 codend, ease of repair when damaged, and its potential to improve size-selection provides some advantages over other mesh orientations used to enhance codend selectivity, such as knotless square mesh (Perez-comas et al., 1998; He, 2007; Wienbeck et al., 2014). This T90 mesh configuration, originally designed for use in cod fisheries, has gained increased interest in other fisheries such as the Norway lobster (*Nephrops norvegicus*) otter trawl fishery in the Kattegat–Skagerrak area (Madsen et al., 2012) and in the Mediterranean Sea multispecies demersal trawl fishery (Tokaç et al., 2014). Compared to diamond mesh codends with similar mesh sizes, T90 mesh codends have demonstrated the ability to reduce catches of smaller-sized roundfishes (Wienbeck et al., 2011; Herrmann et al., 2013a; Tokaç et al., 2014). In the DTS complex fishery over the continental shelf break and upper slope of the eastern North Pacific, use of T90 mesh codends could have potential to improve catch composition by reducing catches of smaller-sized sablefish relative to Dover sole. If effective, the change in catch composition would allow fishers more opportunities to capitalize on their Dover sole IFQ and increase their net economic benefits while still attaining their quota shares of sablefish and thornyheads.

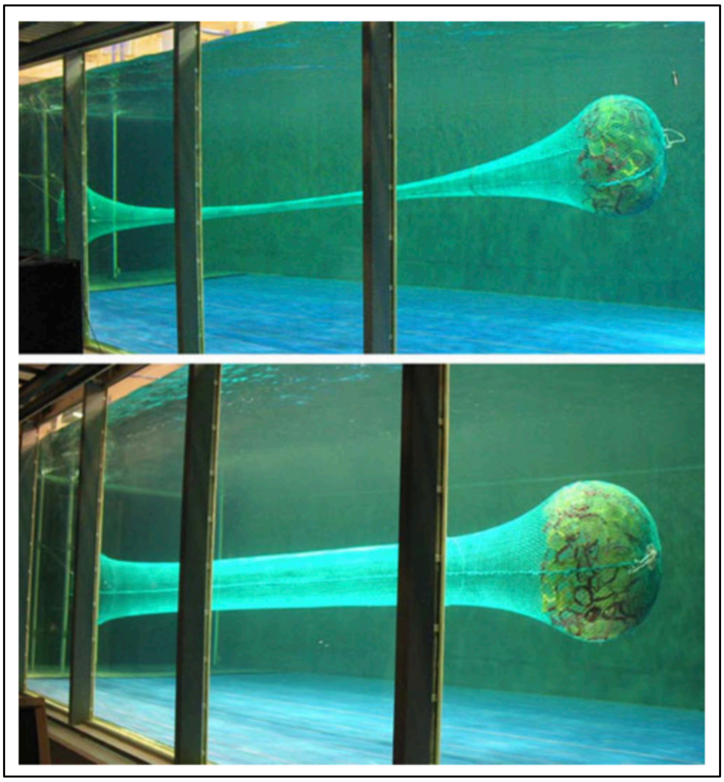


Figure 5. Flume tank model of a diamond mesh configuration codend (top image) and T90 mesh configuration codend (bottom image) stretched under longitudinal tension. Source: Digre et al. (2010).

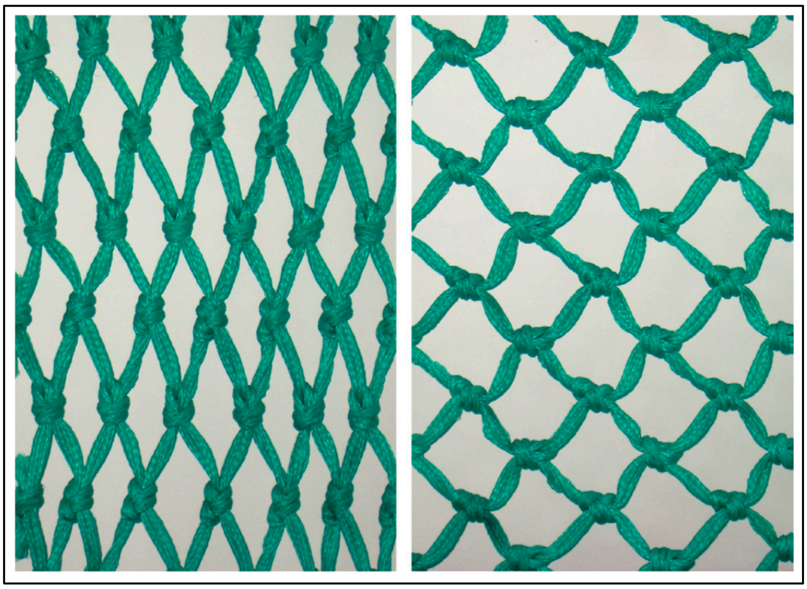


Figure 6. Example of diamond mesh (left image) and T90 mesh (right image) configurations. Source: Herrmann et al. (2007).

3.3. Escape windows

Bycatch reduction devices that consist of escape windows or large mesh openings (Figure 7) can improve trawl selectivity (Grimaldo et al., 2007; Lomeli and Wakefield, 2012; Krag et al., 2014). These BRDs rely upon fishes ability to swim out the escape area to avoid capture, as opposed to sorting grid devices that separate fish physically. In Skagerrak off Northern Denmark, Krag et al. (2014) tested a trawl with a 12 m long section of 800 mm diamond mesh (in the trawls intermediate section) to evaluate the length-based escape behavior of cod, haddock, saithe (*Pollachius virens*), witch flounder (*Glyptocephalus cynoglossus*), and lemon sole (*Microstomus kitt*). Results showed the 800 mm diamond mesh windows significantly reduced the catches of these species over a large range of length classes. In the Gulf of Alaska midwater trawl fishery for walleye pollock (*Gadus chalcogrammus*), a BRD consisting of large escape openings, positioned in the intermediate section of the net, reduced Chinook salmon bycatch by 34–54% (Gauvin et al., 2015). Escapement of walleye Pollock ranged from 1.2-9.8%. Further, in the Pacific hake midwater trawl fishery, initial testing of an open escape window BRD to reduce bycatch of Chinook salmon and rockfishes has occurred (Lomeli and Wakefield, 2012). These studies above suggest there is potential to reduce Chinook salmon bycatch using an open escape window BRD type of design.

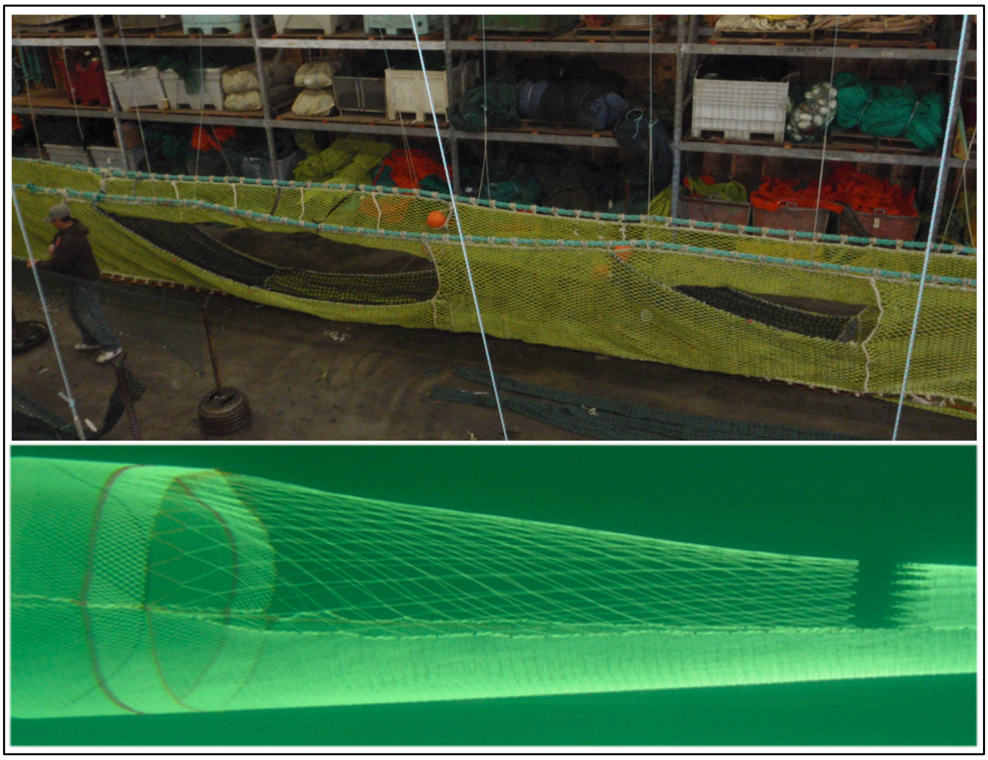


Figure 7. Open escape window BRD designed to reduce Chinook salmon bycatch in the Pacific hake fishery (top image; Source: Lomeli and Wakefield [2012]); example of a large mesh panel BRD (bottom image; Source: Krag et al. [2014]).

3.4. Use of artificial illumination

Research has shown fish encountering trawl gear components respond behaviorally to changes in visual stimuli (Glass and Wardle, 1995; Glass et al., 1995; Ryer and Olla, 2000; Ryer et al., 2010), indicating the potential to use color or artificial illumination (Figure 8) to reduce bycatch. When examining the footrope of a groundfish survey trawl, Weinberg and Munro (1999) found flathead sole (*Hippoglossoides elassodon*) tended to pass under the footrope when artificial illumination was present. Similarly, Rose and Hammond (2014) placed LEDs along an experimental footrope and found escapement rates for southern rocksole (*Lepidopsetta bilinetata*) under the footrope was approximately three times than that of flathead sole and walleye pollock when illumination was present. Further, in the ocean shrimp fishery, Hannah et al. (2015) tested if placing artificial illumination along the fishing line of an ocean shrimp trawl could reduce bycatch of eulachon and juvenile groundfishes by illuminating escape areas near the fishing line. Findings showed eulachon bycatch was reduced by 91% by weight while maintaining ocean shrimp catches. Their work also noted catch reductions of 82% for darkblotched rockfish and 56% for other juvenile rockfishes. These results suggest that use of artificial illumination could have potential bycatch reduction applications in the West Coast groundfish bottom trawl fishery and Pacific hake midwater trawl fishery where darkblotched rockfish, sablefish, Pacific halibut, and Chinook salmon are constraining species.

Figure 8. Images of artificial illumination placed along the fishing line of an ocean shrimp trawl as a technique to reduce fish bycatch. Source: Hannah et al. (2015).

Chapter 4. Specific research questions

Following the review of “Trawl gear modifications to reducing bycatch” in Chapter 3, the subsequent specific research questions for reducing bycatch were formulated for testing in eastern North Pacific trawl fisheries:

i) Can sorting grid devices reduce Pacific halibut bycatch and catches of constraining species in the West Coast groundfish bottom trawl fishery?

ii) Can T90 mesh codends improve catch composition in the DTS complex fishery by reducing catches of juvenile and sub-adult sablefish?

iii) Can use of artificial illumination reduce fish bycatch in eastern North Pacific trawl fisheries? An emphasis on eulachon, Chinook salmon, and constraining groundfishes including Pacific halibut.

Chapter 5. Size selectivity: techniques for collecting and modeling size selectivity data for trawl gear

In this chapter, a general description of size selectivity for trawl gear is presented. First, the concept of trawl size selectivity is described then a description of methods for collecting absolute size selectivity data occurs. Subsequently, a description of models most commonly used to describe absolute size selectivity data for complete trawls or parts of trawl is presented followed by methods for evaluating and estimating model uncertainty. Lastly, methods for collecting and modeling relative size selectivity data between trawls are presented. The focus of this chapter is on sampling methods, and modeling and estimation techniques used in the research papers presented in Chapter 6 of this thesis.

A size-selection process occurs when the size distribution of fish caught in the trawl is different than the size distribution of the population fished (Wileman et al., 1996). Size-selection can be measured for the complete trawl or for specific parts of the trawl (i.e., codend, sorting grids, mesh panels). Across the size distribution of fish being available to enter the trawl, fish of each length (l) class will have a certain probability of being retained by the trawl. In the simplest cases, for example, if the size-selection in question is through codend meshes it will often be well described by an S-shaped size-selection curve with retention probability increasing from 0.0 to 1.0 with fish length. Between the fish of similar size, the retention probability will be affected by factors such as fish morphology, fish condition when attempting to escape, fish orientation when encountering the mesh or selective device, variation in mesh size and openness, and catch rates contributing to the variability in the selection process (Stewart and Robertson, 1985; Wileman et al., 1996; Herrmann, 2005; Grimaldo et al., 2018).

5.1. Methods for collecting absolute size-selection data

Methods for collecting absolute size-selection data fall into two categories: i) covered-gear methods, and ii) paired-gear methods. The covered-gear method can be applied to parts of the trawl such as codends, grids, or mesh panels, while the paired-gear method can be applied to parts of the trawl or the complete trawl. However, examples also exist where the two methods are combined (Larsen et al., 2018).

For the covered-gear method (which includes placing a mesh cover over a selective gear such as a codend, grid, or mesh panel), size selectivity can be estimated by comparing the total number of fish that escaped out the selective device to the population of fish that actually entered the gear (Grimaldo et al., 2008). When using this sampling technique, it is important that the cover is configured correctly so that it does not mask the selective device and hinder fish from escaping out the selective device. When applied to a codend (Figure 9), this technique is termed covered-codend (Wileman et al., 1996; Herrmann et al., 2013a; Wienbeck et al., 2014; Grimaldo et al., 2016, 2018), whereas when it is applied to panels or grids (Figure 10) this technique is termed covered-device (Grimaldo et al., 2015; Lomeli and Wakefield, 2015). The advantages to this sampling technique is that it measures the absolute selectivity of the population fished, provides L_{50} and SR values (described below in section 5.2), can generate a selection curve for single tow data as well as pooled tow data, and relatively limited tows are

Figure 9. Example images from a tow using the covered-codend sampling technique. Covered-codend during haulback at the sea surface (left image); catch retained in the trawl codend (top right image); catch that escaped out the trawl codend and was retained in the cover (bottom right image).

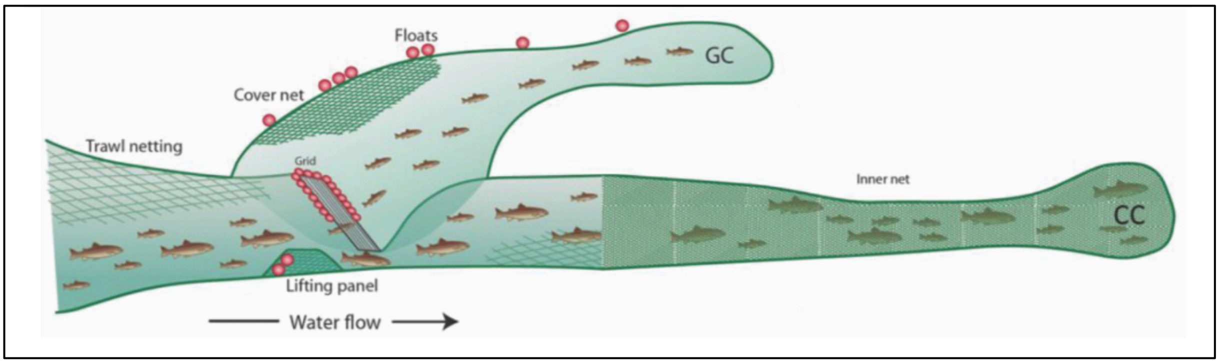


Figure 10. Example image of the covered-gear method applied to a grid. Source: Grimaldo et al. (2016).

needed to achieve high precision size selectivity estimates. The disadvantage of this method is that it can cause handling difficulties when deploying and retrieving, the cover can potentially mask the meshes or escape sections of the selective device being tested and hinder fish escapement, and it may not reflect actual commercial fishing conditions. Of the methods for collecting absolute size-selection data, the covered-gear method is the only technique that can directly estimate the selectivity of the test gear.

Paired-gear methods differ from covered-gear methods in that they compare length-dependent catches between two trawls of equal overall dimensions with one trawl serving as the *treatment* and the other trawl as the *control* (e.g., non-selective trawl). In the *control* trawl, a non-selective small mesh liner (termed blinded codend) occurs within the codend to allow all fish entering the codend to be retained, whereas fish entering the *treatment* trawl may or may not be retained depending on the retention probability of that codend (Figure 11). This allows the size selectivity of the *treatment* trawl to be estimated. Examples of paired-gear methods used to collect size absolute selectivity data include:

- Trouser trawl method: a single trawl that from its extension section aft has been divided into two sections and codends that allow one section to serve as the *treatment* trawl and the other section as the *control* trawl (Grimaldo et al., 2008; Sistiaga et al., 2008).
- Twin trawl method: two trawls are fished from one vessel simultaneously with one serving as the *treatment* trawl and the other as the *control* trawl (Frandsen et al., 2009; Sistiaga et al., 2009).
- Parallel tow method: two vessels fishing parallel to each other with one vessel towing the *treatment* trawl and the other vessel towing the *control* trawl (Holst and Revill, 2009).
- Alternate tow method: *Treatment* and *control* trawls fished separately in an alternate tow order from one vessel (Wileman et al., 1996; Sistiaga et al., 2015).

Advantages of using the paired-gear method is that it eliminates the potential catch bias that can occur when using the covered-gear method, can generate a selection curve for single tow data as well as pooled tow data, and can be used to measure codend selectivity as well as complete gear selectivity. Some disadvantages to this sampling technique is that the population structure of fish encountered by the two trawls may not be equal and an additional parameter (the split parameter, defined below in section 5.3) describing this needs to be estimated, the fishing force of the trawls may not be equal, and it requires a larger number of fish to be caught

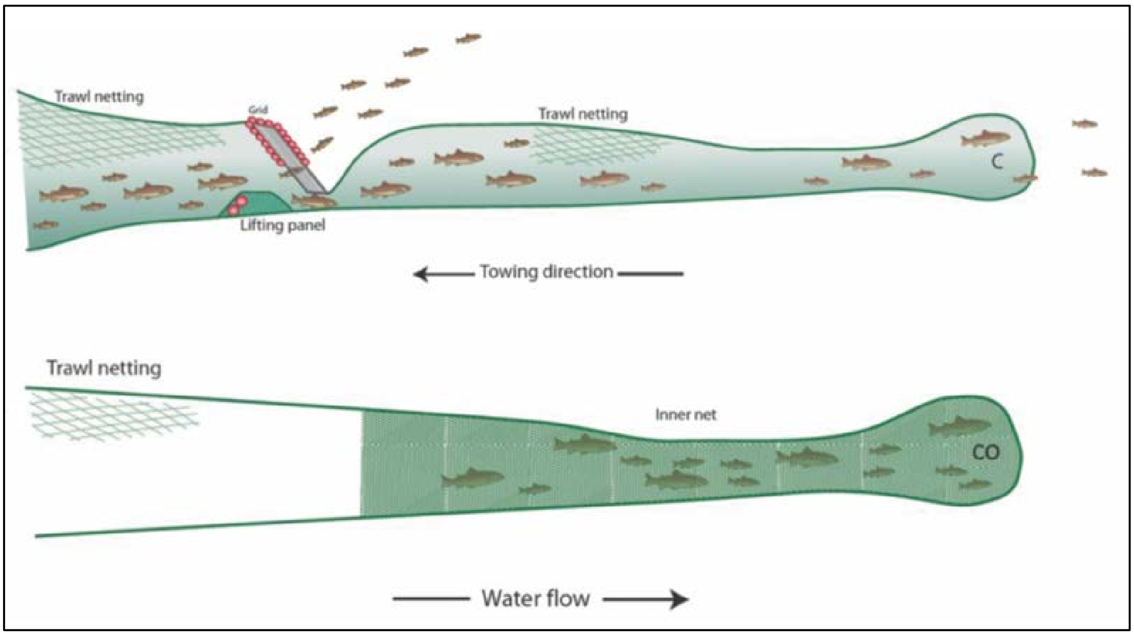


Figure 11. Example of the paired-gear method for collecting absolute size selectivity data. Source: Grimaldo et al. (2016).

and length measured to achieve precision estimates similar to covered-gear methods (Herrmann et al., 2016).

5.2. Common models used to describe size selectivity (absolute size selectivity)

The most used S-shaped size-selection model is the *Logit* model (Wileman et al., 1996):

$$r(l, L_{50}, SR) = \frac{exp(\frac{\ln(9)}{SR} * (l - L_{50}))}{1.0 + exp(\frac{\ln(9)}{SR} * (l - L_{50}))} \quad (1)$$

where L_{50} (length at which a fish has a 50% probability of being retained) and SR (selection range; the length difference between L_{75} and L_{25}) are the size-selection model parameters (Figure 12). The SR parameter defines the steepness (e.g., shape) of the selection curve. The smaller the SR value the steeper the selection curve will be. The steeper the selection curve, the less selective the gear will be across a wider range of lengths compared to a selective device with a higher SR value.

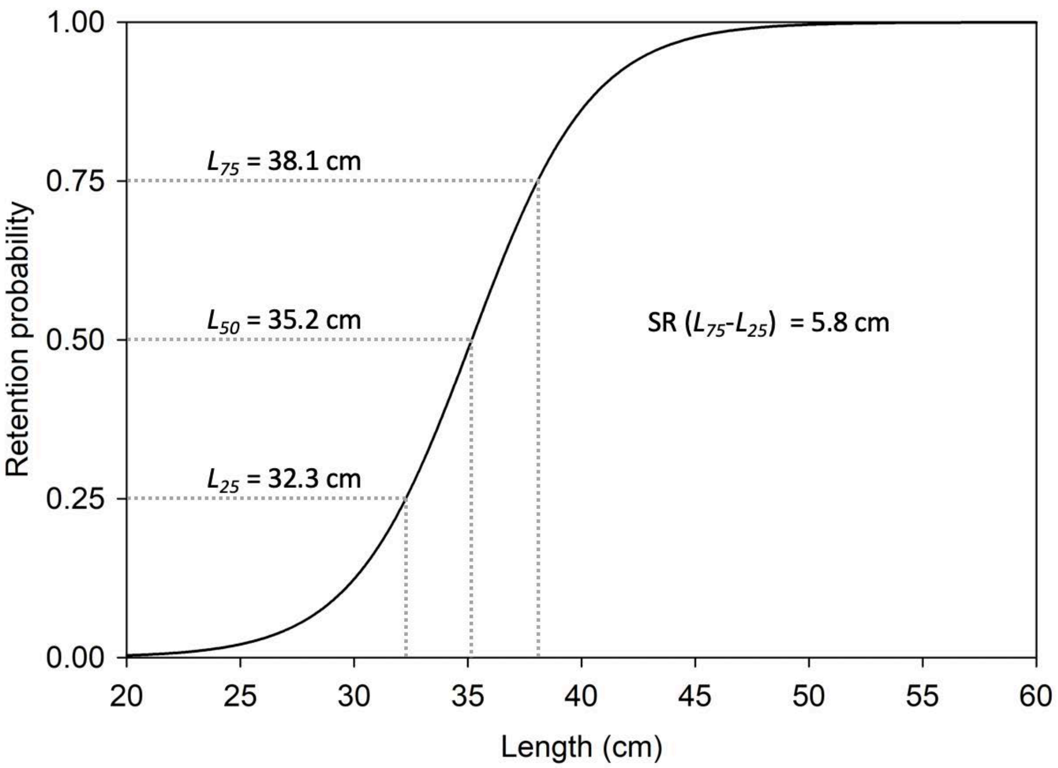


Figure 12. Example of a West Coast groundfish bottom trawl logistic selection curve for Dover sole depicting the model parameters L_{50} and SR from a 114 mm diamond mesh codend. Data source: Paper IV.

However, other simple S-shaped size-selection models are also used (Wileman et al., 1996; Larsen et al., 2019):

$$Probit(l, L_{50}, SR) \approx \Phi\left(1.349\,\frac{(l-L_{50})}{SR}\right) \tag{2}$$

$$Gompertz(l, L_{50}, SR) \approx \exp\left(-\exp\left(-\left(0.3665 + \frac{1.573}{SR}(l - L_{50})\right)\right)\right) \tag{3}$$

The last of the four basic size-selection curves considered here is the *Richards* curve, which has an extra parameter, named *1/δ* (*δ* = Delta). This parameter controls the degree of asymmetry of the curve. When *δ* = 1 the curve simplifies to the *Logit* curve. The equation for a *Richards* size selection curve is the following (Wileman et al., 1996; Larsen et al., 2019):

$$Richards(l, L_{50}, SR, \delta) = \left(\frac{exp\left(logit(0.5^{\delta}) + \left(\frac{logit(0.75^{\delta}) - logit(0.25^{\delta})}{SR}\right) * (l - L_{50})\right)}{1 + exp\left(logit(0.5^{\delta}) + \left(\frac{logit(0.75^{\delta}) - logit(0.25^{\delta})}{SR}\right) * (l - L_{50})\right)}\right)^{1/\delta} \tag{4}$$

Although the above traditional S-shaped size-selection models have been applied in many cases, they are not able to account for size selectivity through devices such as sorting grids or square mesh panels in cases where only a fraction of the fish will contact the device to be size selected by it or in situations where all fish are not subjected to the same size-selection process in a codend. Based on these limitations, more complex models often based on the *Logit* model have been developed. A model that has been developed to better estimate size selectivity of codend meshes in different states of the tow process that can potentially lead to more than one size-selection process contributing to the overall size-selection is the *Double Logit* model, termed the *DLogit* model (Herrmann et al., 2016). For the *DLogit* model, a primary assumption is that a fraction of the fish encountering the codend (C_1) will be exposed to one logistic size-selection process and is described by parameters L_{501} and SR_1, while the remaining fraction (1.0 – C_1) will be exposed to another also logistic size-selection process and is described by parameters L_{502} and SR_2. The overall L_{50} and SR parameters for the *DLogit* model consider both the C_1 value and the 1.0 – C_1 value. The equation for the *DLogit* model is the following:

$$DLogit(l, C_1, L_{50_1}, SR_1, L_{50_2}, SR_2) = C_1 * \; Logit(l, L_{50_1}, SR_1) + (1.0 - C_1) * Logit(l, L_{50_2}, SR_2) \tag{5}$$

A model that has been developed to enable estimating the likelihood that fish entering the zone of a selection device, for example a grid, will contact the device is the *Contact Logit* model. This model is termed the *CLogit* model and accounts for that not necessarily all fish that arrive to the zone of the size sorting device will contact it and be subjected to a fish size dependent probability of passing through the device (Herrmann et al., 2013b). If for example the device is a sorting grid, then the *CLogit* model is described by the selection parameters L_{50grid} (length at which a fish has a 50% probability of contacting and passing through the grid), SR_{grid} (= L_{75grid} – L_{25grid}), and C_{grid} (grid contact probability). In this model, C_{grid} values range from $0 \leq C_{grid} \leq 1.0$, with $C_{grid} = 1.0$ meaning all fish contacted the grid and attempted to pass through. The equation for the *CLogit* model is the following:

$$r\left(l, C_{grid}, L_{50_{grid}}, SR_{grid}\right) = CLogit\left(l, C_{grid}, L_{50_{grid}}, SR_{grid}\right) = C_{grid} * \left(1.0 - Logit\left(l, L_{50_{grid}}, SR_{grid}\right)\right) = \frac{C_{grid}}{exp\left(\frac{\ln(9)}{SR_{grid}} * \left(l - L_{50_{grid}}\right)\right)} \tag{6}$$

CLogit models have also often been used to model size-selection for escape panels (Zuur et al., 2001; O'Neill et al., 2006; Santos et al., 2016b; Brčić et al., 2016; Krag et al., 2017; Herrmann et al., 2018).

5.3. Methods for estimating absolute size selectivity data

When fitting selection curves to covered-codend data, five models are commonly used. The five models are *Logit*, *Probit*, *Gompertz*, *Richards*, and *DLogit*. The functional forms for these models are presented above in equations 1-5 with the model parameters estimated using a Maximum Likelihood Estimation (MLE) approach to the data. Depending on the study objective, the model parameters can be estimated from single tow data or multi-tow data (e.g., data pooled across all tows). For estimating the selection parameters $\mathbf{v}$, in the simplest case $\mathbf{v} = (L_{50}, \mathrm{SR})$, on single tow data, the following MLE approach would be used:

$$-\sum_l \left\{ \frac{nc_l}{qc} * \ln\big(r(l,\mathbf{v})\big) + \frac{ncc_l}{qcc} * \ln\,(1.0 - r(l,\mathbf{v}))\right\} \tag{7}$$

where nc_l and ncc_l are the number of fish in length class l for the codend and gear cover, respectively. Parameters qc and qcc are the related subsampling factors (fraction of the catch length measured) for the codend and gear cover, respectively. However, when estimating $\mathbf{v}$ on pooled data across m tows, the MLE approach to use would be:

$$-\sum_l \sum_{i=1}^{m} \left\{ \frac{nc_{li}}{qc_i} * \ln(r(l,\mathbf{v}) + \frac{ncc_{li}}{qcc_i} * \ln(1.0 - r(l,\mathbf{v})\right\} \tag{8}$$

where nc_{li} and ncc_{li} are the number of fish in length class l measured in the tow i for the codend and gear cover, respectively. Parameters qc_i and qcc_i are the related subsampling factors. The MLE approach is a method used to determine values for the model parameters that maximize the likelihood that the process described by the model makes the observed experimental data most likely. By simply adding a minus sign in front of the equation, the maximization problem becomes a minimization problem. The natural logarithm is also applied to the equation to simplify the minimization process. When using the covered-gear method to model the size selectivity characteristics of sorting grids or mesh panels, the *CLogit* model is utilized. This model estimates L_{50}, and SR as well, but in terms of contact probability and passage through the selective device. The *CLogit* model is presented above in equation 6. For the *CLogit* model, the parameter vector $\mathbf{v}$ to estimate by MLE consist of L_{50}, SR and C.

When fitting selection curves to paired-gear data, the SELECT (Share Each Lengths Catch Total) model is commonly used and is defined as (Millar, 1992; Millar and Walsh, 1992; Wileman et al., 1996; Sistiaga et al., 2008, 2009):

$$ø(l) = \frac{SP * r(l,\mathbf{v})}{(1.0 - SP) + SP * r(l,\mathbf{v})} \tag{9}$$

where ø is the conditional probability for a fish of length *l* to be retained in the *treatment* trawl. The *ø(l)* function is described by the estimated retention rate at length *r(l)* and the split parameter *SP*. Further, the *ø(l)* function is non-decreasing and ranges from 0.0 to *SP*. The split parameter *SP* quantifies the proportion of fish entering the *treatment* trawl compared to the *control* trawl (e.g., a measure of the fishing power of the test gear). For estimating the selectivity parameters L_{50}, SR, and *SP* on data pooled over *m* tows in the estimation process, the following MLE function would be minimized:

$$-\sum_l \sum_{i=1}^{m} \left\{ \frac{nc_{li}}{qc_i} * \ln\left(\frac{SP * r(l,\mathbf{v})}{SP * r(l,\mathbf{v}) + (1.0 - SP)}\right) + \frac{ncc_{li}}{qcc_i} * \ln\left(\frac{(1.0 - SP)}{SP * r(l,\mathbf{v}) + (1.0 - SP)}\right) \right\} \tag{10}$$

This function also needs an average split parameter value to be estimated.

5.4. Model evaluation and estimation of uncertainty for size selectivity data

When applying models to describe size selectivity data, it is critical that an inspection occur to assure the models being examined can describe the experimental data sufficiently well. The ability of a model to describe the experimental data can be evaluated based on the *p*-value, which quantifies the probability of obtaining by coincidence at least as big a discrepancy between the experimental data and the model as observed, assuming that the model is correct. Therefore, this *p*-value, which is calculated based on the model deviance and the degrees of freedom, should be >0.05 (more than 5% probability for that the observed deviation between data and modeled size-selection curve is a coincidence). If the fit statistics are $p<0.05$ and/or deviances are greater than two times the degrees of freedom, then further data inspection is needed to determine if it is due to overdispersion of the data or the inability of the model to adequately describe the data (McCullagh and Nelder, 1989). Among the models with acceptable fit statistics, the model with the lowest Akaike information criterion (Akaike, 1974) value is selected as the best model to describe the experimental data.

When pooling tow data (e.g., equations 8, 10), a double bootstrapping method that accounts for both within tow and between tow variation (Fryer, 1991) is often used to provide uncertainty estimates around the mean selection parameters and for the selection curve (Millar, 1993; Herrmann et al., 2012). The uncertainty estimates are most often given as Efron percentile 95% confidence intervals (CIs; Efron, 1982). The double bootstrapping method accounts for uncertainty due to between tow variation by selecting *m* tows with replacement from the *m* tows available during each bootstrap repetition. Within each resampled tow, the data for each length class are resampled in an inner bootstrap to account for the uncertainty in the tow due to a finite number of fish being caught and length measured in the tow. While using the double bootstrapping method that incorporate both uncertainty from individual tows and between tows is often used in estimating uncertainty for fishing gear size selectivity, it is also possible to explicit account for between tow variation by the method described by Fryer (1991).

5.5. Methods for collecting relative size-selection data (catch comparison and catch ratio)

Catch comparison and catch ratio methods are used to provide a direct comparison on the length distribution of catches between two different fishing gears (Sistiaga et al., 2015; Santos et al., 2016a; Lomeli et al., 2019). The paired-gear method can be considered as a special case of the catch comparison method as one trawl servers as a *control* and other as the *treatment*. However, because this method does not use a non-selective *control* trawl, it can only estimate the relative selectivity of the fishing gear tested as the size structure of the population fished is not measured. The main advantages to the catch comparison method is that it can provide a length-dependent catch comparison and catch ratio between two different fishing gears and can quantify the magnitude of difference, and can be easily applied under commercial fishing conditions. Further, the catch comparison method can be applied to paired (Santos et al., 2016a; Brinkhof et al., 2019; Grimaldo et al., 2019) and unpaired tow data sets (Sistiaga et al., 2015; Notti et al., 2016; Lomeli et al., 2019), and provide a fisheries selection curve for how the gear would perform under normal fishing conditions. The disadvantages to this method is that it cannot estimate a size-selection curve, the size selectivity of the gear tested can only be measured relative to the gear included in the test, and large numbers of fish are needed to attain narrow CIs around the mean curve.

5.6. Methods for estimating relative size selectivity data (catch comparison and catch ratio)

When using the catch comparison method to assess the relative length-dependent catch efficiency effect between two trawls, the following catch comparison (CC_l) model is used:

$$CC_l = \frac{\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j}+\frac{nc_{lj}}{qc_j}\right\}} \tag{11}$$

where nc_{lj} and nt_{lj} are the numbers of a given fish species measured in each length class l for the *control* and *treatment* trawl in tow i and j, respectively. Parameters qc_j and qt_j are the related subsampling factors and m is the number of tows carried out with the *control* and *treatment* trawl, respectively. The functional form of the catch comparison rate $CC(l,\boldsymbol{v})$ (the experimental being expressed by equation 11) can be obtained using MLE by minimizing the following equation:

$$-\sum_l\left\{\sum_{j=1}^{m}\left\{\frac{nc_{lj}}{qc_j} * \ln[1.0 - CC(l,\boldsymbol{v})]\right\} + \sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j} * \ln[CC(l,\boldsymbol{v})]\right\}\right\} \tag{12}$$

where $\boldsymbol{v}$ represents the parameters describing the catch comparison curve defined by $CC(l,\boldsymbol{v})$. The outer summation in the equation is the summation over the length classes l. When the catch efficiency of the *control* and *treatment* trawls are equal, the expected value for the summed catch comparison rate would be 0.5. Therefore, this baseline can be applied to judge if there is a difference in catch efficiency between the two trawls. The experimental CC_l can then be modeled by the function $CC(l,\boldsymbol{v})$, on the following form:

$$CC(l,\boldsymbol{v}) = \frac{exp[f(l,v_0,\ldots,v_k)]}{1+exp[f(l,v_0,\ldots,v_k)]} \tag{13}$$

where f is a polynomial of order k with coefficients v_0 to v_k. Based on the estimated catch comparison function $CC(l,\boldsymbol{v})$, the relative catch ratio $CR(l,\boldsymbol{v})$ between fishing with the two trawls can be obtained by the general relationship (Herrmann et al., 2017):

$$CR(l,\boldsymbol{v}) = \frac{CC(l,\boldsymbol{v})}{[1-CC(l,\boldsymbol{v})]} \tag{14}$$

The catch ratio provides a direct relative value of the catch efficiency between the two fishing gears. Thus, if the catch efficiency of both trawls is equal, $CR(l,\boldsymbol{v})$ should always be 1.0. If $CR(l,\boldsymbol{v}) = 1.5$, then it would mean that the *treatment* trawl is catching on average 50% more of a given species with length l than the *control* trawl. In contrast, $CR(l,\boldsymbol{v}) = 0.8$ would mean that the treatment trawl is only catching 80% of a given species of fish with length l that the control trawl is catching.

A length-integrated average value for the catch ratio can also be estimated directly from the experimental catch data by:

$$CR_{average} = \frac{\sum_l \sum_{j=1}^{m} \left\{ \frac{nt_{lj}}{qt_j} \right\}}{\sum_l \sum_{j=1}^{m} \left\{ \frac{nc_{lj}}{qc_{ij}} \right\}} \tag{15}$$

where the outer summation covers the length classes in the catch during the experimental fishing period.

Based on equation 15, the percentage change in average catch efficiency between fishing with the *control* trawl to the *treatment* trawl can be estimated by:

$$\Delta CR_{average} = 100 * \left(CR_{average} - 1.0 \right) \tag{16}$$

The $\Delta CR_{average}$ provides a length-averaged value for the effect of changing from *control* to *treatment* trawl on the catch efficiency. When the percent change in catch efficiency of both trawls is equal, the expected value would be zero. In contrast to the length-dependent evaluation of the catch ratio, $\Delta CR_{average}$ is specific to the size classes encountered during the experimental sea trials.

Likewise for estimation of absolute size selectivity uncertainty for the catch comparison and catch ratio curves can be obtained by the double bootstrap method described above.

Chapter 6. Trawl selectivity studies in eastern North Pacific trawl fisheries

In this chapter, recent trawl selectivity studies conducted in eastern North Pacific trawl fisheries are presented. Papers I -V present findings from studies in the West Coast groundfish bottom trawl fishery evaluating the efficacy of sorting grids to reduce bycatch (Papers I-III), T90 mesh codends to improve catch composition (Paper IV), and artificial illumination to improve trawl selectivity (Paper V). In the ocean shrimp fishery (Papers VI-VII) and Pacific hake fishery (Paper VIII), results from research examining the effectiveness of artificial illumination to reduce bycatch of ESA-listed species and groundfishes are reported. Prior to the studies presented in this chapter, trawl selectivity research in eastern North Pacific fisheries has been limited to diamond mesh and square mesh codend selectivity studies (Wallace et al., 1996; Perez-Comas et al., 1998), testing of a low-rise flatfish trawl design for the groundfish bottom trawl fishery (King et al., 2004; Hannah et al., 2005), development of sorting devices for the ocean shrimp trawl fishery (Hannah and Jones, 2007; Hannah et al., 2011), and evaluating the efficacy of an open escape window BRD for the Pacific hake fishery (Lomeli and Wakefield, 2012).

6.1. Testing of sorting grid devices

When morphological differences occur between target and bycatch species, sorting grid devices can be used to reduce bycatch. However, for selective fishing devices (e.g., sorting grids, mesh panels, codends) to be effective, the probability of fish contacting the gear must be high. Methods to increase contact probabilities have included deflector/guiding devices (Santos et al., 2016a; Papers I-III), lifting panels (Grimaldo et al., 2015), ropes (Papers II and III), and artificial illumination (Grimaldo et al., 2018). Papers I-III report on the testing of sorting grid BRDs in the West Coast groundfish bottom trawl fishery. Paper I specifically addresses Pacific halibut bycatch for fishers targeting assemblages of flatfishes and roundfishes, whereas Papers II and III address bycatch of both Pacific halibut and roundfishes for fishers directly targeting flatfishes.

6.1.1. Examining a sorting grid device for Pacific halibut (Paper I)

The research presented in Paper I reports on the testing of a sorting grid BRD designed to reduce Pacific halibut bycatch for fishers targeting assemblages of roundfishes (e.g., sablefish, lingcod [*Ophiodon elongatus*]) and flatfishes (e.g., Dover sole, petrale sole) in the

West Coast groundfish bottom trawl fishery. In the groundfish bottom trawl fishery, Pacific halibut bycatch quota is relatively limited and can affect fishers ability to fully utilize their catch shares of healthier groundfish stocks. Upon implementation of the Pacific Coast Groundfish Fishery Trawl Rationalization Program in 2011, fishers became individually accountable for Pacific halibut bycatch. This resulted in fishers experimenting with BRDs. Under mandate of the International Pacific Halibut Commission (IPHC), the retention of trawl-caught Pacific halibut is prohibited and Pacific halibut must be discarded. In the catch share program, each Pacific halibut is assessed by an at-sea observer and assigned to a viability category of excellent, poor, or dead following IPHC (Williams and Chen, 2004) and West Coast Groundfish Observer Program protocols (NWFSC, 2010). From this assessment, a percent mortality by weight is calculated and then deducted from the fishers IBQ. The IPHC has estimated mortality rates for trawl-caught Pacific halibut discarded at sea in excellent, poor, and dead condition at 20%, 55%, and 90%, respectively (Hoag, 1975; Clark et al., 1992; Williams and Chen, 2004). For example, a 15 kg Pacific halibut categorized as poor would result in 8.25 kg (15 kg x 55% mortality estimate) of quota deducted from the fishers IBQ. Hence, reducing the incidental catch of larger-sized Pacific halibut is important to fishers as larger-sized fish can have a greater impact on their IBQ level.

The goal of Paper I was:

i) Provide fishers a scientific assessment of a Pacific halibut sorting grid BRD and evaluate its potential efficacy in the West Coast groundfish bottom trawl fishery.

The design tested in Paper I utilizes two vertical panels (grids) of 19.1 cm × 19.1 cm openings to crowd fish and direct large fish toward a downward-angled exit ramp (Figure 13). The concept of this design is that fish smaller than the panel openings can pass through the vertical panels and move aft toward the codend, whereas fish larger than the panel openings will be excluded. In this research, fish retention (% by weight) was quantified using a recapture net (e.g., a covered-gear sampling method), while non-parametric tests were used to compare mean length values between the recapture net and trawl codend. Following Holst and Revill (2009), a generalized linear mixed model, using a logit-linear model, was applied to examine if retention was length-related. The results presented in Paper I show the Pacific halibut BRD evaluated reduced their overall mean bycatch by 61.6% by weight and 57% by numbers. Bycatch reduction was highest for fish larger than 72 cm in length and ca. 4.5 kg in weight. The mean retention of marketable-sized flatfishes ranged from 76.7 to 86.5% by weight, whereas the mean retention of marketable-sized roundfishes ranged from 82.9 to 89.3% by weight.

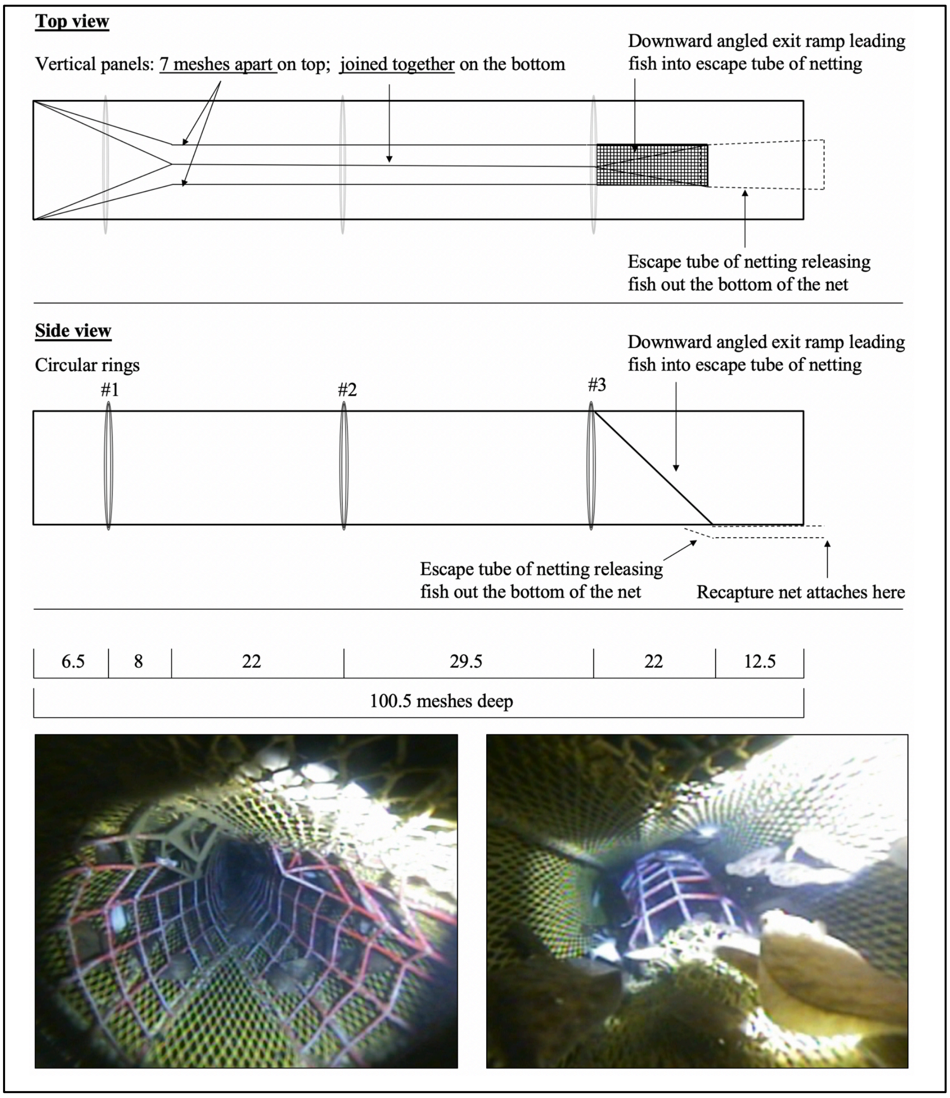


Figure 13. Schematic diagram of the Pacific halibut sorting grid BRD tested in Paper I (top); aft view of the forward portion of the excluder where fish enter and encounter the device (bottom left); forward view of the downward-angled exit ramp with fish moving aft toward the codend (bottom right). Source: Paper I.

Overall, 83% by weight of the marketable-sized fish encountered were retained in the codend. Findings from this paper demonstrate that the BRD examined could prove useful for allowing fishers to harvest assemblages of roundfishes and flatfishes on fishing grounds where Pacific halibut co-occur.

As a result of Paper I, fishers have been provided with an option of using a more selective trawl that could provide access to productive groundfish stocks while minimizing Pacific halibut bycatch. This study has contributed to the design and development of successive Pacific halibut excluders for use in West Coast and Alaska bottom trawl fisheries (Sara Skamser, Foulweather Trawl LLC., Newport, OR, personal communication). Further, Paper I was the first study to provide scientific based measurements of a Pacific halibut sorting grid BRD in the West Coast groundfish bottom trawl fishery. Lastly, results from this paper demonstrated the capability of a sorting grid BRD to reduce Pacific halibut bycatch in the groundfish bottom trawl fishery while retaining a relatively high proportion of the targeted species.

Paper I has addressed research question number i) in Chapter 4 of this thesis.

6.1.2. Testing of a selective flatfish sorting grid device (Papers II, III)

Over the continental shelf of the U.S. West Coast, several economically important flatfish stocks (e.g., Dover sole, petrale sole, English sole) occur in healthy abundances. However, many fishers ability to fully utilize their flatfish IFQs have been constrained by fishes with restrictive catch limits such as darkblotched rockfish, sablefish, and Pacific halibut. Thus, identifying gear modifications that can minimize bycatch, while allowing fishers access to target species, would be beneficial to fishers, managers, and the resource.

Building off the pilot study conducted by Lomeli and Wakefield (2015), Paper II reports on the size-selection parameters of a novel selective flatfish sorting grid device designed to retain flatfishes while minimizing catches of larger-sized roundfishes and Pacific halibut. The goals of Paper II were:

i) Model the size-selection of the BRD developed by Lomeli and Wakefield (2015) for roundfishes, Pacific halibut, and target flatfishes
ii) Evaluate the gears efficacy to retain flatfishes while minimizing catches of larger-sized roundfishes and Pacific halibut

The BRD design tested in this study utilizes two vertical panels with 4.4 x 21.6 cm elongated slot openings that extend longitudinally down a section of netting (Figure 14). The concept to the design (and in the subsequent Paper III) is the same as in Paper I, in that fish smaller than the grid openings can pass through and move aft toward the codend, while fish that do not pass through are excluded out the BRD. A recapture net was used to capture fish exiting out the BRD and allowed for the following analysis to occur. The *CLogit* model presented in equation 6 in section 5.2 of this thesis was used in Paper II to quantify the length-dependent sorting efficiency of the BRD. To account for both within-tow and between-tow variation, a double bootstrap method, as described in section 5.4, was used to estimate the Efron percentile 95% CIs for the mean selectivity curves (Efron, 1982). In this paper, results demonstrate the ability of the sorting grid device to separate flatfishes from larger-sized roundfishes and Pacific halibut. The *CLogit* model showed significant differences in the selectivity parameter L_{50grid} with roundfishes and Pacific halibut having a steeper selection

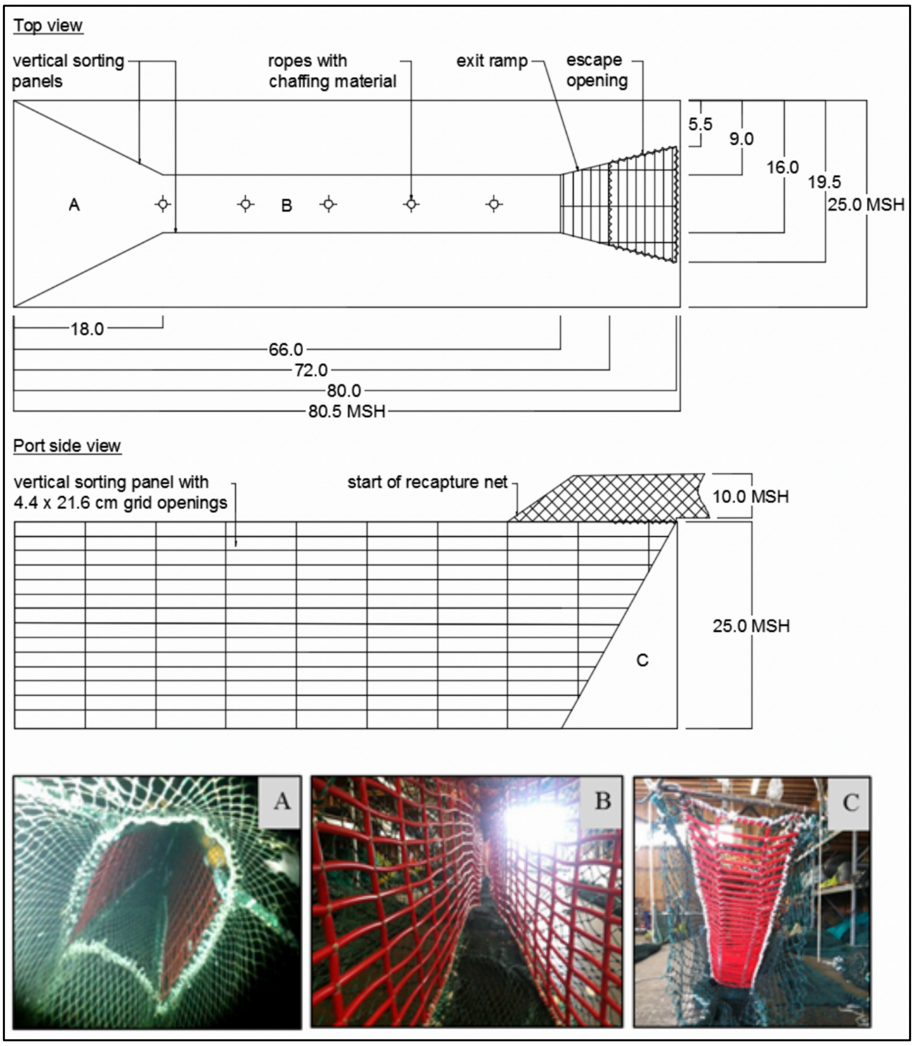


Figure 14. Schematic diagram of the sorting grid tested in Paper II (top); aft view of the forward portion of the gear where fish enter and encounter the device (image A); aft view from inside of the BRD (image B); fore view of the upward-angled exit ramp (image C). MSH = meshes. Note: schematic diagram is not drawn to scale. Source: Paper II.

curve and a significantly lower probability of passing through the grid systems than target flatfishes. The overall mean codend retention of flatfishes was 85% by weight and ranged from 68 to 92%. Mean codend catches of roundfishes and Pacific halibut were reduced by over 64 and 90% by weight, respectively.

Various video footage collected during this study can be viewed at: http://www.psmfc.org/bycatch/videos.html.

Although positive results were achieved in Paper II, it was noted that improvements in the BRD’s ability to retain flatfishes (particularly larger-sized fish with higher economical value) were desired to enhance the gear’s effectiveness in the fishery. Therefore, the objectives of Paper III were:

i) Examine the size-selection characteristics of two alternative sorting grid sizes

ii) Evaluate the alternative sorting grids ability to further improve flatfish retention (relative to Paper II) while reducing the catches of non-target species

The difference between the sorting grids tested in Paper III are the length of the grid openings. The two grids tested were 6.4 cm high × 25.4 cm long (BRD-1) and 6.4 cm high × 30.5 cm long (BRD-2). Compared to the grid tested in Paper I, the grids examined in Paper III were ca. 71% and 105% larger in area, respectively. As in Paper II, a recapture net was used to collect fish exiting out the BRD and the *CLogit* model was applied to the catch data to quantify the length-dependent sorting efficiency of the BRDs tested. To determine if the mean selectivity curves differed significantly between the two BRDs for a given species, the Efron percentile bootstrap 95% CIs were examined for a lack of overlap. If the 95% CIs overlapped, the value was determined non-significant. In this study, the *CLogit* model adequately described the experimental data for the species evaluated between the two BRDs tested. The study found the size-selection for roundfishes and Pacific halibut did not differ significantly between the two BRDs, with each BRD reducing catches of non-target species substantially. The size selectivity for arrowtooth flounder (*Atheresthes stomias*), Dover sole, and petrale sole differed significantly between the two BRDs across some length classes with BRD-1 retaining a higher proportion of these flatfishes than BRD-2. Overall, the mean retention (by weight) of target flatfishes was 89.3% (95% CI = 87.1–91.5%) for BRD-1 and 81.7% (95% CI = 80.0–83.4%) for BRD-2. Compared to findings presented in Paper II, the BRD-1 tested in this study increased the overall mean retention of flatfishes, by ca. 4% by weight. This increase in mean retention was significant. More importantly, the improvement in flatfish retention were of large-sized fishes; which are of higher economical value.

Results from Papers II and III present fishers and managers quantitative results on a novel design that can separate flatfishes from roundfishes and larger-sized Pacific halibut. Over the continental shelf of the West Coast, the attainment of the ACL for many flatfishes has not been fully attained due catches of roundfishes with restrictive harvest limits and Pacific halibut bycatch. Papers II and III collectively contribute to improving trawl selectivity in the West Coast groundfish bottom trawl fishery and have provided fishers a selective option for harvesting flatfishes.

Papers II and III have addressed research question number i) in Chapter 4 of this thesis.

6.2. Modifying codend mesh size and mesh orientation (Paper IV)

Catch accountability has encouraged fishers to fish more selectively to improve the utilization of their catches of IFQ species in the West Coast groundfish bottom trawl fishery. However, catches of stocks with restrictive harvest limits, and juvenile fishes continue to impact fishers ability to maximize their quota shares of healthier groundfish stocks. In the DTS complex fishery, sablefish are the most economically important species harvested. However, their available shore-side trawl allocation (3,415 MT) has constrained fishers from fully utilizing the available Dover sole shore-side trawl allocation (50,000 MT) (NOAA, 2018). Over the past several years, the percentage of the Dover sole allocation attained has been ca. 13-14% (PacFIN, 2019), with constraining species such as sablefish as the primary cause. Further, catches of juvenile and sub-adult sablefish (e.g., sablefish ≤ 1.4 kg and 45 cm in length) are affecting fishers economic utilization of the sablefish ACL as smaller-sized sablefish receive lower ex-vessel prices than larger-size sablefish.

Modifications to codend mesh size and configuration can improve trawl selectivity (He, 2007; Madsen and Valentinsson, 2010; Wienbeck et al., 2014). In the groundfish bottom trawl fishery, the traditional codend mesh configuration is diamond due to its convenience of construction and repair, and its relatively low price of acquisition compared to other mesh configurations such as knotless square mesh. However, use of diamond mesh codends can adversely affect size selectivity as the meshes tend to close when stretched by drag forces (Stewart and Robertson, 1985; Wileman et al., 1996; Figure 5). It is just ahead of the accumulating catch bulge where a few rows of meshes are open that most fish escapement is noted to occur. Thus, fishers seeking to improve trawl selectivity through codend mesh modifications are likely to achieve better results using mesh configurations other than diamond. A codend mesh configuration that has demonstrated the ability to enhance codend selectivity over diamond mesh, particularly for roundfishes, is T90 mesh (Wienbeck et al., 2011; Herrmann et al., 2013a; Tokaç et al., 2014). The goals of Paper IV were:

i) Compare the size-selection characteristics of nominal 114 mm and 140 mm T90 mesh codends and the traditional 114 mm diamond mesh codend

ii) Evaluate the efficacy of T90 mesh to improve catch composition in the DTS complex fishery

In Paper IV, size-selection curves and mean L_{50} and SR values were estimated for shortspine thornyhead, sablefish, rex sole, and Dover sole. Codend selectivity was measured using the covered-coded method as described above in section 5.1. The five models most commonly used for fitting selection curves to covered-codend data (*Logit*, *Probit*, *Gompertz*, *Richards*, and *DLogit*; refer to section 5.2 and 5.3 for model details) were considered for estimating the average size-selection properties for each species and each type of codend. To determine whether the selectivity curves for a given species differed significantly between any two of the three codend types, the *p*-value was calculated as the number of times out of the 1 million pairs of bootstrap L_{50} values that the L_{50} for net A was less than the L_{50} for net B. For a two-sided test (with $\alpha = 0.05$), if this value was less than 25,000 (2.5%), then the difference was deemed significant.

The results presented in Paper IV show the mean L_{50} values for rex sole and Dover sole were significantly smaller in the 114 mm T90 codend than the 114 mm diamond codend. For shortspine thornyhead and sablefish, their mean L_{50} values were smaller in the 114 mm diamond codend than the 114 mm T90 codend. For the 140 mm T90 codend, the selectivity values for rex sole, Dover sole, and shortspine thornyhead were significantly different from those of the 114 mm diamond and 114 mm T90 codends. The mean L_{50} value for sablefish was largest in the 140 mm T90 codend, and that mean was significantly different from the mean L_{50} associated with the 114 mm diamond codend, but not from the mean obtained with the 114 mm T90 codend. For rex sole, Dover sole, and shortspine thornyhead, the 114 mm and 140 mm T90 codends displayed narrower and steeper selection curves than the diamond codend. The 140 mm T90 codend was most effective at reducing catches of smaller-sized fish, however, experienced a considerable loss of marketable-sized fish. These findings of smaller mean L_{50} values for flatfishes, but larger mean L_{50} values for roundfishes occurring in the 114 mm T90 codend relative to those in the 114 mm diamond codend are similar to previous studies that have compared diamond codends to T90 codends (Wienbeck et al., 2011; Herrmann et al., 2013a; Tokaç et al., 2014; Bayse et al., 2016) and square-mesh codends (Wallace et al., 1996; Perez-Comas et al., 1998; He, 2007) with similar mesh sizes.

Paper IV is the first study to examine the size-selection characteristics of T90 mesh codends in the West Coast groundfish bottom trawl fishery. Results presented in this paper suggest that T90 codends have potential to improve catch composition in the DTS complex fishery. Improving catch composition in this fishery would allow fishers more opportunities to capitalize on their Dover Sole IFQ and increase their net economic benefits while more effectively attaining their quota shares of sablefish. Prior to this study, codend selectivity research in the West Coast groundfish bottom trawl fishery had focused on diamond mesh and square mesh codends (Wallace et al., 1996; Perez-Comas et al., 1998). Findings from Paper IV have contributed to developing techniques that could provide fishers an opportunity to more effectively utilize the DTS resource. Because of the findings presented in Paper IV, some fishers in this fishery have changed from diamond mesh codends to T90 mesh codends (Figure 15; Sara Skamser, Foulweather Trawl LLC., Newport, OR, personal communication).

Paper IV has addressed research question number ii) in Chapter 4 of this thesis.

Figure 15. Image of a T90 mesh codend manufactured for a U.S. West Coast groundfish bottom trawl vessel.

6.3. Use of artificial illumination as a bycatch reduction technique

Vision is known to play a major role in how fish detect and respond to trawl gear (Glass and Wardle, 1989; Olla et al., 1997, 2000; Kim and Wardle, 1998, 2003; Ryer et al., 2000, 2010; Ryer and Barnett, 2006; Arimoto et al., 2010). It has been demonstrated as ambient light levels decrease towards dark conditions, that many fishes ability to perceive and respond to trawl gear components diminishes (Olla et al., 1997, 2000; Ryer and Barnett, 2006). In trawl fisheries that operate under low ambient light level conditions, techniques such as deflector/guiding devices (Santos et al., 2016a; Papers I-III), lifting panels (Grimaldo et al., 2015), ropes (Papers II and III), and artificial illumination (Papers V-VIII) have been tested in efforts to increase fishes interactions and/or visual perception of BRDs and escape areas.

Use of artificial illumination as a technique to alter fishing gear selectivity has received considerable attention in recent years (Hannah et al., 2015; Grimaldo et al., 2018; Larsen et al., 2017, 2018; ICES, 2018; Melli et al., 2018). Studies have used illumination to enhance fishes abilities to perceive fishing gear components and escape areas, but also in efforts to startle fish towards selective mesh panels. In the Barents Sea demersal trawl fishery, Grimaldo et al. (2018) positioned LEDs on lines with floats in the center of a square mesh section (creating a moving effect of the stimuli and a physical barrier) in efforts to improve the release efficiency for smaller-sized cod and haddock by startling them towards panels of square mesh netting. Findings showed haddock displayed an erratic behavioral response to the illumination and reacted by swimming quickly either towards the square mesh netting or the codend. When interacting with the square mesh netting, however, they were not optimally oriented for escapement. Cod, on the other hand, did not display a noticeable behavioral response to the illumination and continued to move aft towards the codend. In the Skagerrak Sea, Melli et al. (2018) tested if illuminating a horizontally split trawl codend could separate cod, whiting, and plaice from *Nephrops*. Findings showed significant changes in vertical separation occurred in the presence of illumination, however, a species-specific phototactic response was not noted. Off Norway, Larsen et al. (2017, 2018) tested how placing LEDs along the escape exit above a Nordmøre grid and along the base of the grid in a northern prawn (*P. borealis*) trawl could affect bycatch of fishes such as cod, haddock, and redfish (*Sebastes* spp.). They found the addition of illumination near and on the Nordmøre grid had no significant result on fish bycatch. In eastern North Pacific trawl fisheries, several studies evaluating the efficacy of artificial illumination as a technique to reduce fish bycatch have occurred (Hannah et al., 2015; Papers V-VIII). In Papers V-VIII, results are presented from studies in the eastern North Pacific trawl fisheries where trials testing the efficacy of artificial illumination to reduce fish bycatch were conducted.

6.3.1. Groundfish bottom trawl fishery – constraining species catches (Paper V)

In the groundfish bottom trawl fishery, trawlers fishing shoreward of 183 m bottom depth and north of 40°10′N latitude are required to use a two-seam low-rise selective flatfish trawl designed to minimize bycatch of overfished and rebuilding rockfishes when targeting flatfishes (NOAA, 2014). This trawl exhibits a headrope that is ca. 30% longer in length than the footrope and is intended to allow species that tend to rise of bottom when encountered by the footrope an opportunity to escape before trawl entrainment. The mean headrope fishing height of this trawl is ca. 1.3 m (King et al., 2004; Hannah et al., 2005). While the selective flatfish trawl design has shown effective at reducing catches for several benthopelagic groundfishes, it has been less effective at reducing catches of some of the more benthic groundfishes, such as darkblotched rockfish, and smaller-sized Pacific halibut (King et al., 2004). In this fishery, catches of darkblotched rockfish, sablefish, and Pacific halibut can impact some fishers ability to fully utilize their flatfish IFQs as these species have restrictive catch and bycatch limits. Thus, testing gear modifications to reduce catches of constraining species is needed. As described in section 3.1., one such modification that could potentially reduce bycatch of darkblotched rockfish and other fishes is use of artificial illumination. The objectives of Paper V were:

i) Evaluate if simple enhancements to the visibility of the selective flatfish trawl headrope can improve bycatch reduction for darkblotched rockfish, sablefish and Pacific halibut

ii) Examine how the presence of artificial illumination effects catches of target flatfishes

In Paper V, length-dependent catch comparison and catch ratio analyses were performed on paired catch data between tows made with and without artificial illumination (e.g., green LEDs) along the trawls headrope (Figure 16). Green LEDs were selected as blue-green light is the predominant spectral component of coastal waters and transmits well through coastal and continental shelf waters (Jerlov, 1976; Bowmaker, 1990). The trawl was fished with and without LEDs in an alternate tow randomized block design with the tows in each block occurring next to each other and in the same direction, but without overlapping their trawl paths. Catch comparison and catch ratio analyses, as described in section 5.6 of this thesis, allowed the study to determine if there is a significant length-dependent catch efficiency effect of changing from illuminated to unilluminated headrope. As in Papers II and III, Efron percentile 95% CI for the mean catch comparison and catch ratio curves were estimated using a double bootstrap method that accounts for the uncertainty in the estimation resulting from tow variation in catch efficiency and the availability of fish as well as uncertainty about the size structure of the catch for the individual tows. Further, the percent change in average catch efficiency (a length-integrated average value for the catch ratio) between fishing with the unilluminated trawl to the illuminated trawl was estimated based off equation 16 in section 5.6.

The results presented in Paper V show that illuminating the headrope of a selective flatfish trawl can affect the catch ratios of groundfishes, and depending on fish length and species the effect can be positive or negative. Although the differences in the catch rates and catch efficiencies were not significant, there was a general tendency to catch more

Figure 16. Images of an LEDs attached **(A)** near the center of the trawl headrope on the starboard side and **(B)** along the wing tip on the port side, and their orientations. Source: Paper V.

darkblotched, greenstriped (*S. elongatus*), and canary rockfishes, English sole, and petrale sole, but fewer lingcod, rex sole, and arrowtooth flounder in the illuminated trawl than the unilluminated trawl. For sablefish and Dover sole, their catches differed significantly between the two trawls, with fewer fish caught in the illuminated trawl. Pacific halibut catches differed between the two trawls, with the illuminated trawl catching an average of 57% less Pacific halibut. However, a relatively small sample size (264 individuals) resulted in large 95% CIs of the mean *CR*(*l*,*v*) value that extended above and below the *CR*(*l*,*v*) rate of 1.0.

Findings from Paper V suggest that use of artificial illumination could have potential applications for reducing bycatch under particular situations. For example, fishers seeking to reduce sablefish catches and/or Pacific halibut bycatch when targeting English sole and petrale sole over the continental shelf of the West Coast could potentially benefit from illuminating the trawl headrope, whereas fishers seeking to target Dover sole and/or sablefish but avoid darkblotched rockfish, would likely not benefit from using illumination. As fishers seek methods to improve trawl selectivity, Paper V provides an evaluation of how illuminating the headrope of a selective flatfish trawl can affect groundfish catches.

Paper V has addressed research question number iii) in Chapter 4 of this thesis.

6.3.2. Ocean shrimp fishery – Eulachon and groundfish bycatch (Papers VI, VII)

Sorting grids have significantly reduced fish bycatch in the ocean shrimp fishery (Hannah and Jones, 2007; Hannah et al., 2011). However, bycatch of eulachon*,* whitebait smelt, and juvenile groundfish such as Pacific hake, rockfishes, and flatfishes, can still occur at considerable levels as these fish can pass through the bar spacings of the sorting grids. For eulachon, their bycatch is of special concern because of their southern DPS ESA listing (DOC, 2011; Gustafson et al., 2012).

Hannah et al. (2015) examined whether placing artificial illumination along an ocean shrimp trawl fishing line could reduce eulachon bycatch by illuminating escape openings between the groundline contacting the seafloor and the fishing line, an opening of ca. 39 cm in height. Eulachon bycatch was reduced 91% by weight. This work also noted catch reductions of 82% by weight for darkblotched rockfish and 56% by weight for other juvenile rockfishes. To the best of our knowledge, the Hannah et al. (2015) research was the first peer-reviewed study presented where artificial illumination was successfully used to reduce bycatch in a trawl fishery.

Following the Hannah et al. (2105) study, fisheries managers for the state of Oregon considered implementing the required use of LED fishing lights along ocean shrimp trawl fishing lines to minimize the fisheries impact on eulachon, and groundfishes. However, further research examining the number of LEDs necessary to achieve optimal bycatch reduction was recognized as data needed before implementing the required use of footrope lighting (ODFW, Marine Resources Shellfish Program, per. comm.). The objectives of Paper VI were:

i) Evaluate how catches of ocean shrimp, eulachon, and juvenile groundfishes are affected by using 5, 10, and 20 LED fishing lights along an ocean shrimp trawl fishing line

ii) Examine if the catch efficiencies between the three LED configurations differ from each other

iii) Provide fisheries managers quantitative information for making decisions when developing and implementing the required use of footrope lighting

Using a double-rigged trawl vessel, Paper VI compared the catch efficiencies for ocean shrimp, eulachon, and juvenile groundfishes between an unilluminated trawl and trawls illuminated with 5, 10, and 20 LEDs along an ocean shrimp trawl fishing line (Figure 17). While the spectral sensitivity has not been empirically determined for all the species examined in this study, the species that have been examined possess maximal sensitivity to blue-green light, expectedly, as this is the predominant spectral component of coastal waters (Jerlov, 1976; Bowmaker, 1990; Britt, 2009). Therefore, we selected green LEDs for two reasons: (i) to allow for a comparison of results with the Hannah et al. (2015) study, and (ii) this color best matches the ambient light environment encountered in our study area and transmits well through coastal and continental shelf waters. Catch comparison and catch ratio analyses (as described in section 5.6 of this thesis) were performed to determine if changing from unilluminated to illuminated trawls had a significant length-dependent catch efficiency effect. To determine if any of the three LED configurations differ significantly from each other, 95% CI from bootstrap population of results were independently obtained for each configuration. Using these results, new bootstrap population of results were created and Efron percentile 95% CIs for each LED mean catch ratio curve were obtained. If the 95% CI overlapped the mean Delta catch ratio baseline value of 1.0 (indicating equal catch efficiency between the two trawls), the value was determined non-significant.

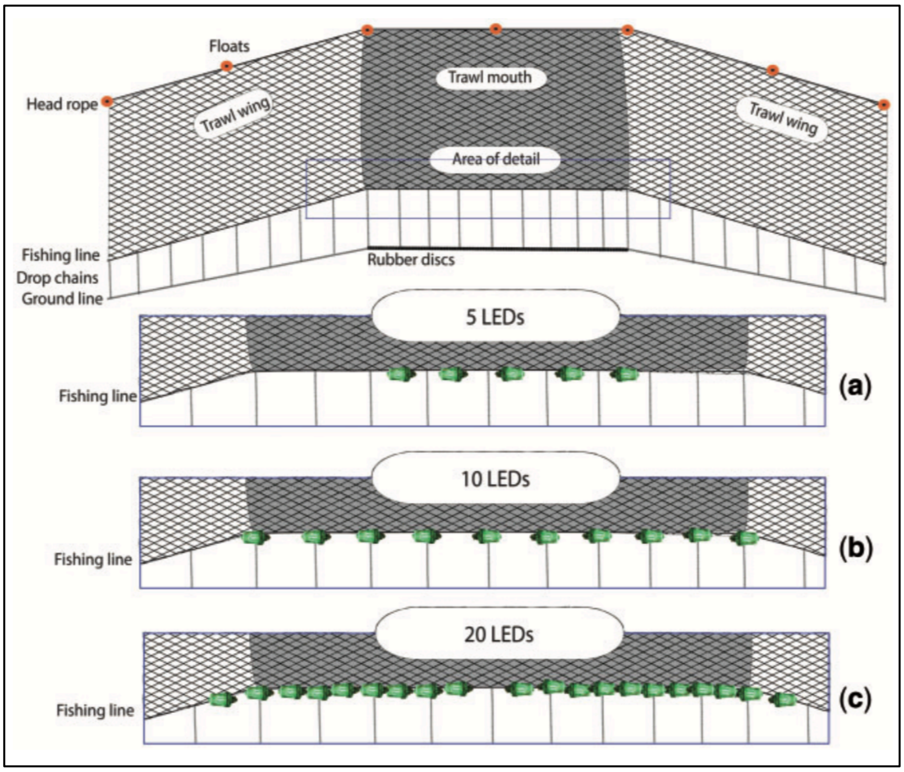


Figure 17. Schematic of an ocean shrimp trawl viewed from the front (top image) and diagrams depicting the placement and orientation of the LEDs along the trawl fishing line for the 5 (a), 10 (b), and 20 LED (c) configurations. Note: diagram not to scale. Source: Paper VI.

Findings presented in Paper VI show that the addition of illumination along the trawl fishing line significantly affected the average catch efficiency for eulachon, rockfishes, and flatfishes, with the illuminated trawls catching fewer individuals than the unilluminated trawl without impacting ocean shrimp catches. Further, the three LED configurations performed similarly to each other at reducing bycatch of these species. This finding suggests that the light emitted by the 5 LED configuration provides sufficient illumination for most fishes to perceive the contrast between the trawl fishing line and the seabed and thus avoid capture, and that use of more illumination provides no clear added bycatch reduction benefit.

Because of Paper VI and the work by Hannah et al. (2015), the Oregon Fish and Wildlife Commission, and Washington Department of Fish and Wildlife commission have implemented the required use of LED fishing lights along ocean shrimp trawl fishing lines to reduce bycatch of eulachon and groundfishes (WDFW, 2017; ODFW, 2018;). The regulation requires fishers landing ocean shrimp off Oregon and Washington to use a minimum of five green LEDs (spaced 1.2 m apart starting from the center section of the fishing line) within 15.2 cm of the forward leading edge of the bottom panel of the trawl netting. At this current time, it is unknown if the state of California will pursue actions requiring ocean shrimp trawl fishers to use lighting devices along their trawl fishing lines.

While substantial catch reductions were noted in Hannah et al. (2015) and in Paper VI, data from these studies were collected from the residual bycatch of trawls fished with sorting grids with 19.1 mm bar spacing. This hindered the studies ability to determine the degree that eulachon across all length classes (and other fishes) are escaping trawl entrainment in response to the illumination. Thus, determining the overall efficacy of LEDs placed along ocean shrimp trawl fishing lines and knowing the degree that eulachon and groundfishes escape (or do not escape) trawl entrainment in response to illumination is essential for understanding potential trawl catch impacts (e.g., physical contact with the sorting grids and/or netting, post-release and unobserved mortality, etc.) on non-target species. To fill this data gap, the objective of the study presented in Paper VII was:

i) Estimate the degree that eulachon, and groundfishes escape trawl entrainment in response to LED illumination along an ocean shrimp trawl fishing line.

Paper VII compared the catch efficiency between two simultaneously fished ocean shrimp trawls (one illuminated and the other unilluminated) without sorting grids installed. Five Lindgren-Pitman Electralume® green LED fishing lights, centered on a wavelength of 519 nm (Nguyen et al., 2017), were used to illuminate the central trawl fishing line area. As occurred in Papers V and VI, length-dependent catch comparison and catch ratio analyses were performed following the methods described in section 5.6 to determine whether there was a significant difference in catch efficiency between the unilluminated and illuminated trawl. A double bootstrap method was also used to estimate the Efron percentile 95% CIs for the mean selectivity curves.

The results of Paper VII show using artificial illumination along the trawl fishing line can significantly affect the catch rates of eulachon and several groundfishes, without impacting ocean shrimp catches. However, the effect is not consistent across species. The data presented in Paper VII continues to support the hypothesis that there is a significant reduction in eulachon bycatch when artificial illumination is present. For rockfishes and flatfishes, results suggest their ability to escape trawl entrainment in response to illumination along the fishing line is not as strong as previously indicated (Hannah et al., 2015; Paper VI). Compared to the unilluminated trawl, Paper VII found the illuminated trawl caught significantly more stripetail rockfish (*S. saxicola*) and flatfishes. The illuminated trawl also caught more darkblotched rockfish and other rockfishes (except yellowtail rockfish), but not at a significant level. These results differ from prior studies (which included the use of sorting grids) that showed the ability to significantly reduce bycatch of those same species with the addition of illumination along the fishing line (Hannah et al., 2015; Paper VI). Findings presented in Paper VII suggest that the combined use of footrope illumination and sorting grids (as is required in Oregon and Washington fisheries) is the most effective means for reducing bycatch across a larger suite of species and sizes.

As conservation of ESA-listed eulachon is an ongoing management priority, Papers VI and VII contribute new data on the efficacy of footrope illumination to reduce their bycatch. Because ocean distributions of eulachon, and ocean shrimp often overlap, interactions between ocean shrimp trawl gear and eulachon are likely to continue to be an issue facing the fishery and the conservation of ESA-listed eulachon.

Papers VI and VII have addressed research question number iii) in Chapter 4 of this thesis.

6.3.3. Pacific hake fishery – Chinook salmon bycatch (Paper VIII)

In the Pacific hake fishery, Lomeli and Wakefield (2012) tested an open escape window BRD designed to reduce catches of Chinook salmon and rockfishes. Data on gear performance and fish behavior was observed using underwater video camera systems equipped with artificial illumination to provide the necessary light to obtain video of suitable imagery. While the research was not focused on the effect of artificial illumination on fish behavior and escapement rates, the study found that for the Chinook salmon that escaped, a significant proportion ($p<0.05$) exited out an escape window toward which artificial illumination was directed. This behavior was not noted in rockfishes. These data suggest that artificial illumination could potentially be used to reduce Chinook salmon bycatch. In Paper VIII, two separate experiments evaluating the influence of artificial illumination on Chinook salmon behavior and escapement out a BRD in a Pacific hake midwater trawl were conducted. The objective of Experiment 1 was:

i) Test whether artificial illumination can influence where Chinook salmon exit out the BRD

The objective of Experiment 2 was:

i) Determine if artificial illumination can enhance Chinook escapement overall

The BRD used in the experiments presented in Paper VIII was built around a four-seam tube of diamond netting that was 135 meshes deep and 136 meshes in circumference, excluding meshes in each selvedge. This BRD design consisted of two Ultra Cross knotless square mesh netting (107.9 mm center-to-center nominal mesh size, 800 ply) ramps that were inserted inside the BRD tube of netting. The square mesh ramps are designed to guide actively swimming fish toward two large sets of escape windows cut out of each side of the net on the upper portions of the port and starboard side panels (Figure 18). This device is specifically designed to exploit the differences in swimming ability between Chinook salmon and Pacific hake. When encountering the BRD that is subject of Paper VIII, Pacific hake have been described to be tumbling, passively drifting, or actively swimming, but still drifting aft under the square mesh ramps towards the codend. This behavior contrasts with that observed for Chinook salmon and rockfishes, which have been noted actively swimming port to starboard and forward and aft throughout the BRD (Lomeli and Wakefield, 2012). For both experiments presented in Paper VIII, Lindgren-Pitman Electralume® blue LED fishing lights, centered on 464 nm (Nguyen et al., 2017), were used as the artificial light source. Blue colored LEDs were selected as this wavelength transmits the furthest in water and the predominant spectral component of coastal and continental shelf waters in this region is blue-green light (Jerlov, 1976; Bowmaker, 1990). To test whether artificial illumination could attract Chinook salmon out specific escape windows of the BRD (Experiment 1), LEDs were attached inside the net along the outer edge of the top panel of either the port or starboard side escape windows. The sequence in which the port and starboard side escape windows were illuminated was randomly selected and alternated between tows. Data on fish behavior and escapement was collected using underwater video camera systems. A one proportion Z test was used to examine whether the proportion of

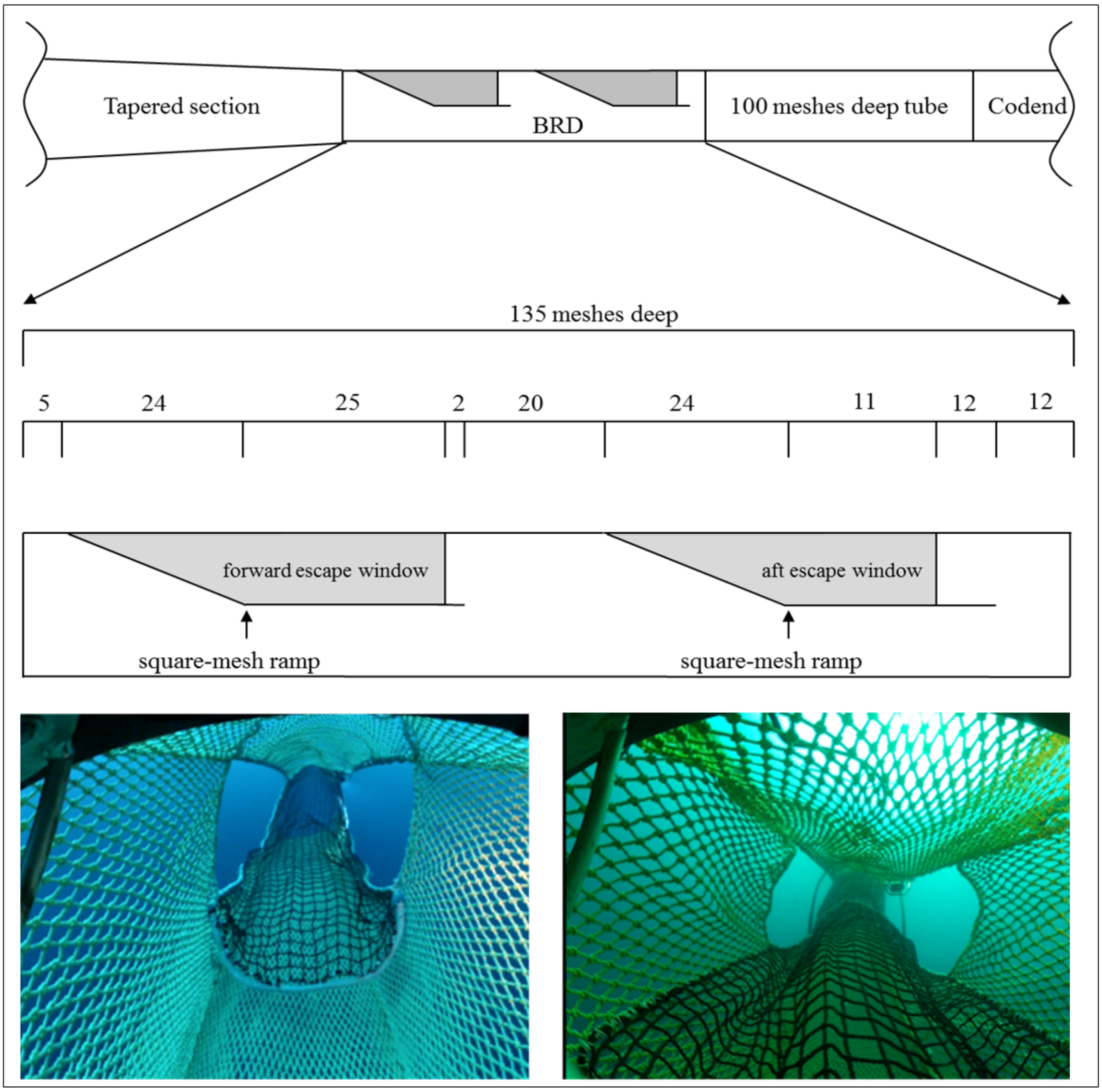


Figure 18. Schematic diagram of the open escape window BRD used in Paper VIII (top); forward view of the forward set of escape windows under ambient light (left image); forward view of the aft set of escape windows under ambient light (right image). Note: diagram not to scale. Source: Paper VIII.

Chinook salmon to exit out an illuminated escape window was significantly greater than the proportion of Chinook salmon to exit out a non-illuminated escape window. To determine the effect that illumination had on the overall escapement of Chinook salmon (Experiment 2), tows were conducted with and without artificial illumination on the BRD (e.g., an alternate tow method). The sequence in which the trawl was fished with and without artificial illumination was randomly selected. A recapture net (e.g., a covered-gear method) was used to enumerate fish escapement out the BRD in Experiment 2 (Figure 19). A Student's t-test was used to: 1) examine whether the proportion of Chinook salmon to exit the BRD when artificial illumination

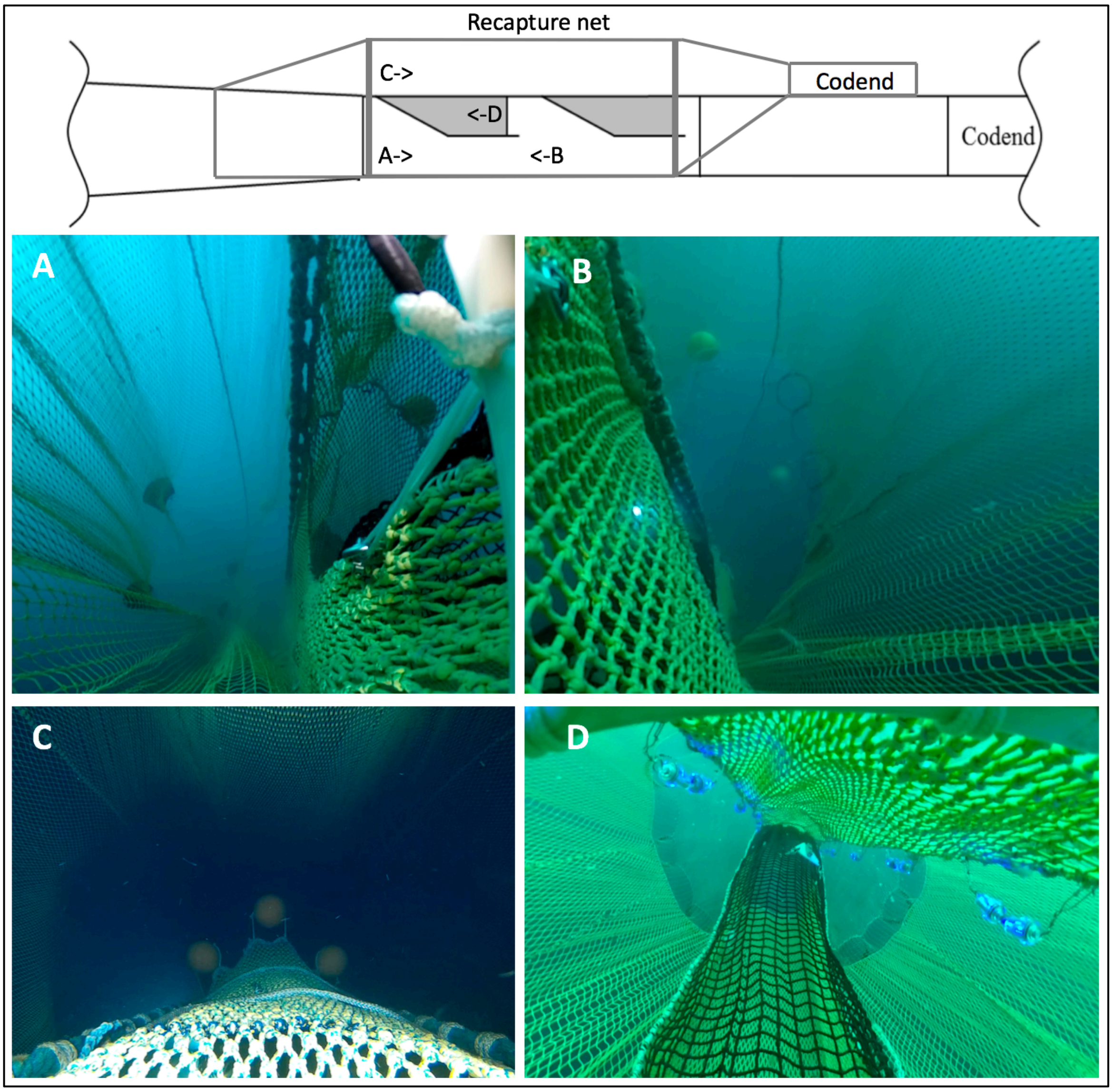


Figure 19. Schematic diagram and images under ambient light examining the recapture net over the BRD in Experiment 2 presented in Paper VIII. A = port-side aft view from outside of the BRD; B = starboard-side forward view from outside of the BRD; C = top panel aft view from outside the BRD; D = forward view of the forward set of escape windows from within the BRD. Note: diagram not to scale. Source: Paper VIII.

was present was significantly greater than the proportion of Chinook salmon to exit the BRD when artificial illumination was absent, and 2) analyze the Chinook salmon length data.

In Experiment 1, video observations were made on 438 Chinook salmon, of which 299 individuals escaped (68.3%, 95% CI = 63.8-72.4%). Of the 299 Chinook salmon to escape, 243 individuals exited out a window that was illuminated (81.3%, 95% CI = 76.5-85.3%). The proportion of Chinook salmon exiting out an illuminated escape window was significantly greater (p<0.0001) than the proportion to exit out a non-illuminated escape window. In

Experiment 2, 24 Chinook salmon encountered the BRD when artificial illumination was present. Escapement occurred in 18 of those individuals, an escapement rate of 75.0% (95% CI = 56.3-93.6%). During tows made without artificial illumination, 38 Chinook salmon encountered the BRD with escapement occurring in 20 of those individuals, an escapement rate of 52.6% (95% CI = 35.9-69.2%). Overall, the proportion of Chinook salmon to exit the BRD when artificial illumination was present was significantly greater (p=0.0362) than the proportion to exit the BRD when artificial illumination was absent. When artificial illumination was present, the mean length of Chinook salmon caught in the recapture net versus the codend was 59.7 cm (SE ±3.2 cm) and 67.1 cm (±4.4), respectively (p=0.2017). When artificial illumination was absent, the mean length of Chinook salmon caught in the recapture net versus the codend was 70.4 cm (SE ±3.4 cm) and 55.7 cm (±2.9), respectively (p=0.0028). While these Findings from Paper VIII demonstrate that artificial illumination can influence where Chinook salmon exit out the BRD tested. These findings support previous research by Lomeli and Wakefield (2012) suggesting that illumination can influence where Chinook salmon exit out a BRD. Results from Paper VIII also demonstrate that illumination can be used to enhance their escapement overall. Because ocean distributions of Chinook salmon and Pacific hake often overlap, interactions between Pacific hake trawl gear and Chinook salmon are likely to continue to be an issue facing the fishery and the conservation of ESA-listed Chinook salmon. Findings from Paper VIII provide data on a gear modification that can minimize Chinook salmon bycatch. As conservation of ESA-listed Chinook salmon is an ongoing management priority, Paper VIII contributes new information on how artificial illumination can minimize adverse interactions between the Pacific hake fishery and Chinook salmon. results are from a relatively limited sample size, it suggests that length could potentially be a contributing factor of Chinook salmon escapement.

Various video footage of Chinook salmon observed during Experiment 1 can be viewed at: http://www.psmfc.org/bycatch/videos.html.

Papers VIII has addressed research question number iii) in Chapter 4 of this thesis.

Chapter 7. Discussion

In this thesis, i) a description of eastern North Pacific trawl fisheries along with bycatch challenges facing the fisheries in this region was presented, ii) the overall thesis objective to "*identify, adapt, and test gear modifications that have potential to reduce bycatch and improve catch composition in eastern North Pacific trawl fisheries*" was established, iii) a review of trawl gear modifications that have potential to reduce bycatch in this region occurred, iv) specific research questions that include trawl gear modifications that can potentially reduce bycatch were formulated for testing, v) sampling and modeling techniques that can be used to measure trawl selectivity were introduced, and vi) research Papers I-VIII that address the thesis overall objective were presented.

In Papers I-IV, gear modifications designed to separate fish by morphological differences were tested in the West Coast groundfish bottom trawl fishery. As catches of constraining species such as Pacific halibut, sablefish, and/or darkblotched rockfish can impact fishers ability to fully utilize their IFQs of more abundant groundfish stocks, identifying and evaluating trawl modifications that can minimize their bycatch are increasingly important. In Papers I-III, the specific research question "*Can sorting grid devices reduce Pacific halibut bycatch and catches of constraining species in the West Coast groundfish bottom trawl fishery?*" was examined. The outcomes of Papers I-III demonstrate that *yes*, sorting grid devices can be effective at reducing bycatch of Pacific halibut and catches of constraining species in this fishery while retaining a relatively high proportion of the target species. This result provides fishers information on trawl gear modifications that can be used to alleviate catch constraints caused by Pacific halibut and roundfishes with restrictive harvest limits. Further, as the Pacific halibut stock is projected to decrease gradually over the period from 2018 to 2020 (IPHC, 2017), fishers trawling over the continental shelf are likely to be further constrained by their bycatch as less bycatch quota is anticipated to be available to the fishery. Thus, Papers I-III provide valuable information on gear modifications that can significantly reduce Pacific halibut bycatch. Furthermore, in the Gulf of Alaska, where bycatch of Pacific halibut at times has impacted fishers ability to fully utilize the available resource consisting of rex sole, arrowtooth flounder, Dover sole, and flathead sole (*Hippoglossoides elassodon*) (Rose and Gauvin, 2000), application of the BRD design evaluated in Papers II and III may prove useful for improving trawl selectivity in that flatfish fishery. The concept of the BRD design tested in Papers II and III could also have potential applications in trawls fisheries internationally were separating flatfishes from roundfishes are desired; for example, the Baltic cod directed fishery where efforts to separate plaice and flounder from the cod catch have occurred (Santos et al., 2016a).

An evaluation of T90 mesh codends occurred in Paper IV to determine if this mesh configuration could improve catch composition in the DTS complex fishery. In this West Coast groundfish bottom trawl fishery, sablefish quota is limited relative to the Dover sole quota (constraining fishers ability to fully utilize their Dover sole IFQ) and catches of smaller-sized sablefish are affecting fishers economic utilization of the sablefish ACL. Thus, the specific research question "*Can T90 mesh codends improve catch composition in the DTS complex fishery by reducing catches of juvenile and sub-adult roundfishes?*" was addressed in Paper IV. Results presented in this paper suggest that catch composition can be improved using T90 mesh codends in this fishery. This study has benefited fishers by providing a simple technique that can enhance catch composition and utilization of the DTS resource. In other fisheries internationally where similar catch issues as described in Paper V may arise, results from this study could prove beneficial when evaluating techniques to improve catch composition.

Use of artificial illumination as a bycatch reduction technique was tested in Papers V-VIII. These papers address the third specific research question of this thesis "*Can use of artificial illumination reduce fish bycatch in eastern North Pacific trawl fisheries?*". In Paper V, the research tested how illuminating the headrope of a low-rise selective flatfish trawl could alter catches of constraining species in the West Coast groundfish bottom trawl fishery. Results from this paper suggest that use of illumination could be effective at reducing catches of sablefish and Pacific halibut over the inner continental shelf for fishers targeting flatfishes such as English sole and petrale sole. However, this technique would not be effective in the DTS complex fishery where sablefish are the most economically important species harvested. As mentioned earlier that the Pacific halibut stock is projected to decrease gradually over the period from 2018 to 2020 and likely further constrain fishers, Paper V provides another gear modification that could potentially help trawlers further reduce Pacific halibut bycatch. Further, results from this study contributes new data to the growing international field of research exploring catch effects of artificial illumination on trawl gear (Grimaldo et al., 2018; Larsen et al., 2017, 2018; ICES, 2018; Melli et al., 2018).

In Papers VI-VII, use of artificial illumination as a technique to reduce bycatch of eulachon and groundfishes in the ocean shrimp fishery was presented. Findings from these papers demonstrate that *yes*, use of artificial illumination can be an effective technique for reducing eulachon bycatch. However, its ability to reduce bycatch of groundfishes remains unclear as Paper VII presented data showing catches of rockfishes (except yellowtail rockfish) and flatfishes were either increased or not affected by the presence of illumination. This finding conflicts Paper VI and Hannah et al. (2015) that demonstrated the ability to reduce bycatch of groundfishes using artificial illumination in this fishery. As eulachon are an ESA-listed species, the results from Papers VI-VII have positive impacts on the ocean shrimp fishery and the conservation of eulachon as this fishery is the primary fishery in the eastern North Pacific where eulachon bycatch occurs (Gustafson et al., 2012). Further, Paper VI has contributed to regulations being implemented that require fishers landing ocean shrimp in Oregon and Washington to use lighting devices near the trawl fishing line to reduce eulachon bycatch and contribute to their conservation (WDFW, 2017; ODFW, 2018). This is the first trawl fishery (regionally and internationally) to mandate the required use of artificial illumination to reduce bycatch. Lastly, the techniques applied in Papers VI-VII could potentially be used in other trawl fisheries internationally; for example, the ocean shrimp trawl fishery off British Columbia, Canada where fishers have requested management to allow use of illumination to reduce eulachon bycatch (DFO, 2018), and northern prawn trawl fisheries in the North Atlantic where bycatch of marine fishes occur (He and Balzano, 2013; Larsen et al., 2017, 2018).

As described in Paper VIII, Chinook salmon bycatch is an issue facing the Pacific hake fishery. As Chinook salmon have several Evolutionary Significant Units listed as "endangered" or "threatened" under the U.S. ESA (NMFS WCR, 2017), identifying techniques to reduce their bycatch are increasingly important to fishers, management, and the conservation of ESA-listed Chinook salmon. The experiments presented in Paper VIII confirm that artificial illumination can significantly influence where Chinook salmon exit out of at a BRD, but also that artificial illumination can be used to enhance their escapement overall. This finding shows that *yes*, artificial illumination can be an effective technique for reducing Chinook salmon bycatch, and supports previous work by Lomeli and Wakefield (2012) suggesting that artificial illumination can influence Chinook salmon escapement out a BRD in a Pacific hake trawl. As a result of Paper VIII, a gear modification that can reduce adverse interactions between the Pacific hake fishery and Chinook salmon has been identified. Although Paper VIII has obvious regional impacts, results from this study could have potential applications in the Bering Sea walleye pollock midwater trawl fishery and in the Icelandic pelagic mackerel (*Scomber scombrus*) trawl fishery where salmon bycatch also occurs (Stram and Ianelli, 2015; Olafsson et al., 2016).

7.1. Future research directions

In 2019, research in the West Coast groundfish bottom trawl fishery and Pacific hake fishery will continue to investigate if artificial illumination can reduce Pacific halibut and

Chinook salmon bycatch, respectively. Building off Paper V, research in the groundfish bottom trawl fishery will test if artificial illumination along the upper bridles and wings of a low-rise selective flatfish trawl can reduce Pacific halibut bycatch by enhancing their ability to perceive escape areas around the trawl before trawl entrainment. Results from this study are anticipated to identify the efficacy of using artificial illumination along the trawls upper bridles and wings as bycatch reduction technique for Pacific halibut. Building off Paper VIII, research in the Pacific hake fishery will seek to identify the optimal level of artificial illumination necessary (e.g., number of LEDs) to achieve maximum Chinook salmon escapement rates out a BRD integrated into a Pacific hake midwater trawl. Results from this study are anticipated to identify the optimal level of artificial illumination necessary to achieve maximum Chinook salmon escapement rates.

Research in Europe (Eryaşar et al., 2014; Sala and Lucchetti, 2011; Sala et al., 2016; Wienbeck et al., 2011) and Australia (Broadhurst and Millar, 2009; Graham et al., 2009) have demonstrated that reducing the number of meshes in the circumference of a bottom trawl codend (by up to 50%) can significantly improve its size-selection properties, as reflected in higher mean L_{50} values. Reducing the number of meshes in the circumference increases the openings of the meshes (as sections of the codend reach maximum diameter faster from the accumulating catch and drag forces) and the probability of fish encountering the mesh while decreasing the amount of net folding. Thus, allowing larger L_{50} values to be achieved. In reference to square mesh and T90 mesh codends, this would result in larger-sized roundfishes escaping. Thus, research examining the size-selection characteristics between T90 codends with- and without-reduced circumferences and evaluating their ability to enhance catch composition in the West Coast groundfish DTS complex fishery would be useful. Investigating the effects of twine thickness, and twine number (single vs double twine) would be beneficial as well.

In the ocean shrimp fishery, fishers landing shrimp in Oregon and Washington are now required to use LEDs to reduce bycatch of eulachon and groundfishes (WDFW 2017; ODFW 2018). However, results from Paper VII indicate that groundgear configuration may affect the efficacy of LEDs to reduce bycatch, particularly groundfishes. As fisheries managers seek to implement techniques to maximize the fisheries ability to reduce bycatch, knowing whether groundgear configuration can influence the effectiveness of a fishing device that is required in the fishery (e.g., LEDs) is critical for effectively managing the fishery, contributing to the conservation of ESA-listed eulachon, and knowing its potential impact to other regional trawl fisheries. Future research exploring whether changes in groundgear configuration affects the efficacy of LED illumination to reduce bycatch is this fishery is needed.

In Paper VIII, use of artificial illumination had a positive effect on reducing Chinook salmon bycatch. While the mechanism(s) triggering Chinook salmon to exhibit the behaviors observed in this study is unclear, the presence of artificial illumination appears to enhance their visual perception and their ability to perceive the contrast between the trawl gear and the surrounding environment that otherwise they would not be able to perceive as well under dark conditions. How Chinook salmon perceive and interact with this BRD under conditions when artificial illumination is absent is unclear. Further research using imaging sonar equipment such as ARIS (Adaptive Resolution Imaging Sonar) or DIDSON (Dual-Frequency Identification Sonar) to observe how Chinook salmon interact with this BRD under dark conditions could provide insights that could help improve our knowledge of what makes artificial illumination affective at reducing their bycatch.

In the Pacific hake fishery, bycatch of rockfishes such as Pacific ocean perch, and darkblotched, widow, and canary rockfishes has been an ongoing issue facing the fishery. In the early 2000's, these stocks were declared overfished and rebuilding strategies were established. The rebuilding strategies, developed and executed between management and industry, have been effective as these stocks have recently been rebuilt above managements target level of B40% (% of unfished spawning biomass) (He et al., 2011; Thorson and Wetzel, 2016; Wallace and Gertseva, 2017; Wetzel et al., 2017). However, as the biomass of these stocks have increased so have their interactions in the fishery. In areas of increased Pacific hake catch rates, high bycatch rates of these rockfishes can also occur. As a result of these increased interactions and bycatch rates, these stocks continue to constrain the fishery (even though they are rebuilt) as their allocation across the shore-side, mothership, and catcher processor sectors of the fishery still remain relatively low when compared to the Pacific hake allocation across the sectors. Further, when rockfishes are present in considerable numbers, vessels are often forced to move off productive fishing grounds to avoid exceeding their allocation for rockfishes. While moving to different fishing grounds may minimize bycatch of rockfishes, it can result in moving to areas where Pacific hake abundances are considerably lower and/or are of sizes of lesser or non-marketable value. Under these situations, fishers cost efficiency to harvest Pacific hake can be substantially impacted (e.g., increased tow durations and fuel consumption, lower product ex-vessel value). In addition to impacting fishers access to productive Pacific hake fishing grounds, rockfish bycatch can also affect the ex-vessel value and marketability of Pacific hake in the production of head and gut, and fillets as rockfish spines can puncture and penetrate the muscles of Pacific hake when packed into the codend and/or the fish holds and damage the product to a level that is non-marketable. Hence, identifying, developing, and adapting gear modifications that can reduce rockfish bycatch in this fishery is needed.

7.2. Final remarks

In summary, this thesis presented recent selectivity research conducted in eastern North Pacific trawl fisheries. Prior to this thesis, trawl selectivity research in this region has been limited to diamond mesh and square mesh codend selectivity studies (Wallace et al., 1996; Perez-Comas et al., 1998), testing of a selective flatfish trawl design for the groundfish bottom trawl fishery (King et al., 2004; Hannah et al., 2005), development of sorting grids for the ocean shrimp fishery (Hannah and Jones, 2007; Hannah et al., 2011), and evaluating the efficacy of an open escape window BRD for the Pacific hake fishery (Lomeli and Wakefield, 2012). Because of Papers I-VIII, considerable advancements in developing and adapting trawl gear modifications that can reduce bycatch and contribute to the conservation of ESA-listed species (e.g., eulachon and Chinook salmon) have been made. Collectively, these papers contribute to eastern North Pacific trawl fisheries by presenting fishers and managers new data on trawl gear modifications that can allow fishers to fish more selectively in times and/or areas where constraining species, prohibited species, and/or ESA-listed species are affecting their access to target resources. This thesis has clearly demonstrated that trawl gear modifications can be effective at reducing bycatch in the West Coast groundfish bottom trawl fishery, Pacific hake fishery, and ocean shrimp fishery. Further, this thesis has achieved its overall objective to "*identify, adapt, and test gear modifications that have potential to reduce bycatch and improve catch composition in eastern North Pacific trawl fisheries*". Lastly, while Papers I-VIII presented in this thesis were developed to address bycatch challenges facing eastern North Pacific trawl fisheries, results from this thesis could have potential applications in other trawl fisheries nationally and internationally where similar bycatch issues may occur.

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Papers I-VIII

Paper I

“A flexible sorting grid to reduce Pacific halibut (*Hippoglossus stenolepis*) bycatch in the US west coast groundfish bottom trawl fishery”

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A flexible sorting grid to reduce Pacific halibut (*Hippoglossus stenolepis*) bycatch in the US west coast groundfish bottom trawl fishery

Mark J.M. Lomeli[a,*], W. Waldo Wakefield[b]

[a] *Pacific States Marine Fisheries Commission, 2032 SE OSU Drive, Newport, OR 97365, USA*
[b] *Fishery Resource Analysis and Monitoring Division, Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 2032 SE OSU Drive, Newport, OR 97365, USA*

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ABSTRACT

This study examined a flexible sorting grid excluder designed to reduce Pacific halibut (*Hippoglossus stenolepis*) bycatch in the US west coast groundfish bottom trawl fishery. Tests occurred off Washington during 2011 aboard a commercial trawler. A recapture net was used to quantify the retention rates of target and non-target species. Pacific halibut bycatch was reduced 61.6% by weight and 57.0% by numbers. Exclusion was greatest for Pacific halibut weighing more than 4.5 kg. A significant difference in the mean total length was also noted between Pacific halibut caught in the codend and the recapture net, with larger fish occurring in the recapture net. The retention of primary target groundfishes of marketable-size ranged from 76.7 to 89.3%. We demonstrated the capability of a flexible sorting grid excluder to reduce Pacific halibut bycatch in the groundfish bottom trawl fishery while retaining a relatively high proportion of the targeted species.

1. Introduction

The US west coast groundfish bottom trawl fishery ranges from southern California to northern Washington and seaward to depths exceeding 500 m. A mixture of flatfishes, roundfishes, and skates are targeted with sablefish (*Anoplopoma fimbria*), petrale sole (*Eopsetta jordani*), lingcod (*Ophiodon elongatus*), and Dover sole (*Microstomus pacificus*) being the most important species of commercial value. While most groundfish stocks in this fishery are healthy (PFMC and NMFS, 2012; NMFS, 2012), bycatch of overfished and prohibited species (i.e. Pacific halibut [*Hippoglossus stenolepis*], Chinook salmon [*Oncorhynchus tshawytscha*]) constrains the fishery such that a substantial portion of allowable harvest is left in the ocean (PFMC and NMFS, 2010).

Starting in 2011, the west coast limited entry groundfish trawl fishery was managed under a catch share program (PFMC and NMFS, 2010). This new program established annual catch limits and individual fishing quotas along with individual bycatch quotas (IBQs). For many bottom trawl fishermen participating in this program, a major bycatch species of concern is Pacific halibut which is a prohibited species. Individual fishermen could reach their Pacific halibut IBQ before reaching their groundfish catch share quotas, thereby ending their fishing season. This scenario occurred in 2011 for some fishermen. The implementation of a catch share program has created increased demand among fishermen to reduce Pacific halibut bycatch.

Sorting grid bycatch reduction devices (BRDs) have shown success at reducing bycatch in trawl fisheries (Broadhurst and Kenney, 1996; Kvalsvik et al., 2002, 2006; Sardà et al., 2004). In a bottom trawl targeting aggregated deep-water flatfishes, Rose and Gauvin (2000) examined a rigid sorting grid with 15 cm × 15 cm openings and observed a 94% reduction in the incidental catch of Pacific halibut. The overall retention of the targeted species was 68%. When examining a 17.8 cm × 17.8 cm flexible (mesh) sorting grid in the same fishery, Pacific halibut bycatch was reduced by approximately 55%. The overall retention of the targeted species, however, increased to over 80% (Craig Rose, NOAA Fisheries-Alaska Fisheries Science Center, Seattle, WA, personal communication). In the US west coast pink shrimp (*Pandalus jordani*) trawl fishery, sorting grids have shown to be just as effective (Hannah and Jones, 2007; Hannah et al., 2011).

While studies examining sorting grids have often found the most successful results when rigid grids are used (Broadhurst and Kenney, 1996; Broadhurst et al., 1997; Hannah et al., 2003), rigid grids are known to provide handling difficulties on vessels with restricted deck space or that use net drums for setting and hauling their net. Because most vessels in the US west coast groundfish bottom trawl fishery are less than 30 m in overall length and have limited deck space, and use net drums, the use of flexible sorting grids are more acceptable in this fishery. The current study tested a flexible sorting grid to reduce Pacific halibut bycatch and evaluated its efficacy in the US west coast groundfish bottom trawl fishery.

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* Corresponding author. Tel.: +1 541 867 0544; fax: +1 541 867 0505.
E-mail address: mlomeli@psmfc.org (M.J.M. Lomeli).

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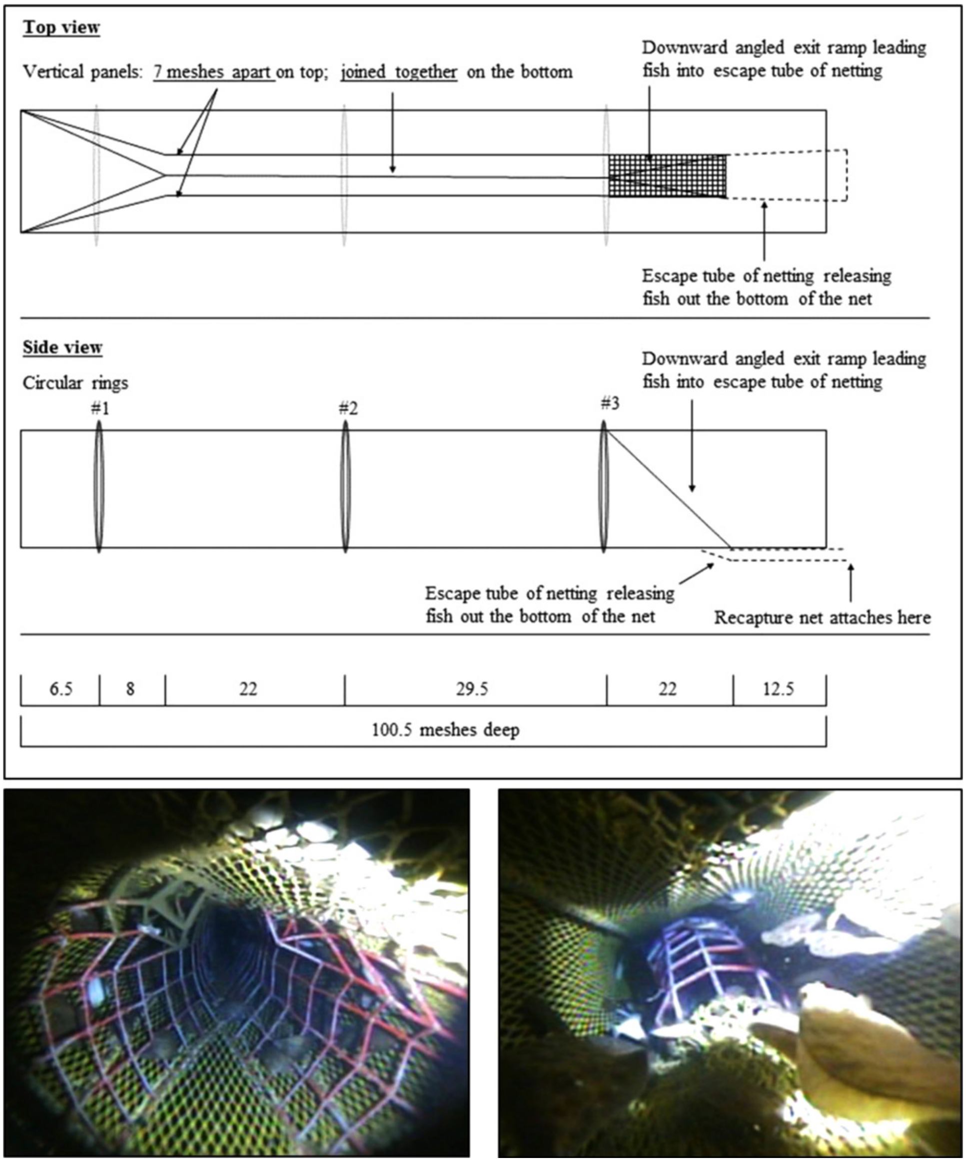

Fig. 1. Schematic diagram of the Pacific halibut flexible sorting grid excluder tested (top); aft view of the forward portion of the excluder where fish enter and encounter the device (bottom left); forward view of the downward-angled exit ramp with fish moving aft toward the codend (bottom right).

2. Materials and methods

The trawl used for this study was a two-seam Eastern 400 low-rise selective flatfish trawl with a cutback headrope designed to fish behind the footrope. The headrope was 40.3 m in length, whereas the chain footrope was 31.2 m in length and covered with rubber disks 17.8 cm in diameter. Past research has shown this trawl to exhibit a mean headrope height between 1.25 and 1.3 m (Hannah et al., 2005; King et al., 2004). This trawl is specifically designed to allow fish that have a tendency to rise when encountering the footrope to escape. This trawl also lacks floats along the central portion of the headrope to reduce any diving reactions that fish may exhibit in reaction to floats. Under regulatory mandate, bottom trawlers fishing north of 40°10′N latitude in depths shallower than 183 m during 2011 were required to use this trawl design to minimize bycatch of overfished *Sebastes* species (NOAA Fisheries NWR, 2010).

The Pacific halibut BRD was constructed within a four-seam tube of netting that was 100.5 meshes deep (fore to aft) and 100 meshes in circumference, excluding meshes in each selvedge (Fig. 1). The BRD was designed to be inserted between the intermediate section of a bottom trawl and the codend. The design utilizes two vertical panels (grids) of 19.1 cm × 19.1 cm openings to crowd fish and direct large fish toward a downward-angled exit ramp, a panel of 14.0 cm × 14.0 cm openings. The vertical panels and exit ramp were built of 5 mm diameter Spectra® line placed through 13 mm diameter AQUAPEX® tubing to create a semi-rigid square grid. The concept of this design is that fish smaller than the panel openings will pass through the vertical panels and move aft toward the codend, whereas fish larger than the panel openings will be excluded.

The vertical panels of this BRD extend longitudinally down the experimental section of netting 66 meshes deep before connecting to the exit ramp. Over this distance the two panels gradually angle inward over 14.5 meshes deep then straighten to create a narrow "hallway" that extends aft 51.5 meshes deep (Fig. 1). In the "hallway" section of this BRD the vertical panels are 7 meshes apart on the top panel of the net and 0 meshes apart (i.e. joined together) on the bottom panel. At the end of the "hallway", the bottom portion of the vertical panels gradually angle outward, to become 7 meshes

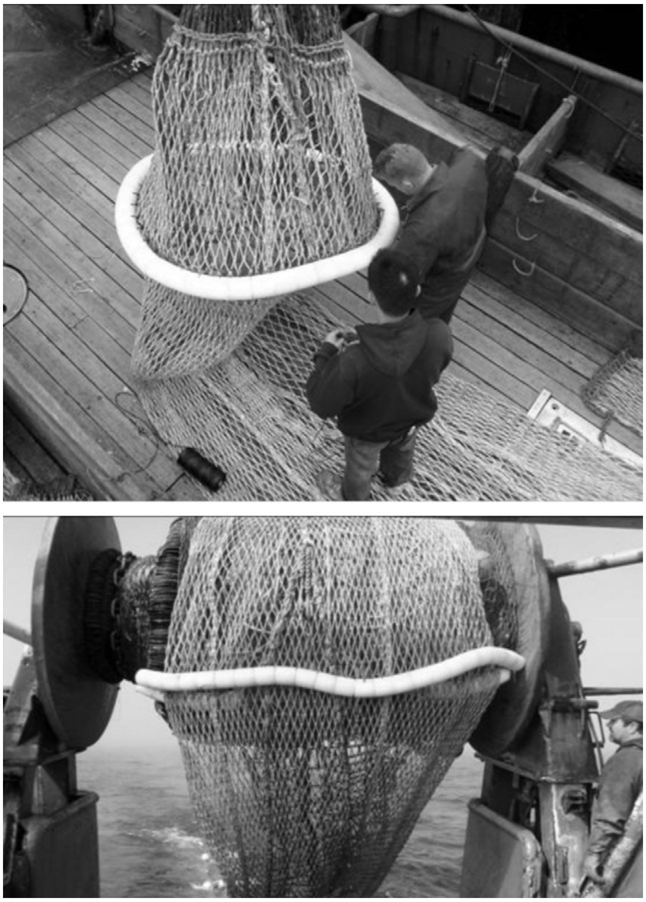

Fig. 2. Image of the forward most positioned circular ring system being installed on the BRD (top); image of the forward most positioned circular ring system compressing when being brought onto the net drum (bottom).

apart, to allow for the exit ramp and "escape" tube to occur. Fish that do not pass through the panel openings are guided by the exit ramp and exit out the bottom of the trawl through a 2-seam "escape" tube of netting that is 17 meshes deep and 50 meshes in circumference, excluding meshes in each selvedge.

A recapture net was used to quantify the retention of target and non-target species. The recapture net was 50 meshes deep and 50 meshes in circumference, excluding meshes in each selvedge. The recapture net was attached to the "escape" tube of netting to capture fish excluded from the trawl. The mesh size and configuration of the experimental section of netting, recapture net, and codend was 14.0 cm knot to knot diamond mesh.

On the experimental section of netting, three circular ring systems were installed to fix the shape of the BRD and the associated netting. Each ring system consisted of 45 interlocking pieces of rigid nylon attached to the net with braided nylon twine (#260) and held together in a circular shape by two strands of shock cord that were 8 mm in diameter and 2.7 m in connected length. Because of the elasticity of the shock cord, the ring system can compress down when brought onto the net drum without damage (Fig. 2). The circular ring systems were located approximately 30 meshes apart on the experimental section of netting (Fig. 1). To create a more homogenous surface around the outside of the experimental section of netting (to better allow the rings to form a circular shape), riblines were not used. A 16 mm Spectra® line was gored into each selvedge (hung in at 100%) to suffice as riblines. The circular ring system examined in this study was designed by Friis-Rödel et al. (2010) and Dantrawl Inc.

Tests were completed off Washington between 47°24′ and 48°09′N and between 124°44′ and 125°38′W, during August 2011, aboard the chartered *F/V Miss Leona*; a 26.5 m length overall, 850 hp commercial trawler. Towing speed ranged from 2.7 to 3.2 knots, while tow durations ranged from 26.7 to 39.0 min.

Two autonomous, high-resolution, low-light, color video camera systems were used at the start, middle, and conclusion of the study to gather information on fish behavior and confirm that the circular ring systems formed the experimental section of netting into a uniform circular shape (Video clip 1) and that the recapture net was designed and configured correctly and was not impeding fish from entering it. However, for the data presented in this paper, all 30 tows occurred without the use of video cameras and artificial lights.

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.fishres.2013.01.017.

After each tow, all fish caught in the recapture net and codend were identified to species and weighed using a Marel M1100 platform scale. Calibration of the scale occurred after each tow. To examine size selectivity, length data were collected on species of commercial importance. Up to 25 fish per recapture net and codend were randomly selected and measured to the nearest half cm total length. For Pacific halibut, all fish were weighed and measured. Temperature, depth, and light levels at trawling depths were measured using a Wildlife Computers TDR-MK9 archival tag.

Percent retention by weight (codend/(codend + recapture net)) in kg was calculated for all species. For Pacific halibut, percent retention was calculated by weight and numbers of fish. To determine if mean total lengths differed significantly between fish caught in the recapture net and codend, we used either an equal variance two-sample *t*-test, Mann–Whitney U test, or a Kolmogorov–Smirnov test depending on the variance and normality test results for the species being analyzed. Following Holst and Revill (2009) a generalized linear mixed model (GLMM), using a logit-linear model, was applied to examine if retention was length-related. Tow number was included as a random effect in the model to ensure that tows in which the species occurred in large numbers did not influence the results. The glmmPQL function from the MASS package in R (R Core Team, 2012) was used with the function call:

$$\begin{aligned}&\text{glmmPQL(Proportion} \sim \text{Length, random}\\&\quad = \sim 1|\text{Tow, family} = \text{binomial, weights}\\&\quad = \text{Codend} + \text{Retention, data} = \text{retention.data).}\end{aligned}$$

3. Results

Catch per tow ranged from 82 to 1538 kg (Table 1) and contained up to 11 target species (Table 2). Dominant species encountered, in order of abundance, were petrale sole, Pacific cod (*Gadus macrocephalus*), lingcod, English sole (*Parophrys vetulus*), and arrowtooth flounder (*Atheresthes stomias*). Total catch and retention rates of target species, excluding skates (*Rajidae*), from the 30 tows conducted are summarized in Table 3. Additional species caught, but not considered further because of small sample sizes, were spiny dogfish (*Squalus suckleyi*), sandpaper skate (*R. kincaidii*), spotted ratfish (*Hydrolagus colliei*), American shad (*Alosa sapidissima*), Pacific hake (*Merluccius productus*), walleye pollock (*Theragra chalcogramma*), bigfin eelpout (*Lycodes cortezianus*), shortspine thornyhead (*Sebastolobus alascanus*), darkblotched rockfish (*S. crameri*), splitnose rockfish (*S. diploproa*), greenstriped rockfish (*S. elongatus*), canary rockfish (*S. pinniger*), yelloweye rockfish (*S. ruberrimus*), threadfin sculpin (*Icelinus filamentosus*), slender sole

Table 1
Trawl data collected from the 30 tows conducted. Catch values represent fish caught between the recapture net and codend.

	Speed (knt)	Duration (min)	Depth (m)	Catch (kg)	Temperature (°C)	Light (μmol photons m^{-2} s^{-1})
Range	2.7–3.2	26.7–39.0	113–173	82–1538	6.8–7.4	8.96E-09-6.70E-02
Mean	2.9	35.3	126	596	7.1	2.29E-04

Table 2
Percent retention of Pacific halibut and target species by total weight (kg) and total weight of marketable sized fish caught. Values in parentheses represent the number of Pacific halibut captured.

	Total weight			Total weight of marketable-sized fish		
Species	Recapture net	Codend	% Retention	Recapture net	Codend	% Retention
Flatfishes						
Pacific halibut	308 (69)	192 (52)	38.4 (43.0)	n/a*	n/a*	n/a*
English sole	299	1962	86.8	218	1396	86.5
Pacific sanddab	38	208	84.6	38	200	84.0
Rex sole	28	182	86.7	18	67	78.8
Arrowtooth flounder	464	1604	77.6	448	1530	77.4
Dover sole	155	891	85.2	133	438	76.7
Petrale sole	820	3403	80.6	424	2040	82.8
Roundfishes						
Pacific cod	289	2563	89.9	260	2063	88.8
Sablefish	121	694	85.2	91	441	82.9
Lingcod	247	2367	90.6	175	1463	89.3
Skates						
Big skate	69	4	5.5	69	4	5.5
Longnose skate	124	20	13.9	110	16	12.7

n/a*, prohibited species.

(*Lyopsetta exilis*), flathead sole (*Hippoglossoides elassodon*), brown box crab (*Lopholithodes foraminatus*), and Dungeness crab (*Cancer magister*).

Bycatch of Pacific halibut was reduced 61.6% by weight and 57.0% by numbers (Table 2). Overall, the retention of marketable-sized flatfishes ranged from 76.7 to 86.5%, whereas the retention of marketable-sized roundfishes ranged from 82.9 to 89.3% (Table 2). Retention rates were highest, in descending order, for lingcod, Pacific cod, English sole, sablefish, and petrale sole. Retention of skate species ranged from 5.5 to 13.9%. Not including skates, the loss of marketable-sized fish was highest for Dover sole, arrowtooth flounder, and rex sole (*Glyptocephalus zachirus*) 23.3, 22.6, and 21.2%, respectively. Overall, 83% of the marketable-sized fish encountered were retained in the codend.

Pacific halibut encountered during this study ranged from 1.9 to 8 kg (mean 4.1 kg, SE ± 0.1 kg). Exclusion was greatest for Pacific halibut weighing more than 4.5 kg. Of the fish encountered weighing 4.5 kg or greater, 76.9% were caught in the recapture net, whereas only 47.6% of the fish weighing less than 4.5 kg were caught in the recapture net. Pacific halibut weighing over 6 kg were caught exclusively in the recapture net (Fig. 3). The highest number of Pacific halibut encountered in a single tow was 18, with 55.6% of these fish being excluded (Table 3).

There was a significant difference in the mean total length between Pacific halibut caught in the codend and the recapture net, with larger fish occurring in the recapture net (Table 4). This was also observed for Pacific sanddab (*Citharichthys sordidus*), rex sole, Dover sole, Pacific cod, and sablefish. The largest mean total length difference noted were for Pacific halibut (4.5 cm), Dover sole (3.5 cm), and Pacific cod (2.5 cm). No meaningful differences in mean length were shown for English sole, arrowtooth flounder, petrale sole, or lingcod between retained and excluded individuals. When testing if retention was length-related (GLMM) results showed that length was a significant factor effecting the retention of Pacific sanddab, rex sole, arrowtooth flounder, Dover sole, petrale sole, sablefish, and lingcod with a greater proportion of larger fish occurring in the recapture net (Table 5). The GLMM could not be run for Pacific halibut, big skate (*R. binoculata*), or longnose skate (*R. rhina*) because of insufficient sample sizes.

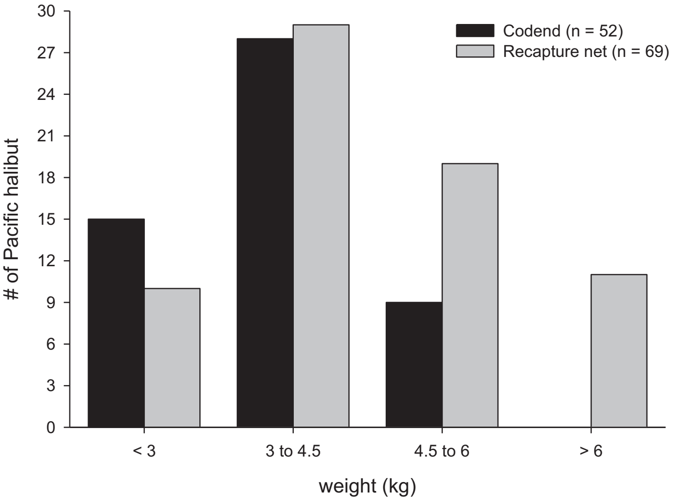

Fig. 3. Comparison of Pacific halibut caught within either the codend or the recapture net by weight class.

Video footage showed as most flatfishes (e.g. English sole, Dover sole, and petrale sole) encountered the BRD they began making attempts to pass through the vertical panels. In several instances, flatfishes would pass through the vertical panels before reaching the "hallway" section. Rarely were flatfishes observed to enter the "hallway" section and move aft without interacting with the panels. Once fish moved into the open space between the side panels of the experimental section of netting and the vertical panels the majority of fish did not attempt to pass back through the panels. Unfortunately, too few roundfishes were observed during tows conducted using video cameras to gain information on their behavior in response to the BRD. Video confirmed that the circular ring systems formed the experimental section of netting into a uniform circular shape (Video clip 1) and that the recapture net was designed and configured correctly and was not impeding fish from entering it.

Table 3
Catch data by weight (kg) from the 30 tows conducted. #, numbers of Pacific halibut; CE, codend; RN, recapture net; %R, percent retention.

	Pacific halibut (#)			Pacific halibut			English sole			Pacific sanddab			Rex sole			Arrowtooth flounder		
Tow	CE	RN	%R	CE	RN	%R	CE	RN	%R	CE	RN	%R	CE	RN	%R	CE	RN	%R
1	0	0	–	0	0	–	142.8	10.1	93.4	0	0	–	4.3	1.1	79.6	81.3	10.9	88.2
2	2	1	66.7	9.3	3.8	70.9	154.3	18.6	89.2	0	0	–	7.8	0	100.0	105.3	18.6	85.0
3	1	4	20.0	3.6	17.5	17.1	70.8	9.9	87.7	1.6	0.3	84.2	6.6	0.5	93.0	38.0	11.2	77.2
4	0	4	0.0	0	17.3	0	78.6	12.9	85.9	1.4	0.0	100.0	4.6	0	100.0	38.7	12.5	75.6
5	1	2	33.3	2.7	6.5	29.3	33.6	7.3	82.2	37.6	8.9	80.9	1.0	0	100.0	39.7	10.6	78.9
6	2	1	66.7	6.9	5.1	57.5	29.1	5.9	83.1	49.5	0	100.0	0.6	0	100.0	57.1	25.2	69.4
7	2	0	100.0	7.1	0.0	100.0	32.7	4.8	87.2	11.0	1.8	85.9	1.0	0	100.0	25.5	10.8	70.2
8	6	2	75.0	22.7	9.8	69.8	108.6	13.2	89.2	15.5	3.2	82.9	0.7	0.2	77.8	54.4	9.5	85.1
9	1	5	16.7	3.9	17.9	17.9	39.7	1.8	95.7	7.8	1.8	81.3	2.4	0	100.0	32.0	2.8	92.0
10	8	10	44.4	28.1	43.1	39.5	134.0	20.3	86.8	23.4	6.4	78.5	1.8	0.3	85.7	39.3	5.6	87.5
11	3	5	37.5	10.5	25.9	28.9	45.7	4.9	90.3	2.7	6.2	30.3	0.7	0	100.0	38.6	8.2	82.5
12	0	1	0.0	0	5.0	0.0	89.4	16.6	84.3	0.7	0.5	58.3	11.2	2.4	82.4	28.4	9.8	74.3
13	3	5	37.5	12.8	20.4	38.6	74.3	6.1	92.4	0	0	–	12.0	0	100.0	28.2	4.2	87.0
14	1	4	20.0	3.9	19.9	16.4	89.1	13.6	86.8	0	0	–	10.5	0.6	94.6	45.6	5.4	89.4
15	2	2	50.0	8.6	7.1	54.8	58.0	13.6	81.0	0	0	–	9.4	2.4	79.7	35.8	19.3	65.0
16	3	4	42.9	10.3	19.7	34.3	54.9	8.3	86.9	0	0	–	14.7	2.3	86.5	53.4	4.9	91.6
17	2	4	33.3	6.1	18.9	24.4	36.9	4.0	90.2	4.9	1.5	75.6	3.6	0	100.0	11.9	7.6	61.0
18	3	2	60.0	10.9	7.6	58.9	69.9	10.5	86.9	38.7	4.7	89.2	2.7	0	100.0	69.0	23.7	74.4
19	0	0	–	0	0	–	0	0	–	0	0	–	0.2	0.4	33.3	9.5	4.1	69.9
20	0	0	–	0	0	–	0.3	0.8	27.3	0	0	–	0.5	0.4	55.6	53.0	19.1	73.5
21	0	0	–	0	0	–	14.8	2.2	87.1	0	0	–	16.1	3.9	80.5	144.7	36.9	79.7
22	0	0	–	0	0	–	3.3	2.2	60.0	0	0	–	7.3	1.8	80.2	105.8	26.2	80.2
23	0	0	–	0	0	–	1.8	0.4	81.8	0	0	–	6.7	2.6	72.0	84.4	17.6	82.7
24	0	0	–	0	0	–	1.0	0	100.0	0	0	–	11.9	2.1	85.0	278.8	139.1	66.7
25	2	3	40.0	6.8	13.2	34.0	52.3	9.5	84.6	2.2	1.2	64.7	0	0.1	0	10.6	7.2	59.6
26	1	0	100.0	3.6	0	100.0	47.3	9.6	83.1	0.7	0.4	63.6	1.9	0	100.0	15.1	2.5	85.8
27	1	2	75.0	4.7	9.5	33.1	26.9	1.9	93.4	9.1	0.9	91.0	0.8	0	100.0	26.1	2.0	92.9
28	3	1	75.0	9.2	2.8	76.7	58.6	6.0	90.7	0.3	0	100.0	9.8	0.2	98.0	19.7	0	100.0
29	1	2	33.3	2.7	8.4	24.3	51.1	7.8	86.8	0	0	–	20.1	3.3	98.9	16.8	4.6	78.5
30	4	5	44.4	17.5	28.2	38.3	361.9	76.0	82.6	0	0	–	10.1	2.4	90.8	18.3	3.3	84.7
Total	52	69		191.9	307.6		1961.7	298.8		207.1	37.8		181.0	27.0		1605.0	463.4	
Mean	1.7	2.3	43.0	6.4	10.3	38.4	65.4	10.0	86.8	6.9	1.3	84.6	6.0	0.9	87.0	53.5	15.4	77.6
SE	0.3	0.4		1.3	1.9		12.7	2.5		2.4	0.4		1.0	0.2		9.7	4.5	

	Dover sole			Petrale sole			Pacific cod			Sablefish			Lingcod		
Tow	CE	RN	%R	CE	RN	%R	CE	RN	%R	CE	RN	%R	CE	RN	%R
1	21.0	1.2	94.6	134.4	24.7	84.4	73.7	8.7	89.4	50.5	1.1	97.9	6.7	1.2	84.8
2	30.7	2.0	93.9	369.7	64.2	85.2	337.6	12.2	96.5	88.8	14.9	85.6	132.1	12.0	91.7
3	5.9	0.5	92.2	107.6	47.7	69.3	71.5	2.7	96.4	6.9	0	100.0	102.7	2.7	97.4
4	5.7	1.2	82.6	130.4	48.6	72.8	68.5	2.6	96.3	11.9	1.2	90.8	80.4	5.9	93.2
5	2.4	0.5	82.8	68.3	17.1	80.0	244.1	26.8	90.1	13.4	0.6	95.7	26.3	9.6	73.3
6	4.7	0	100.0	101.2	25.8	79.7	61.8	8.5	87.9	22.5	4.4	83.6	15.4	0	100.0
7	4.2	0	100.0	68.7	20.0	77.5	71.6	10.2	87.5	23.0	6.1	79.0	17.7	1.7	91.2
8	10.1	0.9	91.8	160.6	22.8	87.6	29.5	10.7	73.4	23.7	3.2	88.1	76.5	5.9	92.8
9	3.4	0.1	97.1	103.6	20.1	83.8	11.7	2.4	83.0	14.7	1.8	89.1	84.4	5.7	93.7
10	8.3	0	100.0	116.1	28.2	80.5	144.5	22.3	86.6	52.4	3.4	93.9	207.6	7.2	96.6
11	3.3	0.4	89.1	158.0	33.6	82.4	59.1	7.1	89.3	35.0	8.6	80.3	109.2	17.7	86.1
12	13.8	1.3	91.4	194.8	43.7	81.7	453.0	36.8	92.5	7.1	2.0	78.0	48.1	4.4	91.6
13	16.4	1.8	90.1	140.3	22.7	86.1	152.0	20.0	88.4	11.0	0	100.0	225.7	17.7	92.7
14	9.2	0.5	94.8	163.4	34.8	82.4	168.3	40.0	80.8	3.2	0	100.0	342.9	28.5	92.3
15	10.3	1.2	89.6	121.0	39.7	75.3	23.3	0	100.0	4.2	1.7	71.2	148.0	44.7	76.8
16	7.8	0.4	95.1	104.4	24.2	81.2	84.3	3.9	95.6	11.0	0	100.0	108.4	6.1	94.7
17	4.0	0.7	85.1	64.8	21.6	75.0	7.0	0	100.0	3.4	2.6	56.7	20.2	7.8	72.1
18	9.8	0.9	91.6	115.1	21.5	84.2	4.9	2.4	67.1	9.9	0	100.0	145.7	14.7	90.8
19	4.0	0.4	90.9	5.8	0.8	87.9	0	0	–	0	0	–	15.2	0	100.0
20	13.5	1.3	91.2	41.9	14.6	74.2	6.7	3.7	64.4	0	0.9	0.0	40.7	5.4	88.3
21	114.9	17.7	86.7	67.2	25.2	72.7	39.3	0	100.0	88.0	31.7	73.5	139.6	19.8	87.6
22	257.0	59.8	81.1	91.5	35.5	72.0	14.4	0	100.0	50.3	3.7	93.1	25.6	14.3	64.2
23	166.4	31.5	84.1	70.5	13.1	84.3	1.2	1.1	52.2	15.1	1.5	91.0	3.7	1.6	69.8
24	33.9	6.2	84.5	17.2	4.6	78.9	0	0	–	20.3	1.5	93.1	26.4	2.5	91.3
25	4.9	0.8	86.0	77.5	25.6	75.2	175.3	18.2	90.6	48.0	12.6	79.2	25.6	0	100.0
26	4.7	0.8	85.5	97.7	22.3	81.4	97.7	11.1	89.8	31.2	6.6	82.5	34.7	1.5	95.9
27	2.1	0	100.0	77.4	13.9	84.8	71.6	22.5	76.1	31.9	5.1	86.2	20.4	4.8	81.0
28	12.7	2.1	85.8	87.0	17.6	83.2	51.4	8.6	85.7	5.1	1.5	77.3	80.1	1.6	98.0
29	12.6	1.1	92.0	103.1	22.4	82.2	17.9	0	100.0	2.4	1.5	61.5	27.8	1.7	94.2
30	93.2	19.7	82.6	243.7	62.8	79.5	20.3	6.3	76.3	10.9	0	100.0	28.4	0	100.0
Total	890.9	155.0		3,402.0	819.4		2,562.2	288.8		695.8	118.2		2,366.2	246.7	
Mean	29.7	5.2	85.2	113.4	27.3	80.6	85.4	9.6	89.9	23.2	3.9	85.5	78.9	8.2	90.6
SE	10.4	2.3		12.6	2.7		19.2	2.0		4.3	1.2		14.2	1.8	

Table 4
Statistical comparison of mean total lengths (cm) between target species and Pacific halibut caught in the recapture net and the codend. (1) = equal variance two-sample *t*-test; (2) = Mann–Whitney U test; (3) = Kolmogorov–Smirnov test; N_r = refers to the number of fish that were measured from the recapture net; N_c = refers to the number of fish that were measured from the codend.

Species	Recapture net mean total length (SE)	N_r	Codend mean total length (SE)	N_c	*P*-value
Flatfishes					
Pacific halibut	74.5 (0.8)	69	70.0 (0.8)	52	$<0.001_1$
English sole	33.5 (0.1)	525	33.0 (0.1)	656	0.201_2
Pacific sanddab	30.0 (0.1)	150	28.5 (0.1)	270	$<0.001_3$
Rex sole	33.0 (0.3)	118	31.0 (0.1)	486	$<0.001_2$
Arrowtooth flounder	48.0 (0.4)	333	48.5 (0.3)	666	0.257_2
Dover sole	37.5 (0.4)	160	34.0 (0.2)	572	$<0.001_3$
Petrale sole	35.5 (0.2)	717	36.0 (0.2)	734	$<0.001_3$
Roundfishes					
Pacific cod	61.5 (0.4)	116	59.0 (0.2)	498	$<0.001_2$
Sablefish	52.0 (0.5)	102	50.0 (0.3)	414	0.014_2
Lingcod	59.5 (0.6)	117	57.5 (0.2)	569	0.147_3

4. Discussion

The BRD examined in the present study was effective at reducing Pacific halibut bycatch while retaining a relatively high proportion of the targeted species, with the exception of big skate, and longnose skate. However, for several fishermen using Pacific halibut BRDs, similar to the design tested in the present study, to retain these species they often place a large mesh recapture bag (38.1–45.7 cm knot to knot) over the escape hole allowing larger-sized skates to be retained while still releasing Pacific halibut (personally communicated to Lomeli and Wakefield by regional commercial fishermen and net manufacturers). The BRD was most effective at excluding larger Pacific halibut, weighing greater than 4.5 kg. These findings are similar to Pacific halibut excluder studies conducted off Alaska (Rose and Gauvin, 2000; Craig Rose, NOAA Fisheries-Alaska Fisheries Science Center, Seattle, WA, personal communication). In the US west coast groundfish catch share program, where IBQ of Pacific halibut is allocated by weight, reducing the incidental catch of larger Pacific halibut is important to fishermen though it may not be as beneficial to conservation.

Because the trawl used in this study exhibits a cut back headrope and a low total rise, it is not an effective trawl design for retaining demersal fishes that rise when encountering the footrope or that are benthopelagic (Hannah et al., 2005; King et al., 2004; Parker et al., 2004). In a study of the behavior of demersal fishes encountering a bottom trawl, Rose (1996) observed that Pacific halibut rose over 1 m before entering the trawl. Pacific halibut greater than 50 cm were also observed to be the strongest swimmers, swimming as much as 2–10 m ahead of the trawl for as long as 8 min. Pacific halibut larger than 90 cm are commonly caught in the US west coast groundfish bottom trawl fishery (Wallace and Hastie, 2009). In the current study the largest Pacific halibut caught was 88.0 cm with the average being 73.0 cm (SE ± 0.6). This low capture rate of larger sized Pacific halibut is likely a combination of the low-rise trawl design used and the relatively short tow durations conducted. When King et al. (2004) compared a low-rise selective flatfish trawl to a conventional four-seam Aberdeen high-rise trawl, a significant difference in the mean length of Pacific halibut was found, with larger fish occurring in the high-rise trawl. This suggests that the BRD examined in the present study may be more effective in reducing Pacific halibut bycatch if used in a conventional trawl. Although tow durations exceeding 1–3 h are common commercial practice in the US west coast groundfish bottom trawl fishery, it is important to point out that short tow durations and/or the use of a low-rise trawl could serve as an additional technique for further reducing Pacific halibut bycatch.

Clogging of large skates and debris is an issue affecting the development and use of sorting grid BRDs in the US west coast bottom trawl fishery. Sorting grid BRDs with upward directed sorting panels or exit ramps can often have large fish (e.g. skates) or debris accumulate on them, causing the gear to clog or become less effective. In this work, the BRD design of two vertical panels and a downward-angled exit ramp appeared to be effective at retaining target species and reducing bycatch without clogging occurring. The “hallway” design of the BRD also appeared effective at crowding and stimulating fish to make attempts to pass through the vertical panels. However, it is important to point out that this behavior could have been in response to the artificial light from the video

Table 5
Generalized linear mixed model (GLMM) results, using a logit-linear model, examining if retention is length-related. β_0 = intercept; β_1 = length.

Species	Parameter	Estimate	SE	*P*-value
English sole	β_0	0.3545	0.7763	0.6485
	β_1	−0.0091	0.0233	0.6952
Pacific sanddab	β_0	4.8218	2.0430	0.0238
	β_1	−0.1585	0.0688	0.0271
Rex sole	β_0	4.7612	1.1870	0.0003
	β_1	−0.1286	0.0366	0.0011
Arrowtooth flounder	β_0	−1.1739	0.3979	0.0040
	β_1	0.0258	0.0079	0.0016
Dover sole	β_0	2.4730	0.8898	0.0093
	β_1	−0.0661	0.0243	0.0107
Petrale sole	β_0	−1.0279	0.3530	0.0040
	β_1	0.0305	0.0100	0.0027
Pacific cod	β_0	1.5158	1.6794	0.3733
	β_1	−0.0173	0.0279	0.5366
Sablefish	β_0	2.5857	1.0445	0.0204
	β_1	−0.0393	0.0202	0.0630
Lingcod	β_0	3.936	0.9783	0.0004
	β_1	−0.0609	0.0169	0.0011

camera systems, which can affect fish behavior around trawl gear (Lomeli and Wakefield, 2012; Ryer and Barnett, 2006; Walsh and Hickey, 1993). The circular ring systems are also thought to have contributed to the BRD performance as they created and maintained a consistent cylindrical shape and maintained an open space between the side panels of the experimental section of netting and the vertical panels ensuring fish passage aft toward the codend. This cylindrical shape was maintained until the experimental section of netting reached the surface during haulback. Throughout this project, the experimental section of netting and circular ring system were easy for the vessel crew to handle, came on and off the net drum smoothly, and added no additional steps to their fishing operations.

Developing techniques to reduce Pacific halibut bycatch while retaining a high proportion of the targeted species in the US west coast groundfish bottom trawl fishery are increasingly important. In the present study the BRD examined was effective at achieving this goal. Because research has demonstrated that fish behavior and activity (Hart et al., 2010; Ressler et al., 2009; Ryer et al., 2010), and catchability can differ between day and night (Petrakis et al., 2001; Walsh and Hickey, 1993), by depth (Casey and Myers, 1998; Hannah et al., 2005), and with differences in trawl design (Hannah et al., 2005; King et al., 2004), it is important that further testing occur over various fishing operations to better determine its effectiveness. The current BRD design is one of many Pacific halibut BRDs used in the US west coast and Alaska flatfish-directed bottom-trawl fisheries.

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Paper II

“Evaluation of a selective flatfish sorting grid bycatch reduction device in the U.S. west coast bottom trawl fishery”

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Evaluation of a sorting grid bycatch reduction device for the selective flatfish bottom trawl in the U.S. West Coast fishery

Mark J.M. Lomeli[a,*], W. Waldo Wakefield[b]

[a] Pacific States Marine Fisheries Commission, 2032 SE OSU Drive, Newport, OR 97365, USA
[b] Fishery Resource Analysis and Monitoring Division, Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 2032 SE OSU Drive, Newport, OR 97365, USA

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ABSTRACT

The U.S. West Coast limited entry groundfish trawl fishery is managed under an individual fishing quota program. For many fishermen targeting flatfishes in this fishery, catches of rockfishes (*Sebastes* spp.), sablefish (*Anoplopoma fimbria*), and Pacific halibut (*Hippoglossus stenolepis*) can be a concern because quota is limited relative to flatfish quotas. Thus, approaches to minimize bycatch of limiting species are important to the economic viability of the fishery. In this study, we examined the size-selection characteristics of a flexible sorting grid bycatch reduction device (designed to retain flatfishes while reducing catches of rockfishes, sablefish, and Pacific halibut) using a recapture net. The mean codend retention of target flatfishes (five species evaluated) ranged from 68.1% to 92.3%. Combined, the mean flatfish retention was 85.6%. Codend catches of shelf rockfishes, slope rockfishes, sablefish, and Pacific halibut were reduced by 80.3%, 64.0%, 97.0%, and 90.3% by weight, respectively. Significant differences in selectivity parameters between flatfishes, rockfishes, sablefish, and Pacific halibut were observed. Over fishing grounds where fishermen need a more selective trawl to harvest flatfishes, the experimental gear tested could provide fishermen a technique to reduce catches of non-target species.

1. Introduction

The U.S. West Coast limited entry (LE) groundfish bottom trawl fishery operates under a catch share program initiated in 2011 that allocates individual fishing quotas (IFQs) and establishes annual catch limits (ACLs) for over 30 groundfish managed units (stocks, stock complexes, and geographical subdivisions of stocks), and individual bycatch quotas for Pacific halibut (*Hippoglossus stenolepis*, a prohibited species) (PFMC and NMFS, 2010, 2012). In this program, fishermen are allocated a proportion of the fishery ACL with the option to transfer, lease, or permanently sell their quota to another shareholder. The catch share program was intended to improve the economic efficiency of the fishery, maximize fishing opportunities, and minimize bycatch. However, stocks with low ACLs have affected many fishermen's ability to maximize their quota shares of more abundant and productive stocks.

Over the continental shelf of the west coast a nearshore flatfish fishery occurs where over 10 healthy flatfish species are harvested. Dover sole (*Microstomus pacificus*) and petrale sole (*Eopsetta jordani*) are the top two species landed by weight and in ex-vessel value (PacFIN, 2015a,b). Fishermen's ability to fully utilize the available flatfish ACLs, however, has been constrained as a result of bycatch of darkblotched rockfish (*Sebastes crameri*), sablefish (*Anoplopoma fimbria*), and Pacific halibut. For example, recent catches of Dover sole have been approximately 6,087 mt (PacFIN, 2014) even though the shorebased trawl ACL was 22,234 mt (NMFS, 2014a) with catches of constraining species, such as darkblotched rockfish, sablefish, and Pacific halibut, as the primary cause preventing fishermen from maximizing their Dover sole IFQ.

Low-rise trawls (i.e., trawls with a low headrope height) with either a reduced top panel or a top panel constructed of large mesh are termed selective flatfish trawls and were developed to reduce bycatch in flatfish fisheries (King et al., 2004; Krag and Madsen, 2010; Madsen et al., 2006; Thomsen, 1993). This trawl was designed to allow non-flatfish species that have a tendency to rise when encountered an opportunity to escape before trawl entrainment. In the LE groundfish bottom trawl fishery, trawlers fishing shoreward of 183 m water depth and north of 40°10′N latitude are required to use a two-seam low-rise selective flatfish trawl to minimize bycatch of rockfishes (NMFS, 2014b). This trawl significantly reduces catches of canary rockfish (*S. pinniger*) and other benthopelagic groundfishes, for example, redstripe rockfish

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* Corresponding author.
E-mail address: mlomeli@psmfc.org (M.J.M. Lomeli).

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(*S. proriger*) and Pacific hake (*Merluccius productus*), while maintaining flatfish catch levels (King et al., 2004; Parker et al., 2004). However, the selective flatfish trawl has been less effective at reducing catches of some of the more benthic rockfishes and other roundfishes (e.g., darkblotched rockfish and sablefish), restricting some fishermen's ability to fully reach their flatfish IFQs, particularly for Dover sole.

In the LE groundfish bottom trawl fishery, Lomeli and Wakefield (2013, 2015) examined Pacific halibut flexible sorting grid (size selection panels with square or rectangular openings) bycatch reduction devices (BRDs) designed for harvesting assemblages of roundfishes and flatfishes. These studies have demonstrated that flexible sorting grid BRDs can be effective at reducing bycatch in the groundfish fishery, are easy for the vessel crew to handle, and add no additional steps to the fishing operations. In 2014, Lomeli and Wakefield (2015) designed a selective flatfish flexible sorting grid BRD for use in the nearshore flatfish fishery. This BRD utilizes two vertical sorting panels with long rectangular slots to allow flatfishes to pass through and move aft towards the codend while excluding larger-sized rockfishes, other roundfishes, and Pacific halibut. Results from this initial work (using a recapture net to quantify fish escapement out the BRD) showed a mean flatfish retention of 85.1% by weight while reducing catches of non-target species by over 72%. Modeling the size-selective properties of the BRD, however, was not performed in the study. The purpose of the current study was to model the size-selection parameters of the BRD developed by Lomeli and Wakefield (2015) for roundfishes, Pacific halibut, and other flatfishes.

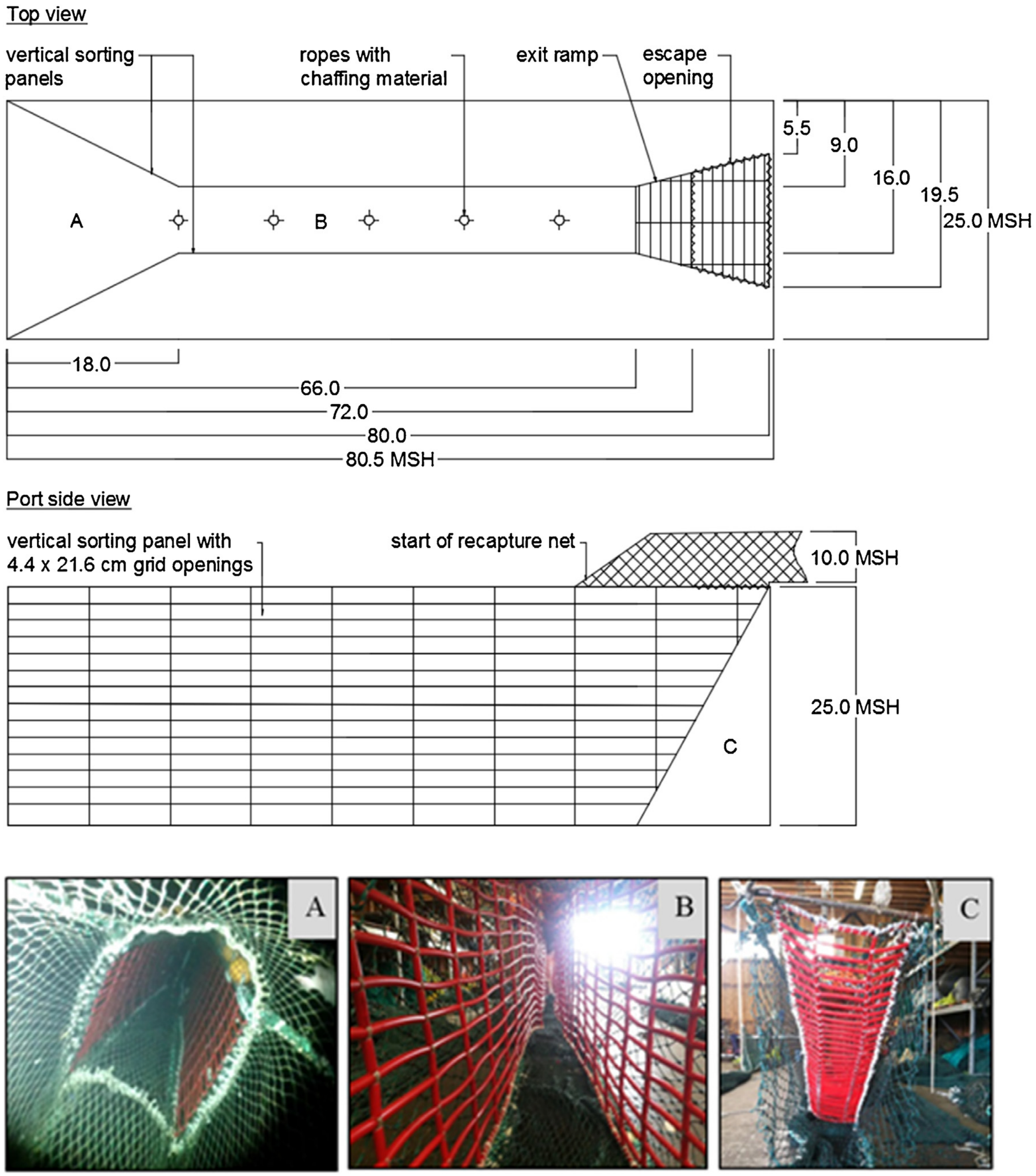

Fig. 1. Schematic diagram of the flexible sorting grid tested (top); aft view of the forward portion of the gear where fish enter and encounter the device (image A); aft view of the "hallway" section of the gear being built (image B); fore view of the upward-angled exit ramp (image C). MSH = meshes. *Note:* schematic diagram is not drawn to scale.

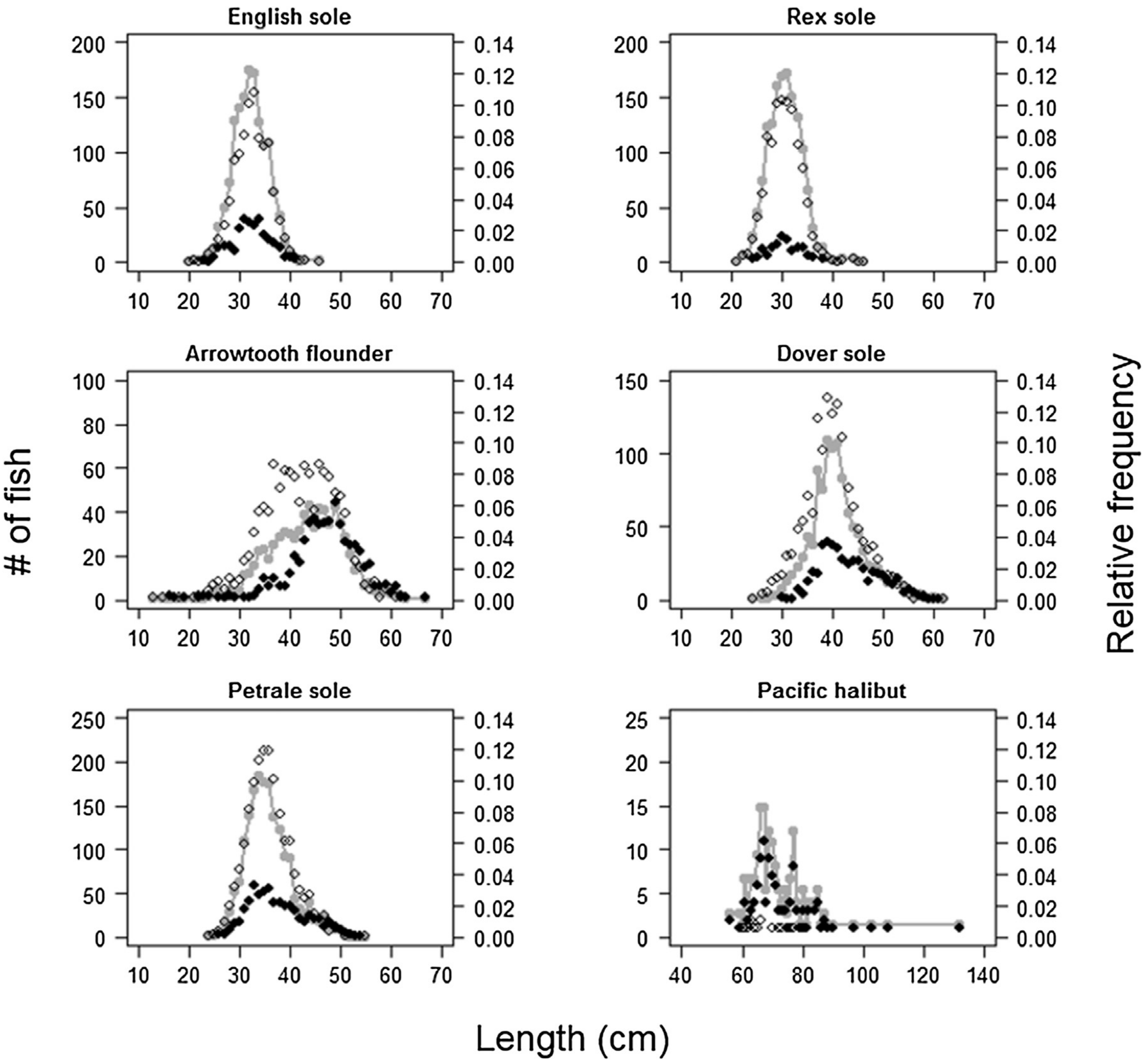

Fig. 2. Number of English sole, rex sole, arrowtooth flounder, Dover sole, petrale sole, and Pacific halibut measured per length from both the codend (open circles) and recapture net (closed black circles) and their length frequency distribution (closed grey circles).

2. Materials and methods

2.1. Trawl design

The trawl used for this study was a two-seam Eastern 400 low-rise selective flatfish trawl with a cutback headrope. The headrope was 40.3 m in length, and the chain footrope was 31.2 m in length and covered with rubber disks, 17.8 cm in diameter. Past research has shown headrope height for this trawl to range between 1.25 and 1.3 m (Hannah et al., 2005; King et al., 2004). This trawl was specifically designed to allow fish that have a tendency to rise when encountering the footrope to escape. This trawl also lacks floats along the central portion of the headrope to reduce any diving behavior by fish in reaction to floats.

2.2. BRD design

The BRD examined in this study is the same device tested by Lomeli and Wakefield (2015) in the nearshore flatfish fishery. The BRD was constructed within a four-seam tube of netting (Fig. 1, Table 1) and inserted between the intermediate section of the trawl and the codend. A 50 mesh deep two-seam to four-seam transi-

Table 1
Specifications of the gear tested. Mesh sizes (mm) are stretched measurements between-knots. DM = diamond mesh; sngl. = single; dbl. = double; LL = long link. * = does not account for meshes gored in each selvedge.

	BRD	Recapture net	Trawl codend
Netting	116 mm DM	116 mm DM	116 mm DM
Twine	4 mm sngl. (top and side panels); 5 mm dbl. (bottom panel)	6 mm dbl.	6 mm dbl.
Circumference*	100	70	88
Meshes deep	80	100	75
Top riblines	32 mm Blue Steel^{TM} Poly rope, hung at 6%	12.7 mm Blue Steel^{TM} Poly rope, hung at 6%	32 mm Blue Steel^{TM} Poly rope, hung at 6%
Bottom riblines	12.7 mm LL chain, hung at 6%	12.7 mm Blue Steel^{TM} Poly rope, hung at 6%	32 mm Blue Steel^{TM} Poly rope, hung at 6%

Table 2
Catch data by weight (kg) from the 38 tows conducted for five flatfish species. recap = recapture net; SE = standard error.

Tow	English sole		Rex sole		Arrowtooth flounder		Dover sole		Petrale sole	
	recap	codend	recap	codend	recap	codend	recap	codend	recap	codend
1	1.4	18.2	0.1	4.4	0	0	0	0.4	1.1	48.7
2	6.2	130.8	0.4	3.3	0	0	0	0	7.8	171.2
3	3.1	47.0	1.0	11.7	17.9	46.8	0	14.5	0	8.4
4	1.4	89.3	0.8	0.9	0	0.2	0	0	33.6	1,348.8
5	14.1	212	0.4	7.1	0	1.3	2.2	21.0	14.9	230.1
6	1.4	28.7	0	6.8	78.2	176.0	1.9	76.6	17.7	429.3
7	0	0	0	7.2	1.0	26.1	3.9	63.4	12.7	175.1
8	0	1.2	0.7	3.8	1.6	11.5	16.6	62.0	7.8	143.2
9	0	0.8	0	2.8	0	3.6	0.9	6.8	7.4	86.2
10	0	3.7	0.1	1.0	0	0	0	1.0	4.9	41.3
11	0	0.3	0	1.7	7.3	13.7	9.0	46.8	8.5	37.4
12	0	0	0.3	2.3	21.3	47.8	5.0	25.7	0	1.5
13	0	0.1	0	3.0	32.5	155.3	4.5	34.4	4.0	129.7
14	0	0.4	0	0.6	23.5	36.4	3.2	25.3	18.1	122.4
15	0.4	0	0	0.7	6.0	6.1	2.5	9.5	2.9	14.9
16	0	0	0	1.4	29.9	9.9	4.3	9.5	0	0
17	1.2	4.2	0	1.6	0	6.3	43.8	72.0	21.2	69.6
18	0.1	5.3	0.1	1.4	1.5	0	10.2	35.6	3.2	13.9
19	1.0	4.4	0	0.7	0	0	0	2.0	41.5	273.3
20	0.9	1.4	0	1.5	27.0	97.2	18.5	96.8	41.0	196.3
21	0.9	0.7	0.7	10.8	12.6	12.2	23.2	142.7	3.0	7.0
22	0	0	1.8	21.0	94.0	71.3	21.0	90.2	0	0
23	0	0	0.4	18.1	53.4	135.8	49.4	774.3	0	0
24	0.9	9.0	1.5	1.0	5.7	14.8	1.6	10.7	7.1	71.4
25	0	0	1.1	12.3	126.6	293.2	11.7	213.7	12.1	5.7
26	0.4	0.7	2.9	20.3	58.9	94.1	24.1	195.6	0	0.8
27	1.7	9.7	0.9	6.8	5.7	37.8	74.8	236.5	0	0.5
28	30.1	269.1	0.8	12.6	1.7	30.7	1.9	17.4	70.5	831.6
29	0	4.2	0.5	5.6	26.5	44.2	7.1	25.3	13.4	40.9
30	0	0.5	4.2	20.3	153.5	329.9	38.3	284.8	4.1	49.3
31	0	0.5	4.3	33.7	251.3	465.4	25.6	128.9	0	5.4
32	0.6	6.3	0.2	5.1	28.7	59.7	2.1	9.0	16.7	136.6
33	11.3	75.8	0.2	4.8	0.2	0.3	0.4	1.5	34.9	454.7
34	2.0	65.8	0.3	5.3	0	1.3	0	1.8	30.8	628.5
35	49.1	264.0	2.2	12.7	7.9	7.6	2.5	29.2	81.4	556.5
36	0	7.5	2.1	9.5	25.9	50.7	28.9	106.3	0	30.9
37	0.8	5.7	0.3	1.6	52.9	156.8	13.9	43.5	61.7	603.0
38	0	1.7	0	2.7	10.4	35.1	0	102.7	11.2	124.7
Total	129.0	1,269.0	28.3	268.1	1,163.6	2,479.1	453.0	3,017.4	595.2	7,088.8
Mean	3.4	33.4	0.7	7.1	30.6	65.2	11.9	79.4	15.7	186.6
SE±	1.5	11.4	0.2	1.2	8.3	16.7	2.7	22.1	3.3	46.1
Retention	90.8%		90.5%		68.1%		86.9%		92.3%	

tional tube of netting connected the trawl to the BRD. The design utilizes two vertical panels, with 4.4 cm high and 21.6 cm long slot-like openings, that extend longitudinally down the tube of netting. The concept to the design is that fish smaller than the grid openings could pass through and move aft towards the codend, whereas fish larger than the grid openings would be excluded. Fish that do not pass through the grid openings are guided by the exit ramp and exit out the top of the trawl. Within the BRD area, ropes with chafing material wedged through them were installed to create a partial obstruction to fish moving aft and stimulate fish to interact with the vertical panels. At the aft end of the BRD, the top portion of the vertical panels angle outward to allow for integration of the exit ramp and the associated escape opening. The trawl codend was a four-seam tube of 116 mm netting. For further detail of the BRD refer to Lomeli and Wakefield (2015).

2.3. *Sea trials and sampling*

Sea trials occurred aboard the *F/V Miss Sue*, a 24.7 m long, 640 horsepower trawler out of Newport, Oregon, USA. We completed a total of 38 tows off central Oregon between 43°50′ and 45°19′N and between 124°10′ and 124°52′W in June 2014. Towing occurred over the continental shelf during daylight hours, between 0651 and 1820 Pacific daylight time, at bottom fishing depths from 106 m to 256 m. The average bottom fishing depth was 174 m (SE ± 3.1 m). Average tow duration was 1 h. (SE ± 4.8 min). Towing speed over ground ranged from 2.2 to 2.6 knots.

We used a recapture net to quantify fish escapement and retention by weight. The recapture net was a four-seam tube of 116 mm netting that was 100 meshes deep and 70 meshes in circumference (25 meshes on the top and bottom panel; 10 meshes on the side panels), excluding meshes in each selvedge (Table 1). Because a codend cover was not used to capture fish passing through the meshes of the trawl codend, the mesh of the recapture net needed to be the same size as the trawl for a direct catch comparison. The recapture net was attached to the BRD just forward of the escape opening to allow excluded fish to be captured. To keep the recapture net from masking the escape opening, two 20.3 cm center-hole floats were placed on each top ribline of the recapture net, above the escape area of the BRD, while two 27.9 cm ear-floats were placed on the top panel webbing in the middle (between the top riblines) of the recapture net. At the start of the study, an autonomous underwater video camera system was used to examine the recapture net and ensure the net was not masking the escape opening. Video confirmed that the recapture net was not masking the escape opening. All 38 tows occurred without the use of video cameras and artificial lights.

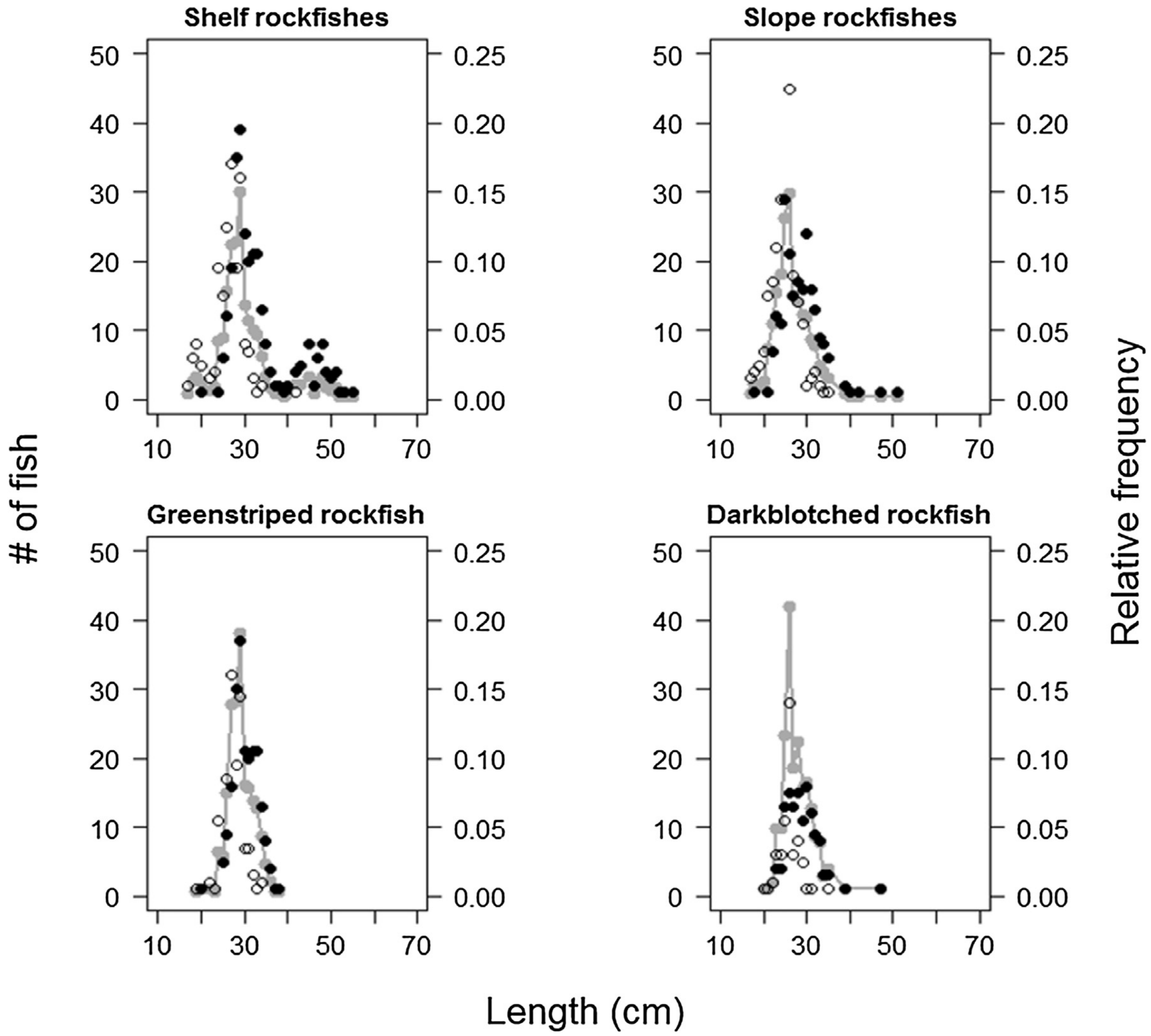

Fig. 3. Number of shelf and slope rockfishes, greenstriped rockfish, and darkblotched rockfish measured per length from both the codend (open circles) and recapture net (closed black circles) and their length frequency distribution (closed grey circles).

After each tow, all fish caught in the trawl and recapture net were identified to species and weighed using a motion compensated platform scale. Individuals of each species (for species of interest in this study) from each the trawl and recapture net were randomly selected per tow and measured to the nearest cm fork length. Subsampling of flatfishes (not including Pacific halibut), sablefish, and lingcod (*Ophiodon elongatus*) were avoided when possible, however, time constraints and relatively large catches of these species often required subsampling for length measurements. All Pacific halibut, and shelf and slope rockfishes (*Sebastes* spp.) were measured. Figs. 2–4 depict the total number of fish measured per species per length from both the codend and recapture net and their length frequency distributions.

2.4. Selectivity analysis

The statistical analysis software SELNET (SELection in trawl NETting) was used to analyze the data (Sistiaga et al., 2010; Herrmann et al., 2012). The *Clogit* model function was used as this method estimates the likelihood that fish entering the grid area will contact the grid system (denoted as C_{grid}):

$$r(l,\ v) = Clogit(l, L50_{\text{grid}}, SR_{\text{grid}}, C_{\text{grid}})$$

$$\equiv 1 - C_{\text{grid}} \times (1 - logit(l, L50_{\text{grid}}, SR_{\text{grid}}))$$

Values range from $0 \leq C_{\text{grid}} \leq 1$, with $C_{\text{grid}} = 1$ meaning all fish contacted the grid and attempted to pass through. $L25_{\text{grid}}$, $L50_{\text{grid}}$,

Table 3
Clogit model mean selectivity results for six flatfishes. Values in parentheses are Efron percentile bootstrap 95% confidence limits. *df* = degrees of freedom; * = value not defined.

Species	$L25_{\text{grid}}$	$L50_{\text{grid}}$	$L75_{\text{grid}}$	SR_{grid}	C_{grid}	p-value	Deviance	*df*
Pacific halibut	* (*–55.3)	* (*–59.9)	* (*–65.6)	* (*–29.6)	0.15 (0.08–0.99)	0.857	23.6	23
English sole	55.0 (40–197.1)	63.1 (41.8–198.4)	70.2 (42.1–203.8)	15.2 (0.3–102.1)	0.92 (0.88–0.99)	0.015	38.5	22
Rex sole	143.1 (42.6–196.3)	192.8 (44.1–197.3)	236.1 (44.1–228.9)	93.0 (0.1–108.7)	0.91 (0.88–0.99)	0.432	22.5	22
Arrowtooth flounder	45.3 (42.3–48.3)	54.8 (50.3–59.1)	63.8 (57.8–72.8)	18.5 (11.3–25.7)	0.97 (0.86–0.99)	0.000	99.9	47
Dover sole	54.4 (48.3–61.2)	68.5 (56.0–79.4)	82.5 (61.3–98.7)	28.0 (10.7–38.4)	0.99 (0.91–0.99)	0.063	48.6	35
Petrale sole	49.0 (47.2–51.9)	53.5 (48.4–58.6)	57.8 (53.4–69.3)	8.8 (5.4–18.1)	0.95 (0.93–0.99)	0.005	51.9	29

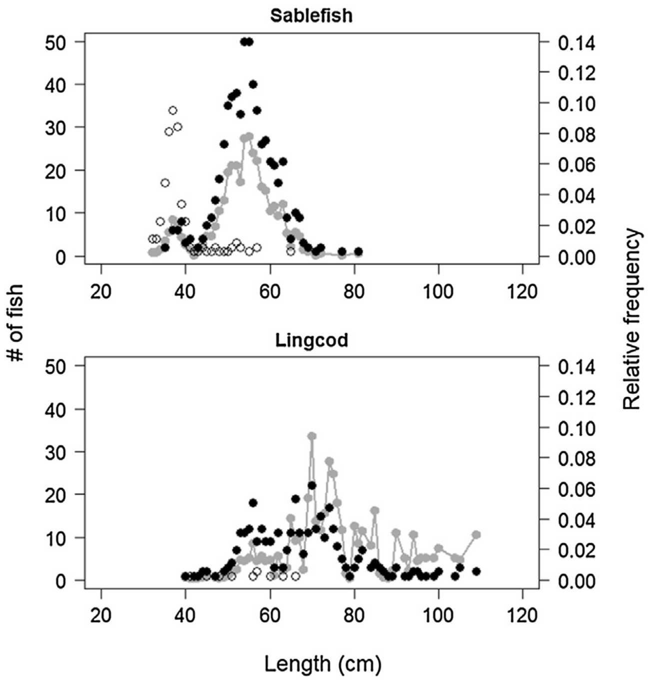

Fig. 4. Number of sablefish and lingcod measured per length from both the codend (open circles) and recapture net (closed black circles) and their length frequency distribution (closed grey circles).

and $L75_{\text{grid}}$ values are defined as the length where 25%, 50%, and 75% of fish, respectively, have the probability of contacting and passing through a grid opening. SR_{grid} is the difference between $L25_{\text{grid}}$ and $L75_{\text{grid}}$. Fit statistics to indicate that the *Clogit* model adequately describes the data are p-values > 0.05, and deviances not to exceed degrees of freedom by approximately two times.

Selection curves were estimated by pooling haul data. All tows and length classes caught were used in the analysis. Efron percentile 95% confidence interval (CI) limits (Efron, 1982) for $L25_{\text{grid}}$, $L50_{\text{grid}}$, $L75_{\text{grid}}$, SR_{grid}, and C_{grid} were estimated off 1,000 bootstrap repetitions using a double bootstrapping method implemented in SELNET to account for both within-haul and between-haul variation. This approach is the same method used by Sistiaga et al. (2010) and Herrmann et al. (2012) to avoid underestimating CI limits for selectivity curves when pooling haul data. For complete *Clogit* model details see Sistiaga et al. (2010) and Herrmann et al. (2013).

3. Results

Flatfishes, not including Pacific halibut, comprised 58.4% (by weight) of the total catch. The remaining 41.6% of the total catch consisted of 32 species and included shelf and slope rockfishes, sablefish, lingcod, skates (Rajidae), unmarketable groundfishes, and Pacific halibut. English sole (*Parophrys vetulus*), rex sole (*Glyptocephalus zachirus*), arrowtooth flounder (*Atheresthes stomias*), Dover sole, and petrale sole accounted for 98.2% of the total flatfish catch for the trawl and recapture net combined.

3.1. Flatfishes

For the flatfishes evaluated (not including Pacific halibut), percent codend retention ranged from 68.1% to 92.3% (Table 2) with retention being highest, in descending order, for petrale sole (92.3%), English sole (90.8%), rex sole (90.5%), and Dover sole (86.9%). Arrowtooth flounder, the lowest valued flatfish in this fishery, exhibited the lowest retention, 68.1%. Compared to the other flatfishes evaluated, arrowtooth flounder were larger in size (in both body thickness and length) than the other flatfishes caught, likely explaining this species low retention. For these five flatfishes combined, the overall retention was 85.6%.

Arrowtooth flounder, Dover sole, and petrale sole displayed significantly larger mean $L50_{\text{grid}}$ values than shelf and slope rockfishes, and sablefish. Mean $L50_{\text{grid}}$ values did not differ significantly between arrowtooth flounder, Dover sole, and petrale sole as indicated by their overlapping 95% CI limits (Table 3). While selectivity parameters were modeled for English sole and rex sole, high codend retention rates across all length classes (Fig. 5) resulted in the model generating mean $L50_{\text{grid}}$ values beyond these fishes maximum size in length, 61 cm (Love, 2011). Mean C_{grid} values (ranging from 0.91 to 0.99) showed flatfishes (not including Pacific halibut) displayed a high probability of contacting the grid system (Table 3).

Table 4

Comparison of mean lengths (cm) between fish caught in the recapture net and the codend. n_r = number of fish measured from the recapture net; n_c = number of fish measured from the codend; n_h = number of hauls that the species was encountered; $_1$ = silvergray, widow, yellowtail, and rosethorn rockfishes, and chilipepper; $_2$ = aurora, and rougheye rockfishes, and Pacific ocean perch. * = subsample lengths taken from a larger species catch.

Species	Mean length (95% CI)				
	recapture net	n_r	codend	n_c	n_h
	Flatfishes				
Pacific halibut	73 (70.9–74.7)	117	68 (64.4–71.2)	17	21
English sole	32 (32.0–32.8)	326	33 (32.4–32.8)	1212*	32
Rex sole	30 (30.0–31.0)	150	30 (30.2–30.5)	1243*	38
Arrowtooth flounder	47 (46.3–47.5)	552*	42 (41.6–42.4)	1140*	33
Dover sole	43 (42.7–43.8)	469*	40 (39.7–40.3)	1489*	36
Petrale sole	38 (37.3–38.1)	688*	36 (35.8–36.2)	2115*	35
	Shelf rockfishes				
Greenstriped rockfish	30 (29.8–30.6)	208	26 (27.1–27.9)	138	21
Canary rockfish	46 (44.8–47.2)	39	–	0	7
Stripetail rockfish	28 (26.5–29.1)	10	23 (21.7–23.7)	49	7
Other (5 species)$_1$	40 (34.7–44.3)	21	28 (22.1–34.1)	7	11
	Slope rockfishes				
Redbanded rockfish	33 (30.7–35.8)	23	26 (22.9–28.3)	5	7
Splitnose rockfish	24 (23.5–24.5)	45	23 (22.4–23.6)	86	5
Darkblotched rockfish	29 (28.2–29.4)	128	26 (25.4–26.4)	77	9
Sharpchin rockfish	30 (28.4–30.8)	14	26 (25.1–26.6)	54	5
Other (3 species)$_2$	34 (14.4–52.6)	2	25 (20.7–29.8)	11	5
	Roundfishes				
Sablefish	54 (54.0–55.0)	602*	38 (37.7–39.3)	170	28
Lingcod	68 (66.3–68.8)	351*	53 (47.2–58.0)	12	33

Table 5
Catch data by weight (kg) from the 38 tows conducted for shelf rockfishes, slope rockfishes, sablefish, lingcod, and Pacific halibut. ^{1} = silvergray, widow, yellowtail, rosethorn, greenstriped, canary, and stripetail rockfishes, and chilipepper; ^{2} = redbanded, splitnose, aurora, rougheye, darkblotched, and sharpchin rockfishes, and Pacific ocean perch; recap = recapture net; SE = standard error.

Tow	Shelf rockfishes^1		Slope rockfishes^2		Sablefish		Lingcod		Pacific halibut	
	recap	codend	recap	codend	recap	codend	recap	codend	recap	codend
1	0	0	0	0	0	0	5.2	0	13.3	3.1
2	0	0	0	0	0	0	10.7	3.3	6.3	0
3	17.0	17.0	4.0	12.7	307.6	3.8	61.5	1.5	7.0	0
4	25.2	0.2	0	0	0	0	941.9	0	0	0
5	0	0	0	0	9.9	15.5	4.3	0	23.4	3.7
6	0	0.5	0	0	0	8.0	52.8	0	8.0	4.0
7	0.6	1.1	0	0	2.2	2.2	6.0	0	5.7	0
8	0	0	0	0	0.5	4.7	4.0	0	0	0
9	0	0	0	0	0	1.7	3.3	0	0	0
10	1.8	0	0	0	0	0	3.3	0	9	0
11	0	0	0	0	0	1.7	0	0	0	0
12	2.1	1.8	37.9	17.2	28.8	8.1	9.1	0	0	0
13	50.6	6.8	0	0.2	2.0	6.8	4.0	0.4	0	0
14	0.8	0	0	0	0	1.5	15.1	0	14.5	0
15	0	0	0	0	0	0	0	0	7.9	0
16	0	0	0	0	4.7	2.8	0	0	0	0
17	0	0	0	0	0	0	11.3	1.9	0	0
18	0	0	0	0	0	0.3	12.1	0	0	0
19	0	0	0	0	0	0	20.3	0	36.9	0
20	0.5	0	0	0	0	0	136.8	3.2	0	0
21	0.3	0	26.6	5.5	37.2	0	2.9	0	0	0
22	0	0	5.3	2.1	82.5	0	5.5	0	0	0
23	7.0	1.4	5.5	2.9	606.4	10.8	0	0	0	0
24	0.8	0	0	0	1.0	0	10.5	0	0	0
25	0	0.2	0	0	558.1	8.9	2.9	0	0	0
26	1.2	0	3.6	2.2	570.1	2.8	0	0	0	0
27	0	1.0	1.2	0	355.4	9.9	2.2	0	0	0
28	29.4	6.4	0	0.5	1.5	1.2	180.7	0	59.2	7.3
29	0	0	0	0	1.3	0	10.5	0	32.1	0
30	5.3	2.4	2.2	2.5	11.6	0	49.9	3.3	54.0	0
31	4.0	1.9	4.2	4.3	6.7	0	35.7	0	81.1	5.0
32	1.5	0	0.3	0	0.5	0.5	0.7	0	10.0	0
33	6.4	6.7	0	0	0	0	58.2	2.7	40.4	20.0
34	38.6	0.9	2.6	0	0	0	3593.6	0	26.1	4.7
35	16.7	2.5	0	0	0.5	0.8	47.8	0	76.9	14.0
36	0.5	2.0	5.8	5.8	428.6	1.9	1.6	0	0	0
37	3.0	0	0	0	1.6	0	20.4	0	14.6	0
38	1.4	0	0	0	0	1.0	46.9	0	51.8	0
Total	214.7	52.8	99.2	55.9	3,018.7	94.9	5,371.7	16.3	578.2	61.8
Mean	5.7	1.4	2.6	1.5	79.4	2.5	141.4	0.4	15.2	1.6
SE ±	1.9	0.5	1.2	0.6	28.9	0.6	96.6	0.2	3.7	0.7
Retention	19.7%		36.0%		3.0%		0.3%		9.7%	

A total of 134 Pacific halibut were caught in the recapture net and trawl combined (Table 4). Pacific halibut ranged from 56 to 132 cm (mean 72 cm, 95% CI 70.4–73.9 cm) in length. Over this size range, a mean retention of 9.7% was noted, a bycatch reduction of 90.3% by weight (Table 5). Of the 134 Pacific halibut encountered, two (72 cm and 75 cm in length) were caught wedged in a sorting grid opening of the BRD. Too few Pacific halibut were retained in the trawl per each length class to fully model their selectivity parameters. Only one tow (tow 35, Table 5) occurred where $L50_{\text{grid}}$ could be estimated. For this tow, the $L50_{\text{grid}}$, SR_{grid}, and C_{grid} values were 63.7 cm, 2.4 cm, and 0.99, respectively.

Acceptable fit statistics were observed for Pacific halibut, rex sole, and Dover sole (Table 3). However, p-values < 0.05 for English sole, arrowtooth flounder, and petrale sole required further assessment to determine if the model was adequately describing the data for these species. The assessments indicated the small p-values were due to overdispersion of the data rather than the inability of the model to adequately describe the data. Mean selection curves for the flatfishes evaluated are shown in Fig. 5.

Table 6
Clogit model mean selectivity results for rockfishes and other roundfishes. Values in parentheses are Efron percentile bootstrap 95% confidence limits. *df* = degrees of freedom; * = not defined; $_1$ = silvergray, widow, yellowtail, and rosethorn rockfishes, and chilipepper; $_2$ = aurora, and rougheye rockfishes, and Pacific ocean perch.

Species	$L25_{\text{grid}}$	$L50_{\text{grid}}$	$L75_{\text{grid}}$	SR_{grid}	C_{grid}	p-value	Deviance	*df*
Shelf rockfishes$_1$	25.2 (22.2–26.2)	27.9 (27.0–28.7)	30.5 (29.5–32.1)	5.3 (3.7–8.4)	0.99 (0.79–0.99)	0.877	23.0	32
Greenstriped rockfish	24.9 (*–26.4)	28.0 (25.2–30.7)	30.5 (30.1–35.3)	5.5 (*–14.0)	0.89 (0.65–0.99)	0.311	18.2	16
Slope rockfishes$_2$	22.8 (*–27.9)	26.8 (24.2–30.7)	30.6 (28.2–33.7)	7.8 (*–10.5)	0.98 (0.60–0.99)	0.225	25.5	21
Darkblotched rockfish	18.8 (*–29.0)	26.2 (24.9–29.9)	28.8 (28.1–31.5)	10.0 (*–10.0)	0.76 (0.52–0.99)	0.303	17.3	15
Sablefish	37.6 (36.2–40.3)	40.4 (38.8–42.0)	43.2 (42.4–45.1)	5.6 (4.1–6.7)	0.99 (0.98–0.99)	0.104	50.4	39
Lingcod	26.1 (*–40.1)	38.8 (* –77.7)	45.6 (*–49.7)	19.5 (*–40.1)	0.78 (0.04–0.99)	0.996	32.2	57

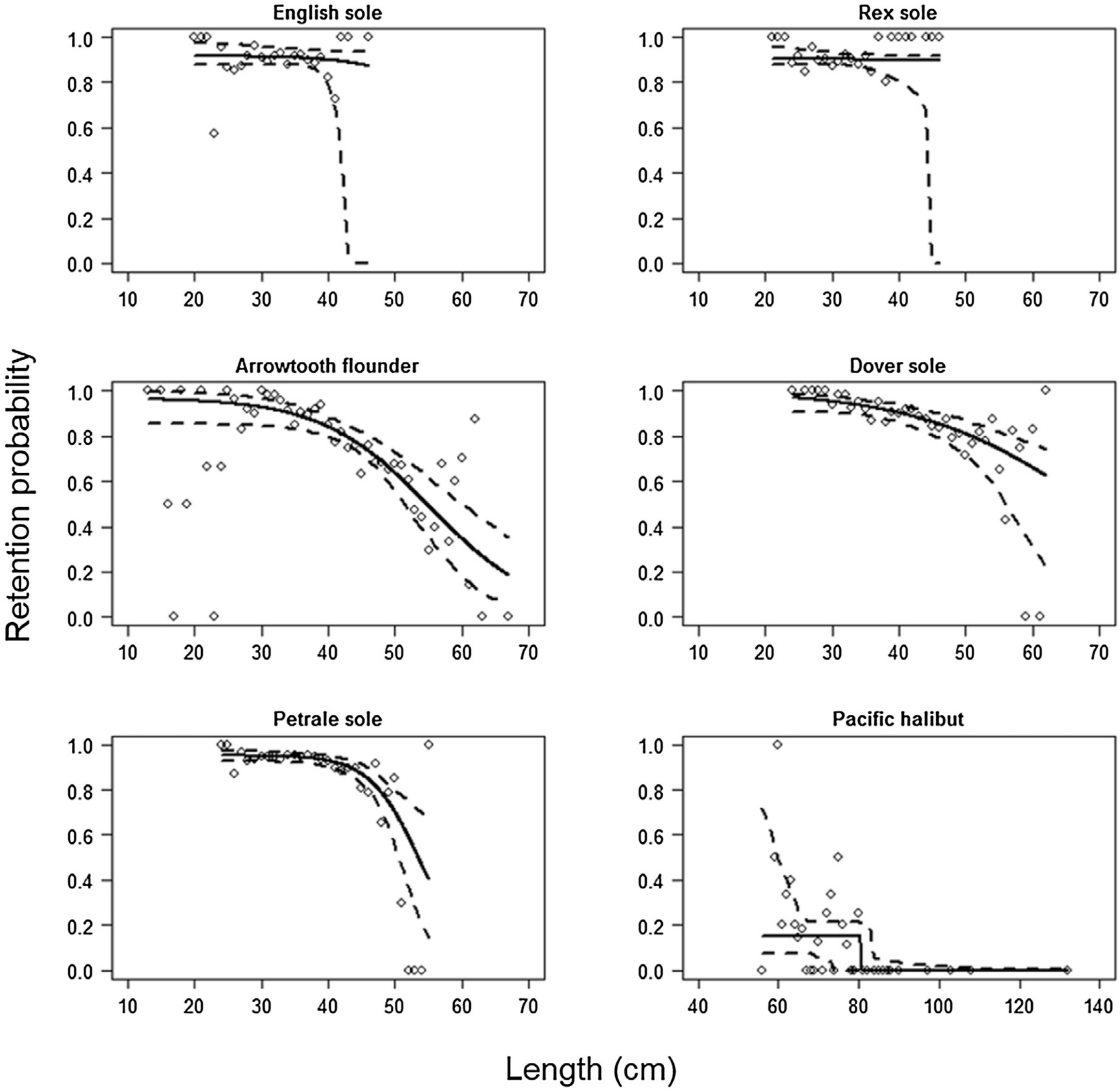

Fig. 5. Mean selectivity curves showing the probability of retaining English sole, rex sole, arrowtooth flounder, Dover sole, petrale sole, and Pacific halibut by length in the trawl codend. Circles are the experimental data; solid lines are the modeled value; dashed lines are upper and lower 95% confidence interval limits.

3.2. Rockfishes and other roundfishes

Catches of shelf and slope rockfishes were reduced by 80.3% and 64.0% by weight, respectively (Table 5). Greenstriped rockfish (*S. elongatus*) was the most frequently encountered shelf rockfish by numbers, whereas darkblotched rockfish was the most frequently encountered slope rockfish by numbers (Table 4). The mean $L50_{\text{grid}}$ value for greenstriped rockfish and darkblotched rockfish were 28.0 and 26.2 cm, respectively (Table 6). The likelihood of contacting the grid system was 0.89 for greenstriped rockfish and 0.76 for darkblotched rockfish. Mean selection curves for shelf and slope rockfishes are shown in Fig. 6.

Codend catches of sablefish and lingcod were reduced by over 96% (Table 5). The mean $L50_{\text{grid}}$ value for sablefish was 40.4 cm. The probability of sablefish entering the grid area and contacting the grid system was 0.99. Mean selectivity parameters were modeled for lingcod (Table 6). However, as only a few individuals were retained in the trawl codend (12 fish, Table 4) large CI limits around the mean selectivity values resulted. Mean selection curves for sablefish and lingcod are shown in Fig. 7.

4. Discussion

Trawl modifications that can provide fishermen increased access to healthy flatfish stocks are increasingly important to fishermen and the IFQ program. In this study, the BRD evaluated retained a relatively high proportion of petrale sole, English sole, rex sole, and a moderate proportion of Dover sole. Substantial catch reductions for arrowtooth flounder, a secondary target species, occurred (31.9% reduction by weight). As shown in the *Clogit* model, the BRD was highly effective at minimizing catches of rockfishes, other roundfishes, and Pacific halibut. Over fishing grounds where fishermen need a more selective trawl to harvest flatfishes, the BRD tested could provide fishermen a technique to reduce catches of non-target species. In this fishery, where quota is deducted by weight, reducing catches of larger-sized non-target species is also important to fishermen as larger-sized fish have a greater impact on their IFQs. Further modification of the BRD, such as increasing the widths and/or lengths of the rectangular grid openings, could potentially improve retention of arrowtooth flounder and other flatfishes, while still effectively reducing catches of non-

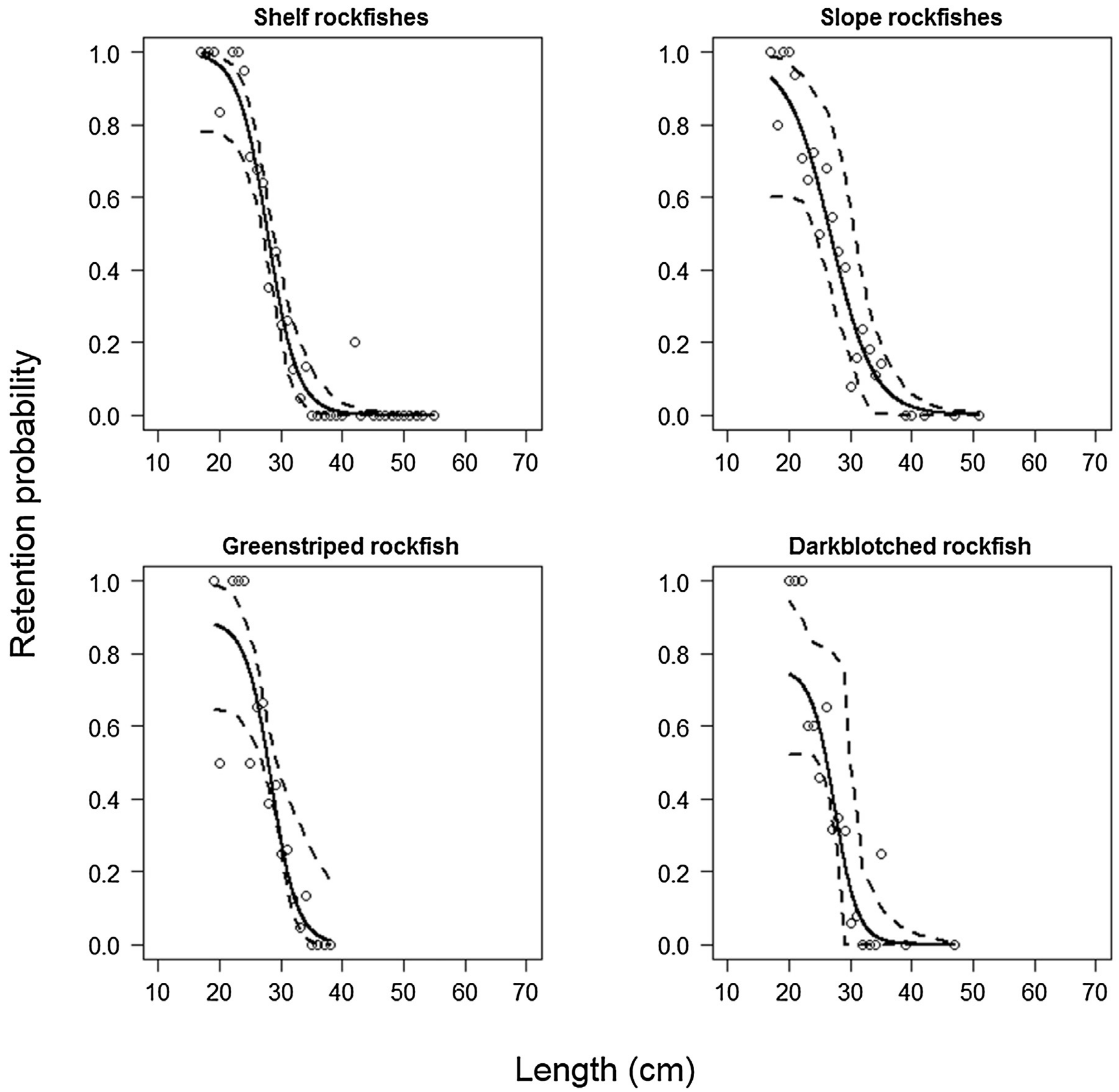

Fig. 6. Mean selectivity curves showing the probability of retaining shelf and slope rockfishes, greenstriped rockfish, and darkblotched rockfish by length in the trawl codend. Circles are the experimental data; solid lines are the modeled value; dashed lines are upper and lower 95% confidence interval limits.

target species. This study has provided an understanding of the BRD size-selective characteristics.

Low-rise trawls with cutback headropes (i.e., reduced top panels) have been developed to reduce bycatch in flatfish trawls (Hannah et al., 2005; King et al., 2004; Krag and Madsen, 2010; Madsen et al., 2006) and shrimp trawl (He et al., 2007). In the U.S. West Coast LE groundfish bottom trawl fishery, King et al. (2004) and Hannah et al. (2005) compared a selective flatfish trawl with a cutback headrope to a conventional high-rise trawl with an overhanging headrope. In both studies, the selective flatfish trawl demonstrated the ability to maintain flatfish catches while reducing catches for several benthopelagic rockfish and roundfishes, and Pacific halibut. Catches of rockfishes and other roundfishes that were not reduced consisted of more benthic species such as greenstriped and rosethorn (*S. helvomaculatus*) rockfishes, and lingcod. In the present study, a type of BRD was evaluated (used on the same trawl tested by King et al. (2004) and Hannah et al. (2005)) that demonstrated the ability to substantially reduce catches of non-target species, including more benthic fishes such as greenstriped and rosethorn rockfishes, and lingcod. Use of this BRD could allow fishermen increased access to shelf flatfishes over fishing grounds where constraining species co-occur, however, would create trade-offs between economic yields and bycatch reduction that individual fishermen would have to assess relative to their bycatch reduction needs, quota mix, and operating costs.

Significant reductions in rockfish and roundfish catches were noted with greater reductions occurring in larger individuals. The rockfishes and roundfishes retained in the trawl consisted primarily of juvenile and unmarketable-sized fish. One technique that could be used to further minimize this catch of juvenile rockfishes and roundfishes would be through the use of T90 mesh codends. T90 mesh is conventional diamond mesh that has been turned 90° in orientation (Herrmann et al., 2007, 2013). This unique configuration allows the meshes over the entire codend to remain more open than those of diamond mesh codends, improving size-selection characteristics. The simple construction of a T90 codend, easy to repair when damaged, ability to maintain its flexibility under large catch volumes, and its potential to improve codend selectivity provides many advantages over other mesh orientations used to improve codend selectivity, such as knotless square mesh codends (He, 2007; Perez-Comas et al., 1998). Compared to diamond mesh codends with similar mesh sizes, T90 mesh codends have demon-

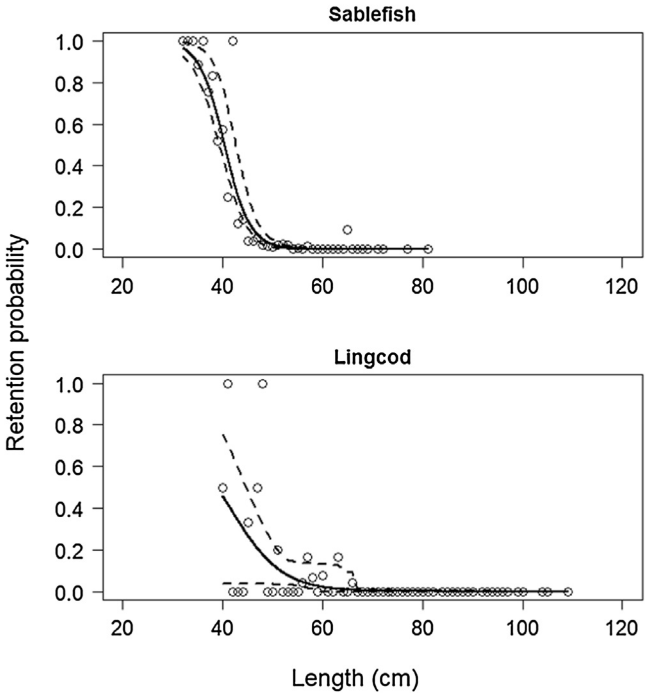

Fig. 7. Mean selectivity curves showing the probability of retaining sablefish and lingcod by length in the trawl codend. Circles are the experimental data; solid lines are the modeled value; dashed lines are upper and lower 95% confidence interval limits.

strated the ability to reduce catches of smaller-sized roundfishes (Wienbeck et al., 2011; Herrmann et al., 2013; Tokaç et al., 2014).

In conclusion, this study examined the efficacy of a selective flatfish sorting grid BRD to improve trawl selectivity in a nearshore flatfish fishery off the U.S. west coast. The BRD demonstrated the ability to substantially reduce catches of rockfishes, sablefish, lingcod, and Pacific halibut while retaining moderate-to-high proportions of petrale sole, English sole, rex sole, and Dover sole. Results indicate that the BRD tested could allow increased access to shelf flatfishes while limiting catches of constraining species. Further testing of this BRD design, such as examining alternative sorting grid sizes or the effect of a T90 codend used in conjunction with this device, would provide valuable information for developing more selective fishing gear.

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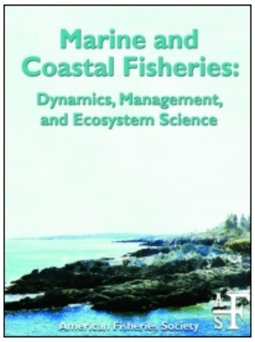
Paper III

“Testing of Two Selective Flatfish Sorting-Grid Bycatch Reduction Devices in the U.S. West Coast Groundfish Bottom Trawl Fishery”



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Mark J. M. Lomeli, W. Waldo Wakefield & Bent Herrmann

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ARTICLE

Testing of Two Selective Flatfish Sorting-Grid Bycatch Reduction Devices in the U.S. West Coast Groundfish Bottom Trawl Fishery

Mark J. M. Lomeli*
Pacific States Marine Fisheries Commission, 2032 Southeast OSU Drive, Newport, Oregon 97365, USA

W. Waldo Wakefield
National Oceanic and Atmospheric Administration, National Marine Fisheries Service,
Northwest Fisheries Science Center, Fishery Resource Analysis and Monitoring Division,
2032 Southeast OSU Drive, Newport, Oregon 97365, USA

Bent Herrmann
SINTEF Fisheries and Aquaculture, Willemoesvej 2, DK-9850 Hirtshals, Denmark

Abstract

In the U.S. West Coast limited-entry (LE) groundfish bottom trawl fishery, catches of stocks with restrictive harvest limits (e.g., Darkblotched Rockfish *Sebastes crameri*, Sablefish *Anoplopoma fimbria*, and Pacific Halibut *Hippoglossus stenolepis*) continue to hinder many fishermen's ability to fully utilize their quota shares of more abundant flatfish stocks (e.g., Dover Sole *Microstomus pacificus* and Petrale Sole *Eopsetta jordani*). We used a recapture net to examine the size-selection characteristics of two selective flatfish sorting-grid bycatch reduction devices (BRDs), which were designed to reduce catches of Pacific Halibut and non-flatfish species while retaining target flatfishes. The two devices were identical in materials and design except that the sorting-grid dimensions differed (BRD-1: 6.4- × 25.4-cm grid size; BRD-2: 6.4- × 30.5-cm grid size). The size selectivity for rockfishes, other roundfishes, Pacific Halibut, English Sole *Parophrys vetulus*, and Rex Sole *Glyptocephalus zachirus* did not differ significantly between the two designs. However, for 53–58-cm TL Arrowtooth Flounder *Atheresthes stomias*, 39–53-cm TL Dover Sole, and 36–49-cm TL Petrale Sole, BRD-1 retained significantly higher proportions of these length-classes than did BRD-2. Combined, the mean flatfish retention by weight (not including Pacific Halibut) was 89.3% (95% confidence interval [CI] = 87.1–91.5%) for BRD-1 and 81.7% (95% CI = 80.0–83.4%) for BRD-2. Compared to previous flatfish sorting-grid selectivity work conducted in the LE bottom trawl fishery, BRD-1 showed the ability to improve the overall retention of flatfishes while reducing catches of nontarget and constraining species.

Implementing practices that enhance utilization of fishery quotas and provide for an economically sustainable fishery is an objective of the catch shares program for the U.S. West Coast limited-entry (LE) groundfish bottom trawl fishery

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Subject editor: Donald Noakes, Vancouver Island University, Nanaimo, British Columbia

*Corresponding author: mlomeli@psmfc.org
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TABLE 1. Specifications of the two bycatch reduction devices (BRDs) tested. Mesh sizes (mm) are stretched measurements between knots (DM = diamond mesh; LL = long link; * = does not account for meshes gored in each selvedge).

Characteristic	BRD-1	BRD-2	Recapture net	Trawl cod end
Grid dimensions (height × length)	6.4 × 25.4 cm	6.4 × 30.5 cm		
Netting	116-mm DM	116-mm DM	116-mm DM	116-mm DM
Twine	4-mm single (top and side panels); 5-mm double (bottom panel)	4-mm single (top and side panels); 5-mm double (bottom panel)	6-mm double	6-mm double
Circumference*	100	100	70	88
Meshes deep	80	80	100	75
Top riblines	32-mm Blue Steel Poly rope, hung at 6%	32-mm Blue Steel Poly rope, hung at 6%	12.7-mm Blue Steel Poly rope, hung at 6%	32-mm Blue Steel Poly rope, hung at 6%
Bottom riblines	12.7-mm LL chain, hung at 6%	12.7-mm LL chain, hung at 6%	12.7-mm Blue Steel Poly rope, hung at 6%	32-mm Blue Steel Poly rope, hung at 6%

(PFMC and NMFS 2011, 2015). In this fishery, participants are held fully accountable for catches of all individual fishing quota (IFQ) species and bycatch of the Pacific Halibut *Hippoglossus stenolepis*, a prohibited species. Catch accountability has encouraged fishermen to fish more selectively to improve the utilization of their catches of IFQ species. However, constraints on stocks with restrictive harvest limits continue to impact fishermen's ability to fully utilize their quota shares of healthier groundfish stocks.

In the LE bottom trawl fishery, fishermen trawling shoreward of 183-m bottom depth and north of 40°10′N latitude are currently mandated to use a two-seam, low-rise selective flatfish trawl (King et al. 2004; Hannah et al. 2005; NOAA 2014). This regulation was implemented in an effort to minimize the catches of overfished and rebuilding stocks of rockfish *Sebastes* spp. when trawling for flatfishes (i.e., English Sole *Parophrys vetulus*, Dover Sole *Microstomus pacificus*, and Petrale Sole *Eopsetta jordani*) over the continental shelf. This trawl has been shown to be successful at reducing catches of some benthopelagic rockfishes (notably Canary Rockfish *Sebastes pinniger*, a previously overfished stock that has recently rebuilt). However, catches of Darkblotched Rockfish *Sebastes crameri*, Sablefish *Anoplopoma fimbria*, and Pacific Halibut often restrict many fishermen from fully utilizing their flatfish IFQs, as relatively limited quota is available. Consequently, developing techniques that minimize catches of constraining species and provide fishermen with more opportunities to fully utilize their catch share quota of healthier fish stocks would be beneficial to fishermen, coastal communities, management, and the resource.

Selectivity studies evaluating sorting-grid bycatch reduction devices (BRDs; Lomeli and Wakefield 2013, 2015, 2016), cod-end mesh sizes and configurations (Wallace et al. 1996; Perez-Comas et al. 1998; Lomeli et al. 2017), and trawl designs (Hannah et al. 2005; King et al. 2004) in the LE bottom trawl fishery have been conducted in an effort to enhance trawl selectivity and catch utilization. For bottom trawl fishermen targeting flatfishes, a sorting-grid BRD was developed to reduce catches of rockfishes, other roundfishes, and Pacific Halibut (Lomeli and Wakefield 2015, 2016). The design consisted of long, rectangular slots (4.4 cm high × 21.6 cm long) to allow flatfishes to pass through and move aft toward the cod end, whereas nontarget species that are unable to pass though the slots are released out of the trawl. During gear trials, the BRD demonstrated the ability to significantly reduce catches of rockfishes, Sablefish, and Pacific Halibut. The mean catch of flatfishes (five species evaluated) ranged from 68.1% to 92.3% by weight, with an overall mean of 85.6%. Although encouraging results were achieved, it was noted that improvements in the BRD's ability to retain flatfishes (particularly larger-sized fish with higher economical value) were desired to enhance the gear's effectiveness in the fishery (Lomeli and Wakefield 2015, 2016).

The objectives of the current study were to (1) examine the size-selection characteristics of two alternative sorting-grid sizes and (2) evaluate their ability to further improve flatfish retention relative to previous studies while reducing the catches of nontarget species.

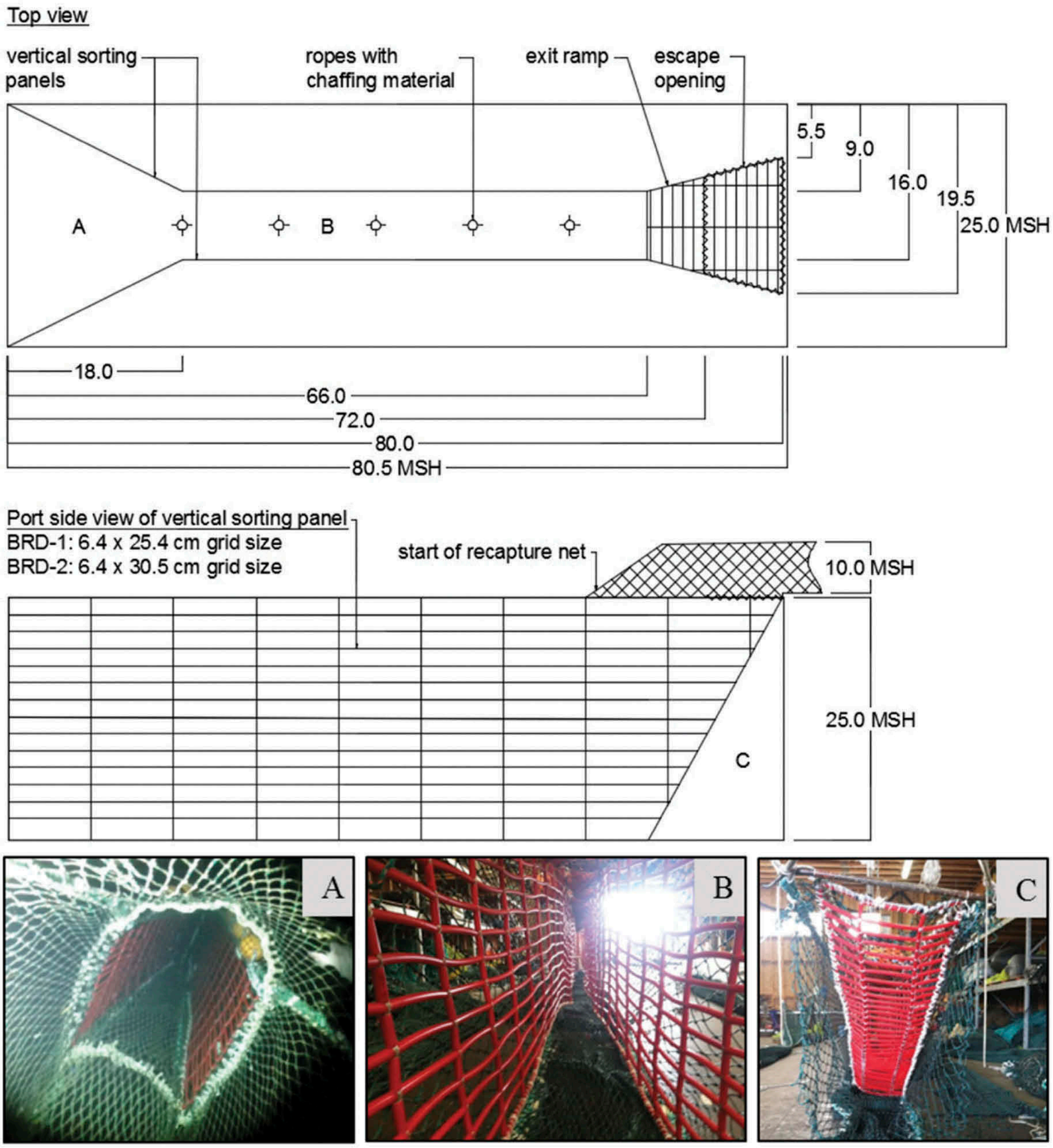

FIGURE 1. Schematic diagram (not to scale) depicting the general design of the flexible sorting grid tested (top; MSH = meshes). The only design difference between the two bycatch reduction devices (BRD-1 and BRD-2) was the grid size. Image A presents the aft view of the forward portion of the gear, where fish enter and encounter the BRD; image B depicts the aft view of the area between the two vertical sorting panels; and image C presents the fore view of the upward-angled exit ramp.

METHODS

*Trawl design.—*The trawl used for this study was a two-seam, Eastern 400 low-rise selective flatfish trawl with a cutback headrope. The headrope was 40.3 m in length, and the chain footrope was 31.2 m in length. The chain footrope was covered with 20.3-cm-diameter rubber discs and outfitted with 35.6-cm-diameter rubber rockhopper discs placed approximately every 58.4 cm over the footrope length. This trawl lacks floats along the central portion of the headrope to reduce fish diving reactions to floats that may occur. Refer to Hannah et al. (2005) and King et al. (2004) for the trawl net plan.

*Gear designs.—*We followed the BRD design of Lomeli and Wakefield (2015, 2016) but tested two different grid dimensions. The BRDs were built within four-seam tubes of 116-mm diamond netting (Table 1) and were inserted between the intermediate section of the trawl and the cod end. A 50-mesh-deep, two- to four-seam transitional tube of netting attached each BRD to the trawl. The two grids tested consisted of elongated slots that were 6.4 cm high × 25.4 cm long (BRD-1) and 6.4 cm high × 30.5 cm long (BRD-2). Each BRD utilized two vertical panels that extended longitudinally down the tube of netting (Figure 1). The concept of the design was that fish smaller than the grid openings would pass through the grid and move aft toward the cod end, whereas fish larger than the grid openings (e.g., roundfishes and most adult Pacific Halibut) would be excluded. Fish that do not pass through the grid openings are guided by an exit ramp and exit out the top of the trawl. Between the two vertical sorting panels, ropes with chafing material wedged through them were positioned to create partial obstructions to fish moving aft; this was done to stimulate fish to move toward the sorting grids. At the aft end of each BRD, the top portion of the vertical panels angled outward to allow for integration of the exit ramp and its associated escape opening. The trawl cod end was a four-seam tube of 116-mm diamond netting. For further design details, refer to Lomeli and Wakefield (2016).

We used a recapture net to quantify fish escapement for the two BRD designs. The recapture net was 100 meshes deep and 70 meshes in circumference (25 meshes on the top and bottom panels; 10 meshes on the side panels) and was constructed of the same webbing material and mesh size as the trawl cod end (Table 1). The recapture net was attached to the BRD just forward of the escape opening to allow excluded fish to be captured. To keep the recapture net from masking the escape opening, two 20.3-cm center-hole floats were placed on each top ribline of the recapture net, above the escape area of the BRD, while two 27.9-cm ear-floats were placed on the top panel webbing in the middle (between the top riblines) of the recapture net.

Gear trials and fish sampling.—We conducted our sea trials aboard the F/V *Miss Sue* (24.7-m-long, 640-hp trawler) off central Oregon (between 44°30′ and 45°32′N and between 124°17′ and 124°48′W) during April 2016. Towing occurred over the continental shelf and shelf break during daylight hours (between 0600 and 1800 hours Pacific daylight time) at bottom fishing depths from 146 to 402 m. The average bottom fishing depth was 249 m. Towing speed over ground ranged from 4.07 to 4.82 km/h (2.2–2.6 knots). Tow durations were set to 1 h. The BRDs were fished in an alternate tow randomized block design. After each tow, all fish were identified to species and weighed by using a motion-compensated platform scale. Flatfishes, Shortspine Thornyheads *Sebastolobus alascanus*, and Lingcod *Ophiodon elongatus* were measured to the nearest centimeter TL, while Sablefish and rockfishes were measured to the nearest centimeter FL.

TABLE 2. Length data used to model (via CLogit) the size selectivity for each bycatch reduction device (BRD) design. Values in parentheses are the fish measurement subsample ratios from the total catch. Flatfishes, Shortspine Thornyheads, and Lingcod were measured to the nearest centimeter TL; Sablefish and rockfishes were measured to the nearest centimeter FL.

Species	Number of tows	Number of fish measured in cod end	Number of fish measured in recapture net	Length range (cm)
BRD-1 (grid size = 6.4 × 25.4 cm)				
Pacific Halibut	10	5 (1.0)	21 (1.0)	55–81
English Sole	13	401 (0.59)	86 (1.0)	23–40
Rex Sole	15	1,170 (0.70)	196 (1.0)	21–52
Arrowtooth Flounder	15	1,028 (0.78)	155 (1.0)	24–66
Dover Sole	15	2,477 (0.43)	451 (1.0)	28–61
Petrale Sole	13	1,492 (0.72)	168 (1.0)	26–56
Darkblotched Rockfish	11	339 (1.0)	176 (1.0)	19–40
Greenstriped Rockfish	12	503 (0.59)	318 (0.55)	19–38
Shortspine Thornyhead	7	298 (0.62)	75 (1.0)	17–44
Sablefish	14	249 (1.0)	556 (1.0)	34–92
Lingcod	13	8 (1.0)	93 (1.0)	45–92
BRD-2 (grid size = 6.4 × 30.5 cm)				
Pacific Halibut	10	5 (1.0)	13 (1.0)	55–91
English Sole	15	261 (0.71)	71 (1.0)	25–42
Rex Sole	15	1,015 (0.68)	191 (1.0)	23–47
Arrowtooth Flounder	15	562 (1.0)	169 (1.0)	26–68
Dover Sole	15	1,919 (0.65)	523 (1.0)	29–61
Petrale Sole	15	1,683 (0.57)	361 (1.0)	26–57
Darkblotched Rockfish	10	171 (1.0)	296 (0.69)	19–45
Greenstriped Rockfish	13	217 (1.0)	183 (1.0)	21–38
Shortspine Thornyhead	6	131 (1.0)	68 (1.0)	19–44
Sablefish	14	102 (1.0)	193 (1.0)	37–77
Lingcod	11	131 (1.0)	207 (0.40)	41–86

Selectivity analysis.—The concept of the tested sorting-grid BRDs is to have flatfishes contact and pass through the grid system and then move aft toward the trawl cod end. Fish that do not contact the grid system are released out of the trawl. Fish that contact the grid system have a length-dependent probability (which decreases for larger-sized

TABLE 3. Catch data by weight (kg) for six flatfish species from the 30 trawl tows conducted in 2016 with two bycatch reduction devices (BRD-1: grid size = 6.4 × 25.4 cm; BRD-2: grid size = 6.4 × 30.5 cm; RN = recapture net; values in parentheses represent 95% confidence intervals).

			Pacific Halibut		English Sole		Rex Sole		Arrowtooth Flounder		Dover Sole		Petrale Sole	
Tow	Date in 2016	BRD	RN	Cod end	RN	Cod end	RN	Cod end	RN	Cod end	RN	Cod end	RN	Cod end
1	Apr 20	2	0	0	0.3	0.4	1.5	10.1	15.1	38.1	20.5	72.8	2.4	28.3
2	Apr 21	1	5.0	0	0	1.6	1.4	12.7	3.2	21.5	21.6	101.3	19.0	283.1
3	Apr 21	1	0	0	0.4	4.2	2.0	14.5	6.0	15.6	10.8	77.2	11.6	123.1
4	Apr 21	1	2.8	13.1	7.6	34.6	4.6	10.8	3.4	10.3	10.5	59.3	12.4	94.1
5	Apr 21	1	11.4	0	2.5	24.5	1.5	27.8	6.8	49.5	12.8	65.8	9.4	74.9
6	Apr 21	1	34.9	0	5.5	37.1	1.9	18.1	24.8	107	25.8	159.4	0.6	76.6
7	Apr 22	2	5.6	0	1.9	15.4	3.3	13.0	11.0	50.4	18.1	102.1	0.9	26.1
8	Apr 22	2	5.3	8.8	0.3	4.2	3.6	11.7	12.8	42.2	50.5	164.2	7.2	24.1
9	Apr 22	2	3.8	0	7.7	28.4	0.5	10.8	0	4.4	9.1	50.2	33.1	58.7
10	Apr 22	2	13.3	0	0.3	2.5	0.5	10.3	5.1	24.3	24.9	95.2	6.0	22.0
11	Apr 22	2	4.8	2.9	0.8	2.3	1.5	9.3	13.0	37.1	31.2	82.4	55.4	242.1
12	Apr 23	1	0	3.1	0	0	2.9	8.6	9.5	62.7	75.9	806.4	0	0
13	Apr 23	1	0	0	0	0	0.9	2.4	8.1	23.0	1.4	16.7	0	0
14	Apr 23	1	0	0	0.3	2.4	1.6	19.2	15.6	114.9	23.6	279.1	3.8	59.5
15	Apr 23	1	0	0	5.7	24.1	0	6.3	0.8	5.7	3.4	20.8	0.8	8.7
16	Apr 23	1	7.9	0	0	8.2	2.1	18.1	26.2	140.6	9.7	119.2	6.9	118.8
17	Apr 24	1	0	0	0	3.0	3.7	30.2	30.7	124.2	76.2	720.0	0	9.0
18	Apr 24	1	14.9	3.4	0	3.8	3.1	51.9	1.6	116.9	28.4	377.0	5.2	60.5
19	Apr 24	1	15.0	0	0.6	1.9	2.3	22.1	11.2	84.8	22.8	200.5	0.7	14.1
20	Apr 26	2	3.7	5.1	4.2	12.1	0.6	15.1	0	3.6	38.4	44.5	31.2	173.3
21	Apr 26	2	4.8	4.0	2.0	2.6	3.2	18.1	1.2	4.3	14.8	49.3	0	62.7
22	Apr 26	2	5.6	2.8	0.3	1.8	7.2	30.9	1.3	6.8	28.5	139.1	23.9	139.8
23	Apr 26	2	10.8	0	0	1.4	1.2	6.7	1.9	42.1	10.9	42.1	7.3	23.3
24	Apr 26	2	0	0	1.5	4.8	1.3	10.5	1.7	4.5	26.1	51.8	44.3	353.7
25	Apr 27	2	0	0	0	0.7	2.3	18.5	11.9	42.4	46.1	167.8	13.1	19.7
26	Apr 27	2	0	0	0	1.8	6.1	26.5	26.4	109.9	37.8	198.0	7.1	0
27	Apr 27	2	0	0	0	0.3	1.5	11.5	4.4	9.2	15.2	51.5	0	1.2
28	Apr 27	2	15.9	0	0.7	7.8	6.4	58.6	6.8	34.1	42.4	342.8	16.3	108.8
29	Apr 28	1	11.8	0	0.3	2.0	9.3	28.0	0.5	4.6	27.6	129.6	22.1	96.7
30	Apr 28	1	4.1	9.9	0.3	1.6	3.3	16.9	0	5.2	6.0	42.9	19.4	169.8
Total, BRD-1			107.8	29.5	23.2	149.0	40.6	287.6	148.4	886.5	356.5	3,175.2	111.9	1,188.9
Cod end retention (%)			21.5		86.5		87.6		85.7		89.9		91.4	
			(19.0–24.0)		(81.7–91.3)		(85.1–90.1)		(82.9–88.5)		(86.0–93.8)		(87.9–94.9)	
Total, BRD-2			73.6	23.6	20.0	86.5	40.7	261.6	112.6	453.4	414.5	1,653.8	248.2	1,283.4
Cod end retention (%)			24.3		81.2		86.5		80.1		80.0		83.8	
			(21.9–26.6)		(77.2–85.2)		(84.0–88.9)		(74.6–85.6)		(77.8–82.2)		(80.0–87.5)	

TABLE 4. Results of the CLogit model of mean selectivity for flatfishes by the two bycatch reduction device (BRD) designs tested ($L50_{grid}$ and SR_{grid} = passage probability parameters; C_{grid} = fish-size-independent grid contact probability; * = value not defined). Values in parentheses are Efron percentile bootstrap 95% confidence limits.

Species	$L50_{grid}$	SR_{grid}	C_{grid}	*P*-value	Deviance	df
BRD-1 (grid size = 6.4 × 25.4 cm)						
Pacific Halibut	* (*–60.8)	* (*–45.8)	0.20 (0.07–0.99)	0.1159	12.9	8
English Sole	46.5 (38.0–195.0)	11.1 (0.6–107.1)	0.89 (0.84–0.99)	0.0049	32.9	15
Rex Sole	67.2 (40.0–192.7)	37.6 (0.1–106.0)	0.97 (0.84–0.99)	0.5715	21.2	23
Arrowtooth Flounder	82.5 (62.8–127.8)	43.2 (12.6–100.0)	0.99 (0.90–0.99)	0.1096	46.7	36
Dover Sole	80.6 (56.7–192.2)	24.4 (2.3–108.3)	0.92 (0.89–0.99)	0.4307	29.7	29
Petrale Sole	190.6 (56.1–199.4)	1.6 (0.3–109.7)	0.91 (0.89–0.99)	0.0807	37.8	27
BRD-2 (grid size = 6.4 × 30.5 cm)						
Pacific Halibut	51.3 (*–63.0)	30.9 (*–70.4)	0.99 (0.17–0.99)	0.0354	16.5	8
English Sole	45.8 (37.4–196.8)	10.0 (0.1–109.4)	0.82 (0.78–0.99)	0.6941	10.9	14
Rex Sole	73.2 (41.5–195.1)	49.1 (0.1–112.4)	0.99 (0.85–0.99)	0.6961	17.3	21
Arrowtooth Flounder	60.4 (55.3–69.4)	24.8 (5.8–38.8)	0.99 (0.86–0.99)	0.0369	51.3	35
Dover Sole	68.2 (56.4–90.9)	39.5 (1.4–77.1)	0.99 (0.81–0.99)	0.0245	45.8	29
Petrale Sole	84.5 (51.1–157.6)	57.2 (0.1–106.6)	0.99 (0.84–0.99)	0.3200	32.0	29

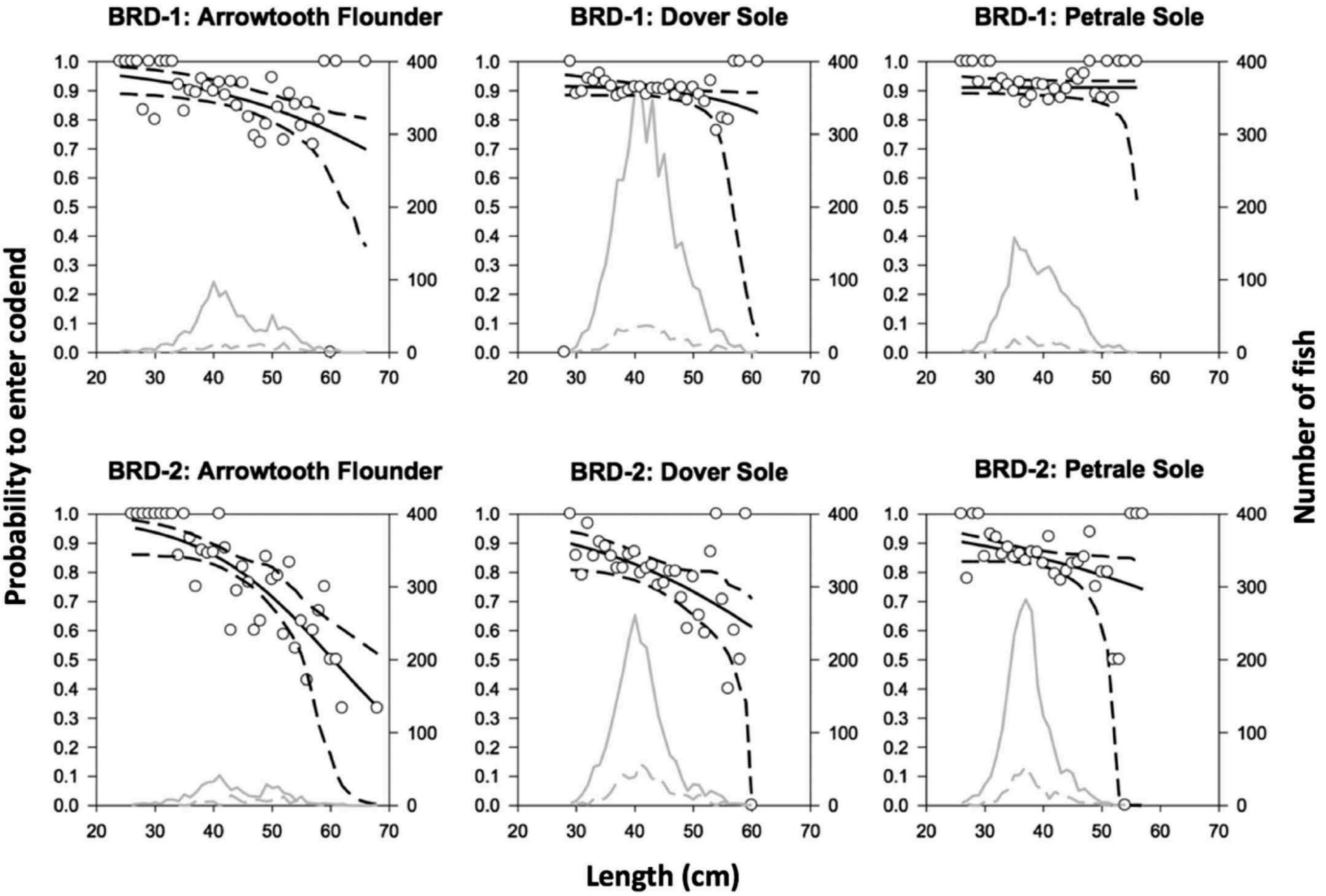

FIGURE 2. Mean selectivity curves quantifying a fish's probability of entering the cod end of a trawl equipped with one of two bycatch reduction devices (BRD-1 and BRD-2), as modeled for Arrowtooth Flounder, Dover Sole, and Petrale Sole (length = cm TL). Black solid lines represent the modeled value; black dashed lines represent the 95% confidence interval limits; open circles denote the experimental proportions of the catch observed in the cod end; gray solid lines represent the number of fish caught in the trawl cod end; and gray dashed lines depict the number of fish caught in the recapture net.

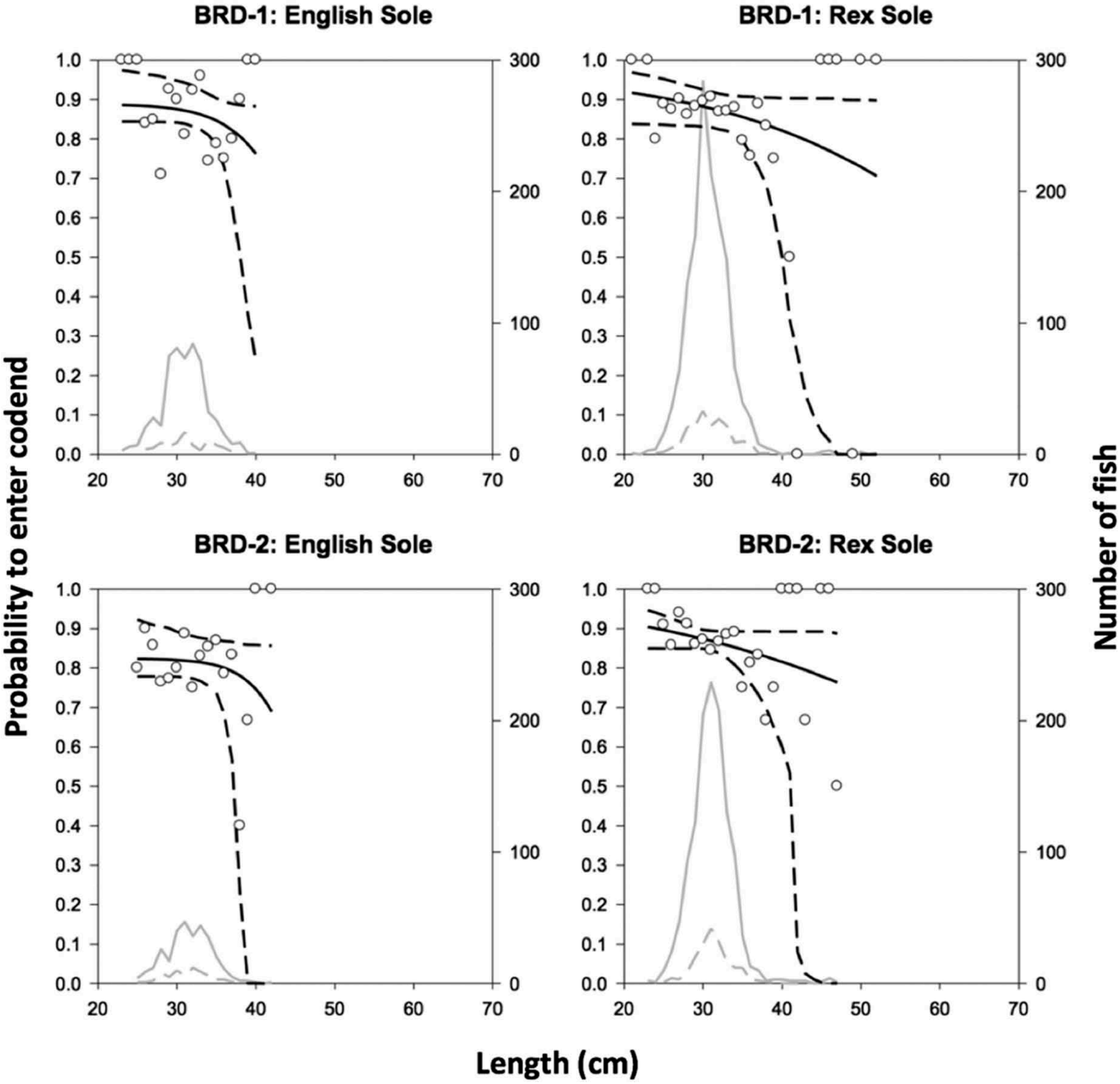

FIGURE 3. Mean selectivity curves quantifying a fish's probability of entering the cod end of a trawl equipped with one of two bycatch reduction devices (BRD-1 and BRD-2), as modeled for English Sole and Rex Sole (length = cm TL). Black solid lines represent the modeled value; black dashed lines depict the 95% confidence interval limits; open circles denote the experimental proportions of the catch observed in the cod end; gray solid lines represent the number of fish caught in the trawl cod end; and gray dashed lines depict the number of fish caught in the recapture net.

individuals) of passing through the grid system and entering the cod end; fish that enter the cod end are then subjected to a second size-selection process. The purpose of our analysis was to quantify the length-dependent sorting efficiency of the two tested BRDs. Specifically, we wanted to quantify the length-dependent probability that a fish arriving to the zone of the BRD would subsequently enter the cod end. To obtain this information, we compared the catches in the cod end and recapture net separately, species by species, as described below.

The across-tows averaged experimental probability that a fish in length-class l would be observed in the cod end was

$$\mathrm{PC}_l = \frac{\sum_{i=1}^{m}\left\{\frac{nc_{li}}{qc_i}\right\}}{\sum_{i=1}^{m}\left\{\frac{nc_{li}}{qc_i}+\frac{nr_{li}}{qr_i}\right\}} = \frac{nc_l}{nc_l+nr_l}, \tag{1}$$

where nc_{li} and nr_{li} are the number of fish of length l measured in the cod end and in the recapture net,

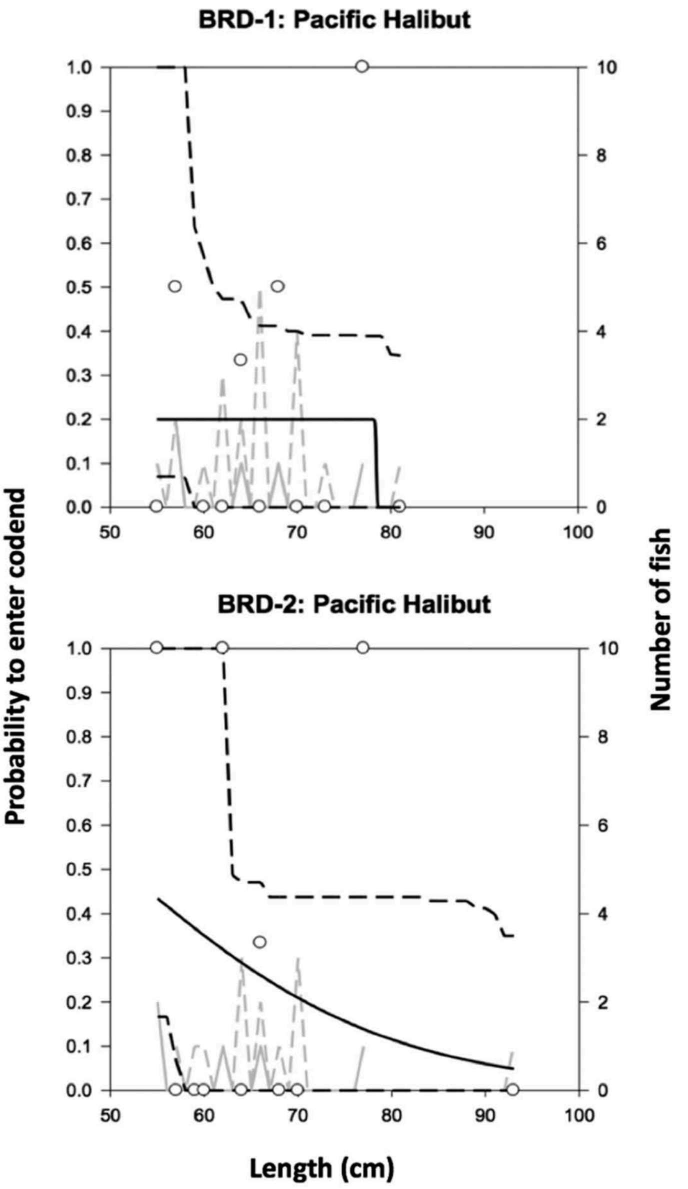

FIGURE 4. Mean selectivity curves quantifying a fish's probability of entering the cod end of a trawl equipped with one of two bycatch reduction devices (BRD-1 and BRD-2), as modeled for Pacific Halibut (length = cm TL). Black solid lines depict the modeled value; black dashed lines represent the 95% confidence interval limits; open circles denote the experimental proportions of the catch observed in the cod end; gray solid lines depict the number of fish caught in the trawl cod end; and gray dashed lines represent the number of fish caught in the recapture net.

respectively, for tow i; and qc_i and qr_i are the related subsampling factors (fraction of the catch for which length is measured) for the cod end and recapture net, respectively. The summation is over the m tows conducted with that specific version of the BRD.

With the outset in equation (1), we wanted (based on the group of tows carried out for each BRD) to estimate a functional description for the average length-dependent probability (PG[l]) that a fish would pass into the cod end through the BRD because this would quantify the size selectivity of the device. To do so, we first needed to identify a relationship between PG(l) and the observed catch proportions in the cod end and in the recapture net. Let n_l be the number of fish belonging to length-class l arriving to the zone of the BRD; the expected values for the numbers to be observed in the catch of the cod end (nc_l) and recapture net (nr_l), respectively, will then be

$$\begin{aligned} \widehat{nc_l} &= n_l \times \mathrm{PG}(l) \times \mathrm{RC}(l), \\ \widehat{nr_l} &= n_l \times [1.0 - \mathrm{PG}(l)] \times \mathrm{RR}(l), \end{aligned} \tag{2}$$

where RC(l) and RR(l) are the selectivity curves for the cod end and the recapture net, respectively. In equation (2), we used the condition that all fish not entering the cod end will enter the recapture net.

Using equation (2) in equation (1) leads to

$$\widehat{\mathrm{PC}_l} = \frac{\mathrm{PG}(l) \times \mathrm{RC}(l)}{\mathrm{PG}(l) \times \mathrm{RC}(l) + [1.0 - \mathrm{PG}(l)] \times \mathrm{RR}(l)}. \tag{3}$$

Because the cod end and recapture net are made of the same netting type and with the same mesh size, we can assume that they will have similar size selection (i.e., RC[l] ≈ RR[l]). Using this assumption, equation (3) simplifies to

$$\widehat{\mathrm{PC}_l} \approx \mathrm{PG}(l). \tag{4}$$

Using equations (1) and (4) together allows us to estimate the functional description for PG(l) based on comparing the catches in the cod end and recapture net. Specifically, we can estimate it by minimizing,

$$-\sum_l \sum_{i=1}^{m} \left\{ \frac{nc_{li}}{qc_i} \times \log_e[\mathrm{PG}(l,\gamma)] + \frac{nr_{li}}{qr_i} \times \log_e[1.0 - \mathrm{PG}(l,\gamma)] \right\}. \tag{5}$$

In equation (5), we express the length-dependent grid passage probability (probability that a fish will enter the cod end) on the parametric form PG(l, γ). The outer summation is over length-classes in the experimental data. The purpose is to find the values for the parameters γ that minimize equation (5), which is equivalent to optimizing the likelihood for the observed experimental data based on a binomial distribution.

To minimize equation (5), we need to select a model for PG(l, γ), and we will base this on the contact logit (CLogit) model

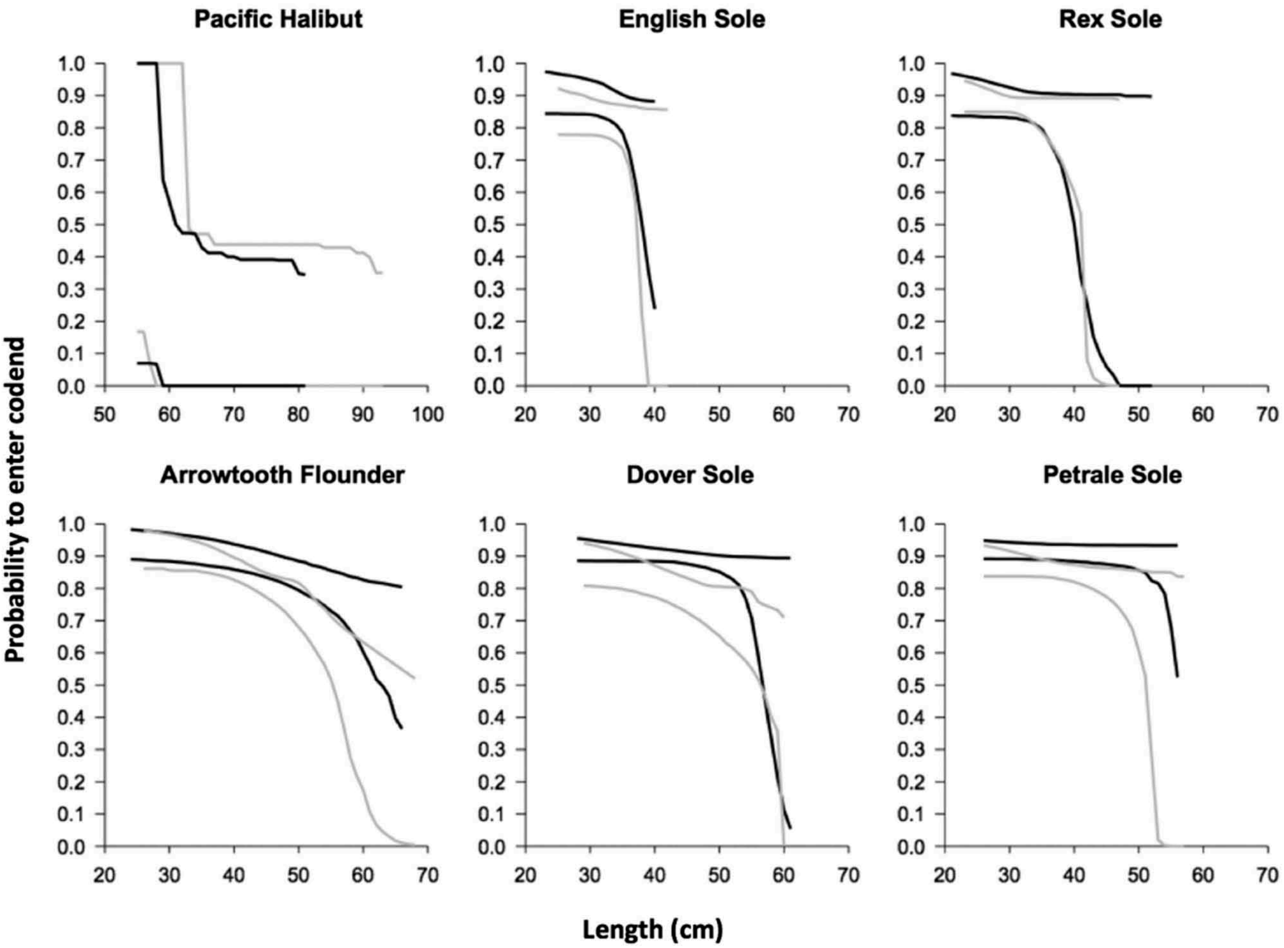

FIGURE 5. Comparison of the 95% confidence interval limits for the size-selection curves quantifying a fish's probability of entering the cod end of a trawl equipped with one of two bycatch reduction devices (BRD-1 and BRD-2), as estimated for six flatfishes (length = cm TL). Solid black lines represent BRD-1 (6.4- × 25.4-cm grid size); solid gray lines represent BRD-2 (6.4- × 30.5-cm grid size).

(Herrmann et al. 2013; Larsen et al. 2016, 2017). The CLogit model accounts for the fact that not necessarily all fish arriving to the zone of the BRD will make contact with it and be subjected to a fish-size-dependent probability of passing through the grid. For fish that make contact with the grid, the CLogit model assumes a standard logit model for the grid passage probability with parameters $L50_{grid}$ and SR_{grid} (Wileman et al. 1996). The grid contact probability is modeled by a fish-size-independent number, C_{grid}, that can take on values in the range of 0.0–1.0. Specifically, based on the CLogit model, PG(l, γ) is modeled by

$$\begin{aligned}\mathrm{PG}\left(l,\ C_{grid}, \mathrm{L50}_{grid}, \mathrm{SR}_{grid}\right) &= 1.0 - \mathrm{CLogit}\left(l,\ C_{grid}, \mathrm{L50}_{grid}, \mathrm{SR}_{grid}\right)\\ &= C_{grid} \times \left[1.0 - \mathrm{Logit}\left(l, \mathrm{L50}_{grid}, \mathrm{SR}_{grid}\right)\right]\\ &= \frac{C_{grid}}{\exp\left[\frac{\log_e(9.0)}{\mathrm{SR}_{grid}} \times \left(l - \mathrm{L50}_{grid}\right)\right]}.\end{aligned} \tag{6}$$

Goodness of fit of the selected model for PG(l, γ) to describe the experimental data was determined based on the P-value, model deviance versus degrees of freedom, and inspection of the model curves' ability to reflect the length-based trends in the experimental data expressed by equation (1). Specifically, in a case of poor fit statistics ($P < 0.05$), the deviances between modeled curve and experimental rates were inspected to determine whether the poor result was due to structural problems when modeling the experimental data or due to overdispersion in the data (Wileman et al. 1996). Consult Sistiaga et al. (2010), Herrmann et al. (2013), Grimaldo et al. (2015), Stepputtis et al. (2016), and Larsen et al. (2017) for complete details on the CLogit model and how to apply it.

All tows and length-classes caught were used in the analysis. Efron percentile bootstrap 95% confidence intervals (CIs; Efron 1982) for $L50_{grid}$, SR_{grid}, C_{grid}, and the PG (l, γ) curve for all relevant fish sizes were estimated from 1,000 bootstrap repetitions using a double bootstrapping

TABLE 5. Catch data by weight (kg) for five roundfish species from the 30 trawl tows conducted in 2016 with two bycatch reduction devices (BRD-1: grid size = 6.4 × 25.4 cm; BRD-2: grid size = 6.4 × 30.5 cm; RN = recapture net; values in parentheses represent 95% confidence intervals).

			Darkblotched Rockfish		Greenstriped Rockfish		Shortspine Thornyhead		Sablefish		Lingcod	
Tow	Date in 2016	BRD	RN	Cod end	RN	Cod end	RN	Cod end	RN	Cod end	RN	Cod end
1	Apr 20	2	5.7	4.1	4.6	3.2	0.4	1.3	37.4	20.1	2.6	0
2	Apr 21	1	0.8	3.9	17.5	13.4	0	0	1.2	0	4.1	1.3
3	Apr 21	1	1.0	8.7	117.6	91.7	0	0	1.2	0	11.7	0
4	Apr 21	1	0	0.2	20.1	12.3	0	0	2.4	0.8	20.2	5.4
5	Apr 21	1	5.4	36.5	7.0	3.4	0	0	13.8	4.9	11.0	1.4
6	Apr 21	1	0	23.4	6.9	8.3	0	0	148.2	31.7	103.0	0
7	Apr 22	2	11.5	8.2	1.6	3.2	0	0.5	22.4	9.5	67.8	10.2
8	Apr 22	2	4.9	3.4	3.6	2.1	0	0	28.9	21.7	22.1	0
9	Apr 22	2	0	0	56.8	26.6	0	0	2.7	1.1	496.9	196.8
10	Apr 22	2	5.3	12.4	2.4	2.1	0	0.2	4.9	7.4	14.4	0
11	Apr 22	2	0.4	0.4	1.7	2.9	0	0	12.1	5.7	0	0.7
12	Apr 23	1	0	0	0	0	7.1	9.7	87.9	26.3	0	0
13	Apr 23	1	0	0	0	0	7.2	5.1	24.0	0	0	0
14	Apr 23	1	1.8	1.0	0.9	1.2	3.1	8.8	84.9	51.7	41.9	0
15	Apr 23	1	0	0	0	0.3	0	0	1.2	0	6.2	1.0
16	Apr 23	1	0	1.0	2.0	1.4	1.8	3.1	9.4	10.8	13.2	0
17	Apr 24	1	73.2	25.5	0	0	14.1	44.7	119.0	26.2	9.3	0
18	Apr 24	1	2.0	0	2.5	12.2	1.3	0.6	100.3	48.7	19.1	1.0
19	Apr 24	1	1.5	3.4	0.7	0.5	1.4	10.4	147.8	58.2	28.4	3.2
20	Apr 26	2	0	0	4.8	8.6	0	0	0	0	0	0
21	Apr 26	2	0.2	0.6	2.7	1.6	0	0	0	0.5	0	0
22	Apr 26	2	0	1.0	6.8	3.2	0	0	2.1	0.9	0	0
23	Apr 26	2	0.3	0.7	0.4	2.7	0	0	11.3	5.6	1.2	0
24	Apr 26	2	0	0	2.2	6.8	0	0	13.6	11.6	10.1	2.1
25	Apr 27	2	1.2	0.2	0.6	0.2	2	4.3	22.0	4.5	2.7	0
26	Apr 27	2	281.6	36.5	0	0	4.9	13.2	62.7	3.6	0	0
27	Apr 27	2	0	0	0	0	20.2	11.7	21.1	2.4	0	0
28	Apr 27	2	0	0	0	7.4	0	0	12.6	6.2	32.9	3.7
29	Apr 28	1	0.5	2.3	13.0	22.7	0	0	1.4	0	11.7	0
30	Apr 28	1	0	0	2.0	2.8	0	0	0	0	2.1	0
Total, BRD-1			86.2	105.9	190.2	170.2	36.0	82.4	742.7	259.3	281.9	13.3
Cod end retention (%)			55.1 (50.6–59.6)		47.2 (42.6–51.8)		69.6 (57.8–81.4)		25.9 (24.6–27.2)		4.5 (1.2–7.8)	
Total, BRD-2			311.1	67.5	88.2	70.6	27.5	31.2	253.8	100.8	650.7	213.5
Cod end retention (%)			17.8 (15.7–20.0)		44.4 (41.7–47.1)		53.2 (42.7–63.7)		28.4 (27.2–29.6)		24.7 (19.5–29.9)	

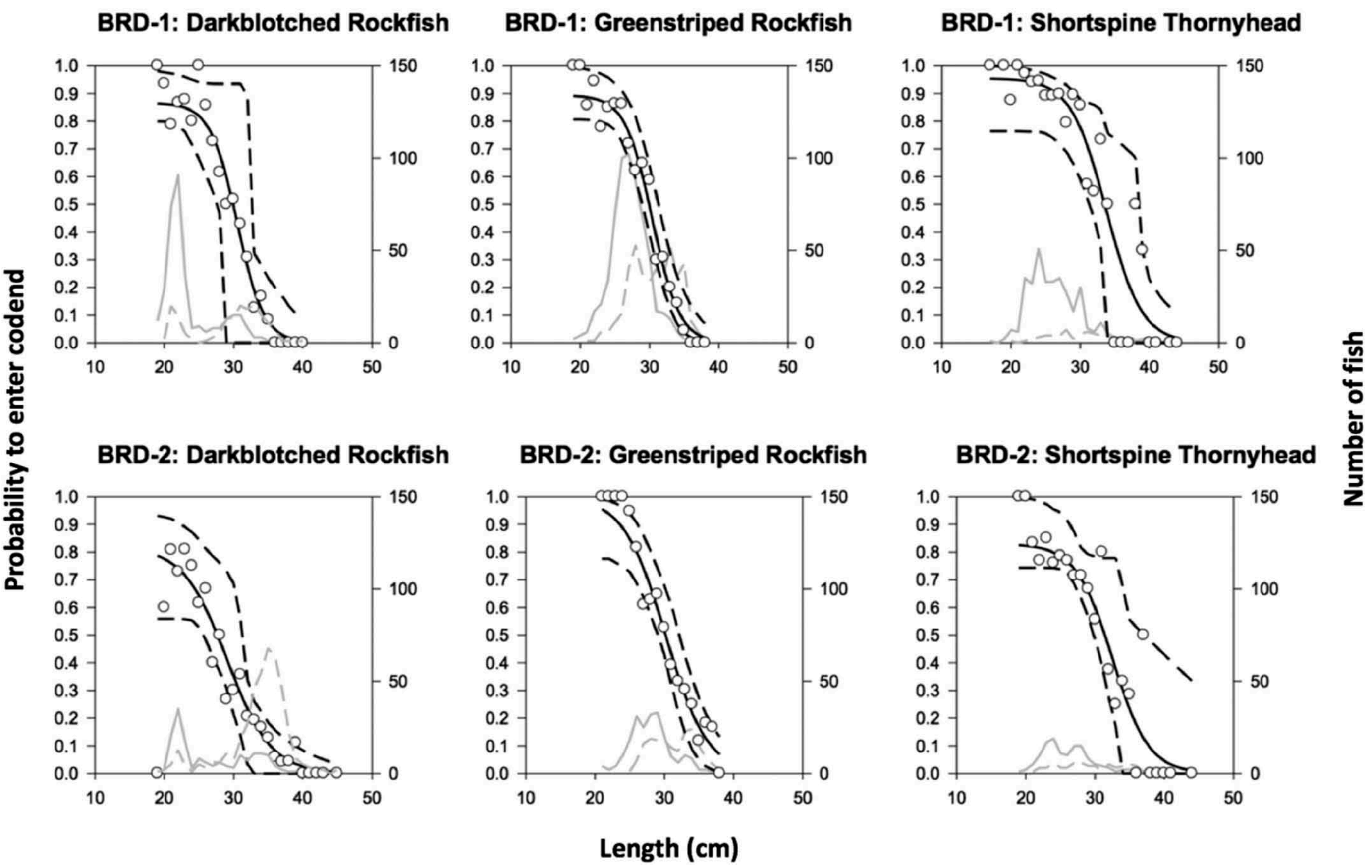

FIGURE 6. Mean selectivity curves quantifying a fish's probability of entering the cod end of a trawl equipped with one of two bycatch reduction devices (BRD-1 and BRD-2), as modeled for Darkblotched Rockfish (length = cm FL), Greenstriped Rockfish (cm FL), and Shortspine Thornyheads (cm TL). Black solid lines represent the modeled value; black dashed lines depict the 95% confidence interval limits; open circles denote the experimental proportions of the catch observed in the cod end; gray solid lines depict the number of fish caught in the trawl cod end; and gray dashed lines represent the number of fish caught in the recapture net.

method to account for both within-tow and between-tow variation. This method is used to avoid underestimating confidence limits for selectivity curves when pooling tow data (Sistiaga et al. 2010; Herrmann et al. 2012).

The statistical analysis software SELNET (SELection in trawl NETting) was used to conduct the analysis (Sistiaga et al. 2010; Herrmann et al. 2012). Table 2 presents the length data that were used to obtain the selectivity results for each BRD design.

RESULTS

We completed 30 tows (15 tows for each BRD design). Combined, flatfishes comprised 62.9% of the total catch by weight, with Pacific Halibut, English Sole, Rex Sole *Glyptocephalus zachirus*, Arrowtooth Flounder *Atheresthes stomias*, Dover Sole, and Petrale Sole comprising 98.3% of flatfish catches. The remaining 37.1% of the total catch consisted of 36 species, including rockfishes (predominantly Darkblotched Rockfish and Greenstriped Rockfish *Sebastes elongatus*), other roundfishes (mainly Shortspine Thornyheads, Sablefish, and Lingcod), and elasmobranchs (primarily Longnose Skates *Raja rhina*). Size-selectivity characteristics for elasmobranchs were not evaluated due to limited sample sizes.

Flatfishes

Mean cod-end retention rates (by weight) for English Sole, Arrowtooth Flounder, Dover Sole, and Petrale Sole were substantially higher in BRD-1 than in BRD-2. The largest differences in mean retention between the two BRDs were observed for Dover Sole and Petrale Sole, with BRD-1 retaining significantly more (by weight) than BRD-2 (Table 3). For BRD-1, Petrale Sole (91.4%) and Dover Sole (89.9%) displayed the highest mean retention. Rex Sole (86.5%) and Petrale Sole (83.8%) showed the highest mean retention for BRD-2. Mean retention of Pacific Halibut and Rex Sole was similar between the two BRDs; however, the sample sizes of these species in the catch were low. Combined, the mean retention (by weight)

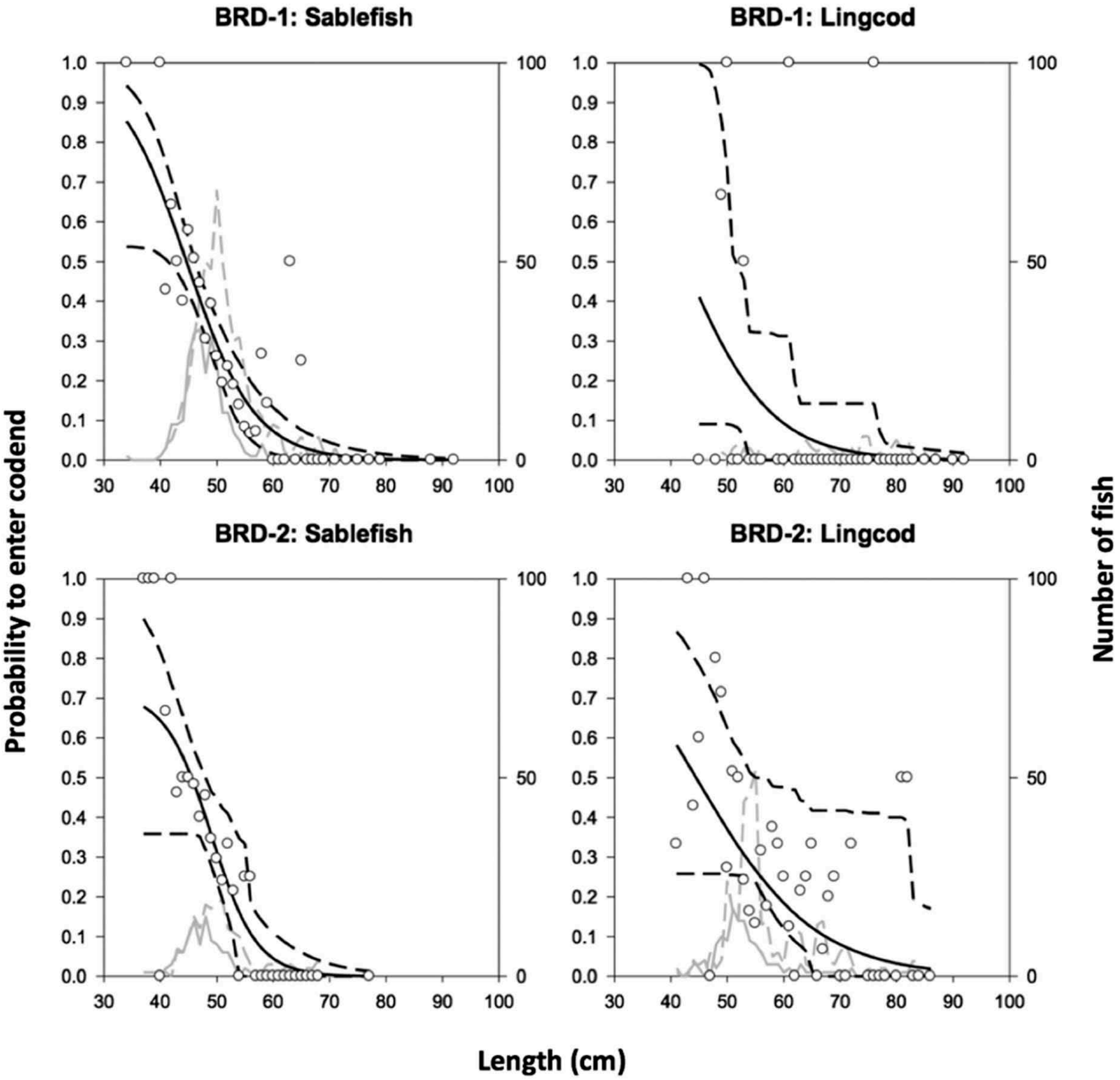

FIGURE 7. Mean selectivity curves quantifying a fish's probability of entering the cod end of a trawl equipped with one of two bycatch reduction devices (BRD-1 and BRD-2), as modeled for Sablefish (length = cm FL) and Lingcod (cm TL). Black solid lines depict the modeled value; black dashed lines represent the 95% confidence interval limits; open circles denote the experimental proportions of the catch observed in the cod end; gray solid lines depict the number of fish caught in the trawl cod end; and gray dashed lines represent the number of fish caught in the recapture net.

of target flatfishes was 89.3% (95% CI = 87.1–91.5%) for BRD-1 and 81.7% (95% CI = 80.0–83.4%) for BRD-2.

Model fit statistics for English Sole in BRD-1 and for Pacific Halibut, Arrowtooth Flounder, and Dover Sole in BRD-2 had *P*-values less than 0.05 and required further assessment to determine whether the models were adequately describing the experimental data for these species (Table 4). Inspection of the fit between the experimental catch data and the modeled mean curve for these species indicated that the *P*-values less than 0.05 were due to overdispersion of the data rather than to the model's inability to adequately describe the data.

The size-selectivity characteristics for BRD-1 and BRD-2 for the six flatfish species evaluated are depicted in Figures 2–4. Mean C_{grid} values, ranging from 0.89 to 0.99 for BRD-1 and from 0.82 to 0.99 for BRD-2, revealed that target flatfishes displayed a high probability of contacting the grid system. The general selectivity trend demonstrated that BRD-1 retained more fish than BRD-2, but the size-selectivity parameters for

TABLE 6. Results of the CLogit model of mean selectivity for roundfishes by the two bycatch reduction device (BRD) designs tested ($L50_{grid}$ and SR_{grid} = passage probability parameters; C_{grid} = fish-size-independent grid contact probability; * = value not defined). Values in parentheses are Efron percentile bootstrap 95% confidence limits.

Species	$L50_{grid}$	SR_{grid}	C_{grid}	*P*-value	Deviance	df
			BRD-1 (grid size = 6.4 × 25.4 cm)			
Darkblotched Rockfish	29.9 (27.6–32.8)	5.4 (0.1–8.9)	0.87 (0.80–0.99)	0.6009	16.8	19
Greenstriped Rockfish	29.9 (28.9–31.3)	5.1 (3.9–7.2)	0.89 (0.81–0.99)	0.5104	16.2	17
Shortspine Thornyhead	33.5 (31.4–38.5)	6.0 (0.1–10.8)	0.95 (0.76–0.99)	0.6511	19.9	23
Sablefish	44.6 (41.3–46.1)	13.3 (*–21.6)	0.99 (0.54–0.99)	0.6990	30.2	35
Lingcod	42.2 (*–51.5)	17.2 (*–35.4)	0.99 (0.91–0.99)	0.6117	33.0	36
			BRD-2 (grid size = 6.4 × 30.5 cm)			
Darkblotched Rockfish	27.6 (25.7–31.3)	10.2 (*–14.6)	0.82 (0.56–0.99)	0.9782	11.4	23
Greenstriped Rockfish	30.2 (29.1–32.1)	6.6 (3.3–9.0)	0.99 (0.79–0.99)	0.6957	11.8	15
Shortspine Thornyhead	31.4 (29.8–37.1)	8.1 (*–19.6)	0.83 (0.74–0.99)	0.9953	8.0	21
Sablefish	45.5 (*–48.0)	* (*–17.8)	0.71 (0.36–0.99)	0.9771	16.6	30
Lingcod	44.4 (*–54.7)	23.0 (*–51.8)	0.99 (0.26–0.99)	0.0032	66.0	38

Pacific Halibut, English Sole, and Rex Sole did not differ significantly between the BRDs, as indicated by their selectivity curves' overlapping 95% CIs (Table 4; Figure 5). However, for 53–58-cm Arrowtooth Flounder, 39–53-cm Dover Sole, and 36–49-cm Petrale Sole, BRD-1 retained significantly more fish of these length-classes (cm TL) than did BRD-2 (Figure 5).

Rockfishes and Other Roundfishes

Both of the tested BRDs were effective at minimizing catches of rockfishes and other roundfishes (Table 5). Both BRDs exhibited relatively steep selectivity curves (Figures 6, 7). For the five roundfish species evaluated, mean $L50_{grid}$ values did not differ significantly between the two BRDs, as indicated by their selectivity curves' overlapping 95% CIs (Table 6; Figure 8). For Darkblotched Rockfish, Greenstriped Rockfish, and Shortspine Thornyheads, mean $L50_{grid}$ values were 29.9, 29.9, and 33.5 cm, respectively, in BRD-1 and 27.6, 30.2, and 31.4 cm, respectively, in BRD-2 (Table 6; Figure 6). Sablefish and Lingcod—species that are more elongated and round in shape than rockfishes and Shortspine Thornyheads—displayed slightly higher mean $L50_{grid}$ values. For BRD-1, mean $L50_{grid}$ values for Sablefish and Lingcod were 44.6 and 42.2 cm, respectively; their mean $L50_{grid}$ values for BRD-2 were 45.5 and 44.4 cm, respectively.

Except for Lingcod, the CLogit model adequately described the data for BRD-1 and BRD-2, as depicted by the model fit statistics (Table 6). Examination of the model output for Lingcod suggested that the *P*-value less than 0.05 was attributable to overdispersion of the data rather than the model's inability to adequately describe the experimental data.

The C_{grid} mean values were relatively high in both BRDs, indicating that the species evaluated have a high likelihood of contacting the grid system. Although the mean values were not significantly different, higher C_{grid} values were observed for Darkblotched Rockfish, Shortspine Thornyheads, and Sablefish in BRD-1 than in BRD-2 (Table 6). The opposite was noted for Greenstriped Rockfish. For Lingcod, mean C_{grid} values were the same between the two BRDs.

DISCUSSION

The two BRDs we tested substantially reduced the catches of rockfishes, other roundfishes, and Pacific Halibut that otherwise would have been retained if the BRDs had not been used. Size-selection characteristics did not differ significantly between the BRDs for two of the target flatfishes, English Sole and Rex Sole. However, there were differences for Arrowtooth Flounder, Dover Sole, and Petrale Sole, with significantly more fish of larger size-classes caught in BRD-1 than in BRD-2. This result was not anticipated, as flatfish retention was expected to be higher in BRD-2 because of its larger grid size. These unexpected results could be due to a relatively low sample size or to a true gear effect of the larger grid size—for example, after fish pass through a grid opening and begin moving back toward the cod end, the larger grid dimensions might increase their probability of passing back through the grid and then being released out of the trawl. Further work using video camera or imaging sonar could reveal whether the latter is happening.

In the LE bottom trawl fishery, the shoreside trawl annual catch limit for Dover Sole has been approximately 45,980 metric tons (NOAA 2015). However, recent catches

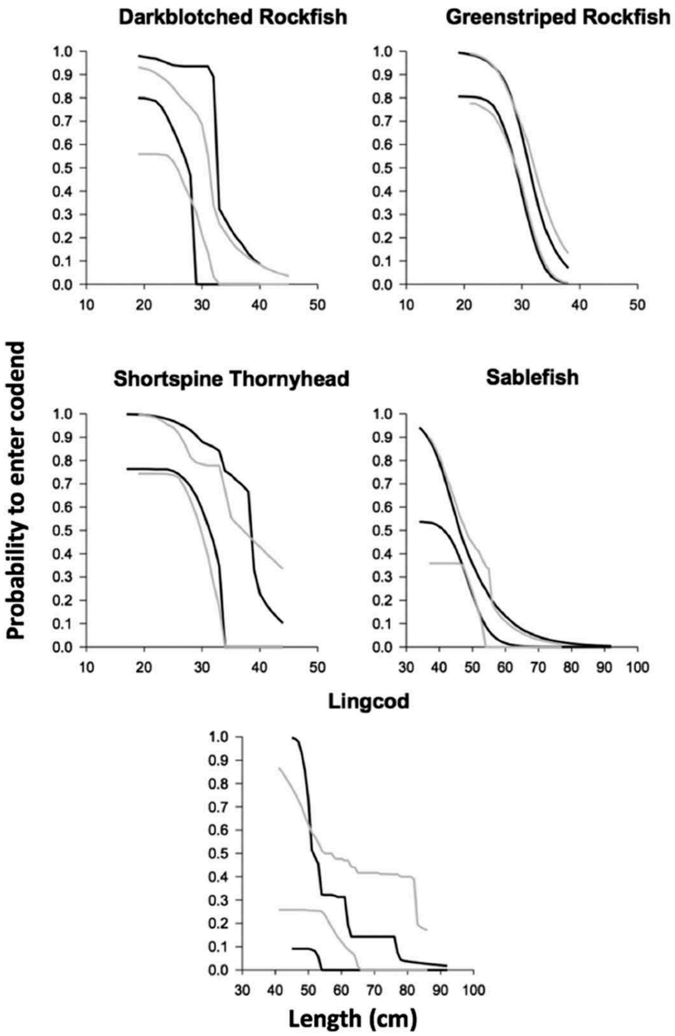

FIGURE 8. Comparison of the 95% confidence interval limits for the size-selection curves quantifying a fish's probability of entering the cod end of a trawl equipped with one of two bycatch reduction devices (BRD-1 and BRD-2), as estimated for five roundfishes (length = cm TL for Shortspine Thornyheads and Lingcod; cm FL for all others). Solid black lines represent BRD-1 (6.4- × 25.4-cm grid size); solid gray lines represent BRD-2 (6.4- × 30.5-cm grid size).

of Dover Sole have been about 6,250 metric tons (PacFIN 2015), which represents only 13.6% attainment of the shoreside trawl allocation, with full attainment being limited by constraining species, such as Darkblotched Rockfish, Sablefish, and Pacific Halibut. In this study, BRD-1 was effective at retaining Dover Sole across all size-classes (89.9% retained by weight overall) while substantially minimizing the catches of nontarget and constraining species. For fishermen seeking more opportunities to capitalize on the Dover Sole allocation and increase their net economic benefits, the BRD-1 design evaluated in this study could provide further opportunities to access this resource.

Results from our prior work (Lomeli and Wakefield 2015, 2016) examining a 4.4- × 21.6-cm grid size showed similar mean flatfish retention rates between the two studies: 84.6% by weight (95% CI = 82.3–87.0%) for the 2015 study versus 85.6% by weight (95% CI = 84.9–86.3%) for the 2016 study. Due to limited vessel time, sampling logistics, and previous results, the 4.4- × 21.6-cm grid size was not incorporated into the current study. Compared to the prior research, the larger grid dimension of BRD-1 (6.4 × 25.4 cm) increased the overall retention of flatfishes by weight while still substantially lowering the catches of rockfishes, other roundfishes, and Pacific Halibut. Overall, BRD-1 retained 89.3% of the flatfishes encountered. The most notable improvement in the gear's performance (compared to the earlier work) was the overall retention of Arrowtooth Flounder. For BRD-1, the mean retention of Arrowtooth Flounder was 85.7% (95% CI = 82.9–88.5%) by weight, whereas the mean retention of this species in the previous research was 68.1% (95% CI = 67.1–69.2%). Catch improvements for larger-sized Dover Sole and Petrale Sole (e.g., >39 cm TL) were also noted for BRD-1. In the Gulf of Alaska, where bycatch of Pacific Halibut at times has impacted fishermen's ability to fully utilize the available resource consisting of Rex Sole, Arrowtooth Flounder, Dover Sole, and Flathead Sole *Hippoglossoides elassodon* (Rose and Gauvin 2000), application of the BRD design evaluated in the current study may prove useful for improving catch utilization in that flatfish fishery.

For sorting grids, mesh panels, modified cod ends (e.g., T90, Bacoma, square mesh, etc.), and other selective fishing devices to be effective, the probability of fish contacting the selective gear must be high. Methods to increase contact probabilities have included deflector/guiding devices (Santos et al. 2016), lifting panels (Sistiaga et al. 2010), and a reduced number of meshes in cod-end circumferences (Herrmann et al. 2007, 2013). In this study, flatfishes and roundfishes exhibited a high probability of contacting the grid systems, as indicated by the high C_{grid} mean values observed for each BRD design. These findings demonstrate that the general BRD design of using two elongated vertical sorting panels to crowd and sort fish was effective at prompting the fish to interact with the sorting grids.

In summary, the size-selection characteristics of two flexible sorting-grid BRDs designed to retain flatfishes while reducing catches of rockfishes, other roundfishes, and Pacific Halibut in the LE groundfish bottom trawl fishery were evaluated. The size-selectivity parameters for rockfishes, other roundfishes, Pacific Halibut, English Sole, and Rex Sole did not differ significantly between the two BRD designs. However, there were differences for Arrowtooth Flounder, Dover Sole, and Petrale Sole, with significantly more fish of larger size-classes caught in BRD-1 than in BRD-2. Compared to previous flatfish sorting-grid selectivity work conducted in the fishery (Lomeli and Wakefield 2015, 2016), the BRD-1 design tested here showed the ability to improve the overall retention of flatfishes while reducing catches of nontarget and constraining species.

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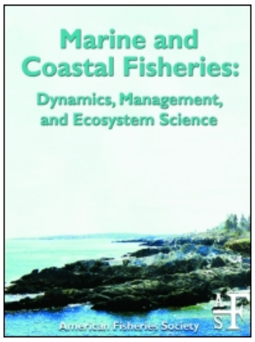
Paper IV

“Improving catch utilization in the U.S. West Coast groundfish bottom trawl fishery: An evaluation of T90-mesh and diamond-mesh cod ends”



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ARTICLE

Improving Catch Utilization in the U.S. West Coast Groundfish Bottom Trawl Fishery: an Evaluation of T90-Mesh and Diamond-Mesh Cod Ends

Mark J. M. Lomeli*
Pacific States Marine Fisheries Commission, 2032 Southeast OSU Drive, Newport, Oregon 97365, USA

Owen S. Hamel
National Oceanic and Atmospheric Administration, National Marine Fisheries Service,
Northwest Fisheries Science Center, Fishery Resource Analysis and Monitoring Division,
2725 Montlake Boulevard East, Seattle, Washington 98112, USA

W. Waldo Wakefield
National Oceanic and Atmospheric Administration, National Marine Fisheries Service,
Northwest Fisheries Science Center, Fishery Resource Analysis and Monitoring Division,
2032 Southeast OSU Drive, Newport, Oregon 97365, USA

Daniel L. Erickson[1]
Oregon Department of Fish and Wildlife, Marine Resources Program,
2040 Southeast Marine Science Drive, Newport, Oregon 97365, USA

Abstract

The limited-entry bottom trawl fishery for groundfish along the U.S. West Coast operates under a catch share program, which is implemented with the intention of improving the economic efficiency of the fishery, maximizing fishing opportunities, and minimizing bycatch. However, stocks with low harvest guidelines have limited the ability of fishermen to maximize their catch of more abundant stocks. Size-selection characteristics of 114-mm and 140-mm T90-mesh cod ends and the traditional 114-mm diamond-mesh cod end were examined by using the covered cod end method. Selection curves and mean L_{50} values (length at which fish had a 50% probability of being retained) were estimated for two flatfish species (Rex Sole *Glyptocephalus zachirus* and Dover Sole *Microstomus pacificus*) and two roundfish species (Shortspine Thornyhead *Sebastolobus alascanus* and Sablefish *Anoplopoma fimbria*). Mean L_{50} values were smaller for flatfishes but larger for roundfishes in the 114-mm T90 cod end compared to the diamond-mesh cod end. For Rex Sole, Dover Sole, and Shortspine Thornyheads, selectivities of the 140-mm T90 cod end were significantly different from those of the other cod ends; the 140-mm T90 cod end was most effective at reducing the catch of smaller-sized fishes but with a considerable loss of larger-sized marketable fishes. Findings suggest that T90 cod ends have potential to improve catch utilization in this multispecies fishery.

Subject editor: Donald Noakes, Vancouver Island University, Nanaimo, British Columbia

*Corresponding author: mlomeli@psmfc.org

[1] Present address: Contractor with Ocean Associates, Inc., National Oceanic and Atmospheric Administration, National Marine Fisheries Service, West Coast Region, Sustainable Fisheries Division, 7600 Sand Point Way Northeast, Seattle, Washington 98115, USA.

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The limited-entry (LE) bottom trawl fishery for groundfish along the U.S. West Coast operates under a catch share program that allocates individual fishing quotas (IFQs) and establishes annual catch limits (ACLs) for over 30 managed groundfish units (PFMC and NMFS 2011, 2015). In this program, fishermen are allocated a proportion of the fishery ACL, are subject to full at-sea observer coverage, and are held fully accountable for all IFQ species' catches, whether discarded or retained.

Over the continental shelf break and upper slope of the U.S. West Coast, fishermen target Dover Sole *Microstomus pacificus*, Shortspine Thornyhead *Sebastolobus alascanus*, Longspine Thornyhead *S. altivelis*, Sablefish *Anoplopoma fimbria*, and (to a lesser extent) Rex Sole *Glyptocephalus zachirus*. In this LE trawl fishery, commonly referred to as the Dover Sole/Thornyhead/Sablefish (DTS) fishery, Sablefish are the most economically important species harvested. Ex-vessel prices for Sablefish can range from US$1.10 to $9.35 per kilogram, with the price increasing with fish weight. However, Sablefish has become a constraining species in the DTS fishery, as their 2015 shoreside trawl allocation (6,028 metric tons) is relatively low in comparison with the Dover Sole allocation (45,986 metric tons; NMFS 2015). Recent catches of Dover Sole have been approximately 6,251 metric tons (PacFIN 2015), which represents only 13% attainment of the shoreside trawl allocation. This low attainment of the Dover Sole ACL is partly due to the attainment of constraining IFQ species, such as Sablefish. Minimizing the catches of smaller-sized Shortspine Thornyheads could also benefit fishermen, as prices for Shortspine Thornyheads can range from US$0.88 to $2.42 per centimeter, with larger-sized individuals receiving the highest price. Dover Sole, on the other hand, are priced at $0.99 per kilogram regardless of length (minimum market size = 33 cm). Hence, reducing the catch rate of smaller-sized Sablefish and Shortspine Thornyheads relative to Dover Sole would allow fishermen more opportunities to capitalize on their Dover Sole IFQ and increase their net economic benefits while still attaining their quota shares of Sablefish and Shortspine Thornyheads.

A simple technique that has been shown to improve trawl selectivity is modifying the size and configuration of the cod end mesh (Perez-Comas et al. 1998; He 2007; Madsen and Valentinsson 2010). Recent studies have focused on the development and use of T90-mesh cod ends (Digre et al. 2010; Wienbeck et al. 2011, 2014; Madsen et al. 2012; Herrmann et al. 2013, 2015; Bayse et al. 2016). The T90 mesh is conventional diamond mesh that has been turned 90° in orientation; this configuration allows the meshes over the entire cod end to remain more open than those of diamond-mesh cod ends, thereby improving size-selection characteristics (Herrmann et al. 2007). Research has demonstrated that diamond-mesh cod ends become distorted into a bulbous shape as catch accumulates and as tension on the netting increases (Stewart and Robertson 1985; Wileman et al. 1996). The majority of escapement occurs just ahead of the accumulating catch bulge, where a few rows of meshes are more open and unblocked by fish. The T90 cod end's simple construction, ease of repair when damaged, and potential to improve size selection provide some advantages over other mesh orientations (e.g., knotless square mesh) that have been used to enhance cod end selectivity (Perez-Comas et al. 1998; He 2007). This T90 mesh configuration, which was originally designed for use in Atlantic Cod *Gadus morhua* fisheries, has gained increased interest from other fisheries, such as the otter trawl fishery for Norway lobster *Nephrops norvegicus* in the Kattegat–Skagerrak area (Madsen et al. 2012) and the multispecies demersal trawl fishery in the Mediterranean Sea (Tokaç et al. 2014). Compared to diamond-mesh cod ends with similar mesh sizes, T90-mesh cod ends have demonstrated the ability to reduce catches of smaller-sized roundfishes (Wienbeck et al. 2011; Herrmann et al. 2013; Tokaç et al. 2014).

The objective of this study was to compare the size-selection characteristics of 114-mm and 140-mm T90-mesh cod ends and the traditional 114-mm diamond-mesh cod end and evaluate whether T90-mesh cod ends can improve groundfish catch utilization in the West Coast LE bottom trawl fishery.

METHODS

Trawl design.—The chartered F/V *Last Straw*, a 23.2-m-long, 540-hp trawler, provided its two-seam trawl for sea trials of the three cod end types. The headrope was 24.1 m in length and utilized sixteen 28.0-cm-diameter deepwater floats for lift. The footrope was 24.7 m in length and incorporated 20.3-cm-diameter rubber disks, with 45.7-cm rockhopper discs placed approximately every 73.7 cm across the length of the footrope. The trawl sweeps were 91.4 m in length and incorporated with 8.9-cm-diameter rubber discs. Thyborøn type-11 standard trawl doors were used.

Cod ends tested.—The cod ends we evaluated were nominal 114-mm T90 mesh (mean mesh size ± SE = 118.5 ± 0.33 mm), 140-mm T90 mesh (139.4 ± 0.37 mm), and 114-mm diamond mesh (119.6 ± 0.46 mm). Mesh sizes were measured using an OMEGA gauge with a 125-Newton stretching force (Fonteyne et al. 2007) following the International Council for the Exploration of the Sea protocol for measuring cod end meshes (Wileman et al. 1996). Each cod end was constructed within a four-seam tube of 6.0-mm, double-twine polyethylene netting with chafing gear protecting the aft-most 50 meshes of the bottom seam. A 50-mesh-length, two-seam to four-seam transitional tube of netting was used to attach each cod end to the trawl when tested. Specifications of the three cod end types are shown in Figure 1.

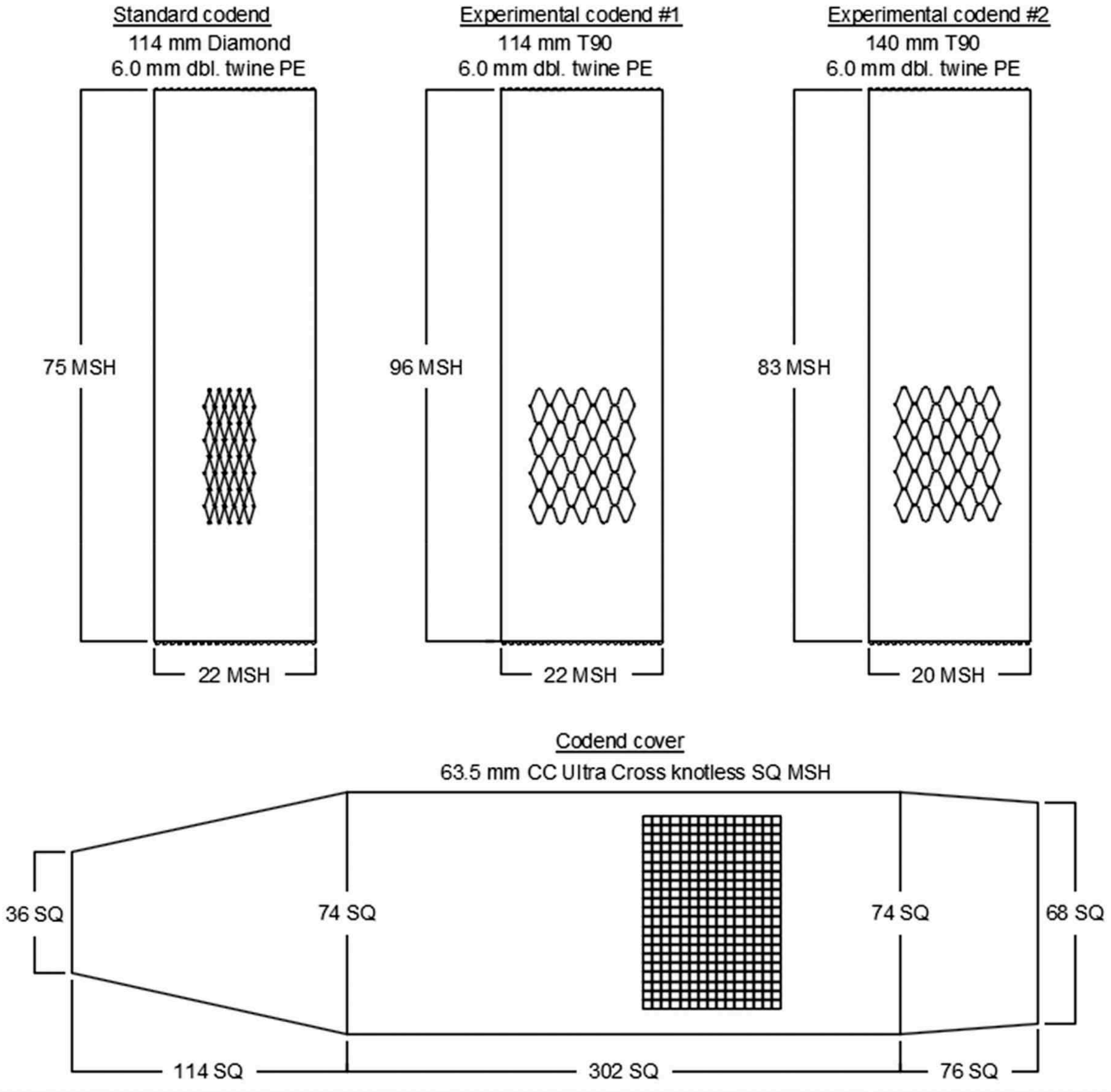

FIGURE 1. Schematic diagram depicting a top-panel view of the cod ends and the cod end cover used in evaluating the cod end types for the West Coast groundfish bottom trawl fishery. Diamond mesh (DM) and T90 mesh sizes are nominal stretched measurements between knots (MSH = mesh; dbl. = double twine; PE = polyethylene; CC = center-to-center mesh measurement; SQ = square). Diagram is not drawn to scale.

Cod end selectivity was measured by using the covered cod end method (Wileman et al. 1996). The cover was a four-seam net constructed of Ultra Cross Dyneema knotless square-mesh netting (63.5-mm center-to-center, 20-ply twine). The cover was attached to the intermediate section of the trawl 30 meshes forward of where the cod end connected to the trawl. At this attachment point, the circumference of the cover was 144 squares, excluding squares in each selvedge. Moving aft, the cover then gradually angled outward over the length of 114 squares to become 296 squares in circumference and 302 squares in length before tapering to 68 squares per panel over the distance of 76 squares (Figure 1). Where the cover encompassed the cod end, the dimensions were approximately 1.5 times the extended width and approximately 1.3 times the extended length of the cod end. Chafing material (102-mm diamond mesh, 5.0-mm single twine) along the bottom seam of the cover was used to protect the aft-most 227 squares from abrasion and net tearing. To keep the cover from masking the cod end, a combination of trapezoidal-shaped kites (0.95-cm-thick conveyor belt material; dimensions = 61 × 31 × 31 cm) and 20.3-cm-diameter floats were used. The kites were positioned along the outer and lower sides of the cover (two sets of four kites on each side) in relation to the fore and aft ends of the cod end, whereas the floats were positioned along the top

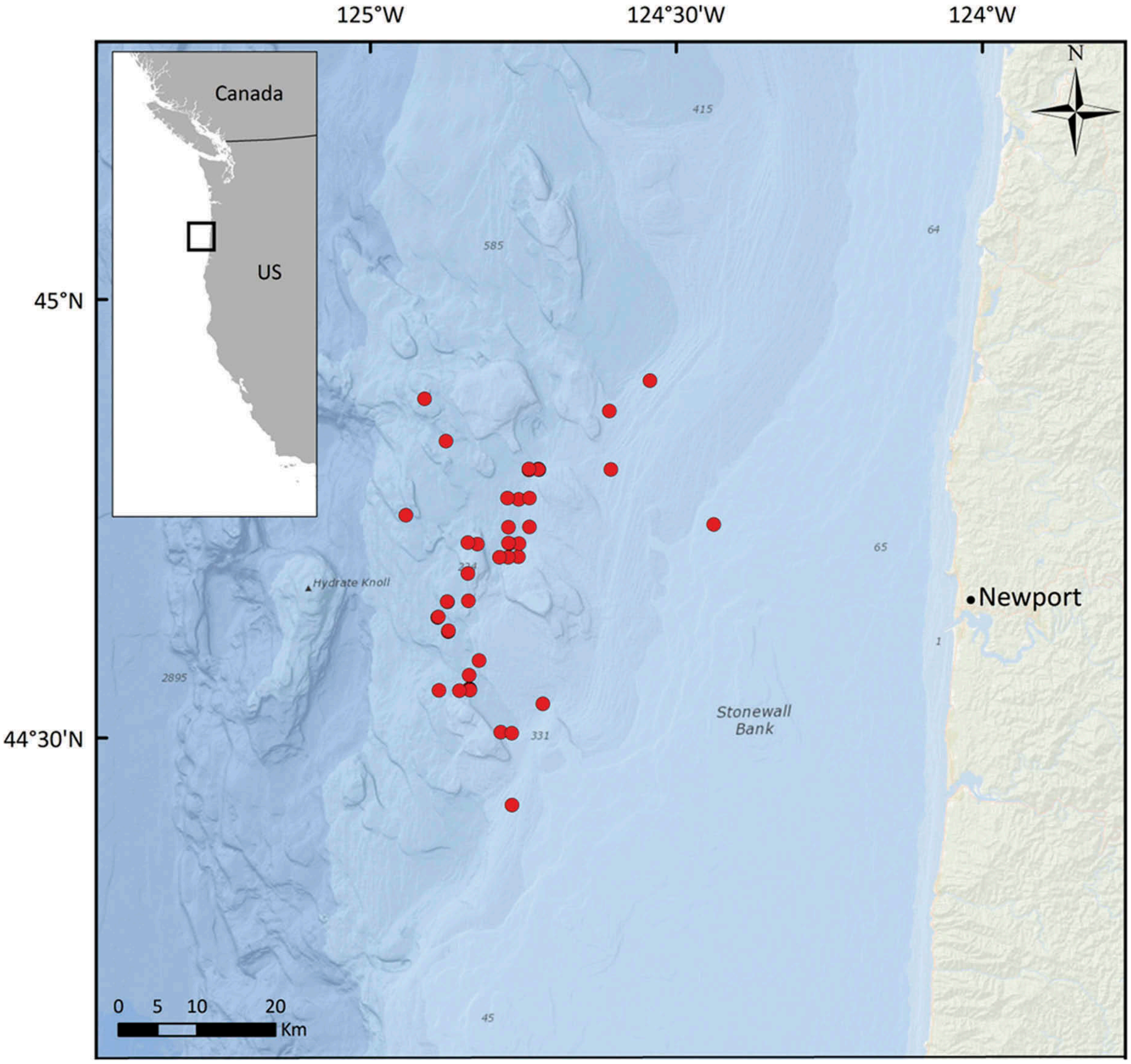

FIGURE 2. Map of the area off the Oregon coast where sea trials were conducted to compare size selectivity of T90-mesh and diamond-mesh cod ends. Bottom trawl tow locations are depicted by the red circles.

riblines (five on each ribline) of the cover. A video camera system was used before data were collected to confirm that the cover was not masking the cod end.

Sea trials.—Tests occurred off the coast of Oregon between 44°25′N and 44°55′N and between 124°27′W and 124°58′W during August 2015 (Figure 2). Towing occurred in the vicinity of the continental shelf break and upper slope during daylight hours (between 0600 and 2000 hours Pacific daylight time) at bottom depths from 311 to 622 m. Towing speed over ground ranged from 4.07 to 4.82 km/h (2.2–2.6 knots). Tow durations were set to 105 min so that all catches could be completely weighed and sampled.

A randomized block design was used to determine the order in which each cod end was tested (Table 1). Overall, 45 tows were completed: 14 tows were made with the 114-mm diamond cod end, 15 tows were made with the 114-mm T90 cod end, and 16 tows were made with the 140-mm T90 cod end. After each tow, all fish that were caught in the cover and in the cod end were identified to species and weighed by using a motion-compensated platform scale. Rex Sole, Dover Sole, and Shortspine Thornyheads from the cover and from the cod end were randomly selected per tow and measured to the nearest centimeter TL, while Sablefish were measured to the nearest centimeter FL. Subsampling was avoided when possible; however, time constraints and relatively large catches often required subsampling for length measurements. Table 2 presents the length data that were used to obtain the selectivity results. During this study, the minimum market size was

TABLE 1. Summary data for the 45 bottom trawl tows completed with three cod end types (114-mm T90 mesh; 140-mm T90 mesh; and 114-mm diamond mesh [DM]) off the Oregon coast in 2015; total catch values were rounded for inclusion in the table ("block" refers to the randomized block design).

Block	Date	Cod end type	Number of tows	Bottom depth range (m)	Total catch range (kg)
1	Aug 2	114 T90	3	366–402	937–3,630
	Aug 3	114 DM	4	380 421	779–1,399
	Aug 5	140 T90	4	397–439	543–1,235
2	Aug 6	140 T90	4	384–622	635–1,091
	Aug 7	114 T90	4	329–393	1,099–1,385
	Aug 10	114 DM	3	311–421	2,051–6,263
3	Aug 11	114 T90	4	395–604	661–3,362
	Aug 12	140 T90	4	512–549	635–1,397
	Aug 15	114 DM	4	487–549	1,110–2,134
4	Aug 16	114 T90	4	402–430	843–1,166
	Aug 17	140 T90	4	386–417	767–1,274
	Aug 18	114 DM	3	494–536	1,300–3,127

31.8 cm for Rex Sole, 33 cm for Dover Sole, and 21.6 cm for Shortspine Thornyheads. There was no minimum market size for Sablefish.

Selectivity analysis.—The statistical analysis software SELNET (SELection in trawl NETting) was used to analyze the data (Sistiaga et al. 2010; Herrmann et al. 2012). Average size-selection curves were estimated by pooling length (l) data across tows for each cod end, $r_{av}(l)$. As various parametric models were evaluated, a vector (v) was included to incorporate the parameters of the model and expressed as $r_{av}(l, v)$. All tows and all length-classes caught were used in the analysis. Five models (logit, probit, Gompertz, Richard, and double logistic [DLogit]) were considered for estimating the average size-selection properties for each species and each type of cod end. The logit, probit, and Gompertz models were described by the L_{50} (length at which fish had a 50% probability of being retained) and selection range (SR; the length difference between L_{25} and L_{75}) parameters. The Richard model was described by the L_{50}, SR, and 1/δ (δ = Delta) selection parameters. The logit, probit, Gompertz, and Richard models assumed that all fish are subjected to the same size-selection process. For the DLogit model (Herrmann et al. 2016), a primary assumption was that a fraction of the fish encountering the cod end (C_1) will be exposed to one size-selection process (i.e., towing process) and is described by parameters $L_{50,1}$ and SR$_1$, while the remaining fraction ($1 - C_1$) will be exposed to another size-selection process (i.e., haulback) and is described by parameters $L_{50,2}$ and SR$_2$. The overall L_{50} and SR parameters for the DLogit model considered both the C_1 value and the $1 - C_1$ value and were estimated by using a statistical method implemented in SELNET. The five model functions evaluated were

$$r_{av}(l,\, v) = \begin{cases} \text{logit}(l, L_{50}, \text{SR}) \\ \text{probit}(l, L_{50}, \text{SR}) \\ \text{Gompertz}(l, L_{50}, \text{SR}) \\ \text{Richard}(l, L_{50}, \text{SR}, 1/\delta) \\ \text{DLogit}\big(l, C_1, L_{50,1}, \text{SR}_1, L_{50,2}, \text{SR}_2\big) \\ \qquad = C_1 \times \text{logit}\big(l, L_{50,1}, \text{SR}_1\big) + (1 - C_1) \\ \qquad \times \text{logit}\big(l, L_{50,2}, \text{SR}_2\big). \end{cases}$$

For complete model details, see Wileman et al. (1996), Wienbeck et al. (2014), and Herrmann et al. (2016).

To determine which model best described the data, we evaluated fit statistics for each model. Fit statistics indicating that a model could adequately describe the data included P-values greater than 0.05 and a deviance value no greater

TABLE 2. Length data that were used to model size selectivity for each cod end type evaluated (114-mm T90 mesh; 140-mm T90 mesh; and 114-mm diamond mesh [DM]) in the West Coast groundfish bottom trawl fishery. Lengths are reported as FL for Sablefish and TL for all other species.

	Rex Sole			Dover Sole			Shortspine Thornyhead			Sablefish		
Variable	114 DM	114 T90	140 T90	114 DM	114 T90	140 T90	114 DM	114 T90	140 T90	114 DM	114 T90	140 T90
Number of tows	13	14	15	14	15	16	14	14	16	14	15	16
Number of fish in cod end (measured)	566	1,040	397	1,090	1,579	974	1,050	1,351	629	1.150	934	844
Number of fish in cod end (raised)	2,073	2,746	503	8,064	7,674	2,657	2,190	2,732	745	5,439	1,893	1,743
Number of fish in cover (measured)	986	1,486	1,196	1,541	1,593	1,754	1,419	1,821	2,010	208	83	290
Number of fish in cover (raised)	3,053	3,975	3,114	7,228	5,194	6,268	4,948	5,794	5,248	208	83	290
Length range (cm)	21–42	19–42	22–42	25–60	24–58	23–60	16–74	16–63	16–74	40–88	43–90	39–92

than approximately 2 times the degrees of freedom. Among the models with acceptable fit statistics, the model with the lowest value of Akaike's information criterion (Akaike 1974) was selected as the best model. After model selection, we estimated Efron bootstrap 95% confidence intervals (CIs; Efron 1982) for L_{50} and SR based on 1,000 bootstrap repetitions using a double-bootstrapping method implemented in SELNET to account for both within-tow and between-tow variation. This is the same approach that was used by Sistiaga et al. (2010) and Herrmann et al. (2012) to avoid underestimating confidence limits for selectivity curves when pooling tow data. To determine whether the selectivity curves for a given species differed significantly between any two of the three cod end types, the P-value was calculated as the number of times out of the 1 million pairs of bootstrap L_{50} values that the L_{50} for net A was less than the L_{50} for net B. For a two-sided test (with $\alpha = 0.05$), if this value was less than 25,000 (2.5%), then the difference was deemed significant.

RESULTS

Total catch per tow (cover plus cod end) ranged from 543 to 6,263 kg (Table 1). Rex Sole comprised 5.7% of the total catch by weight, Dover Sole made up 28.9%, Shortspine Thornyheads constituted 9.1%, and Sablefish comprised 31.7%. The remaining catch consisted of 46 species and included Longspine Thornyheads, secondary target species (i.e., skates [Rajidae] and rockfishes *Sebastes* spp.), unmarketable-sized groundfishes, noncommercial species, and Pacific Halibut *Hippoglossus stenolepis*.

Rex Sole

The mean L_{50} value of Rex Sole caught in the 140-mm T90 cod end was significantly larger than the mean L_{50} values for the 114-mm diamond cod end and 114-mm T90 cod end (Table 3). The mean L_{50} value of the 114-mm diamond cod end was also significantly larger than that of the 114-mm T90 cod end. Mean selectivity curves for Rex Sole showed that selectivity 95% CIs overlapped between the 114-mm diamond cod end and the 114-mm T90 cod end around L_{25} and for all three cod ends well above L_{75}; however, there was a clear separation of the selectivities for the three cod end types at L_{50} (Figure 3). The 114-mm T90 cod end exhibited the narrowest SR and thus the steepest selectivity curve (Table 3). Acceptable fit statistics were observed for the 114-mm diamond cod end and the 140-mm T90 cod end. However, a P-value less than 0.05 for the 114-mm T90 cod end required further assessment to determine whether the model was adequately describing the data for Rex Sole. The assessment indicated that the P-value less than 0.05 was due to overdispersion of the data rather than the inability of the model to adequately describe the data.

Dover Sole

The mean L_{50} value for Dover Sole caught in the 140-mm T90 cod end was significantly larger than the mean L_{50} values for the 114-mm diamond cod end and 114-mm T90 cod end; the mean L_{50} value for the 114-mm diamond cod end was also significantly larger than that for the 114-mm T90 cod end (Table 3). Mean selectivity curves for Dover Sole illustrated the closer similarities in selectivity between the 114-mm diamond and 114-mm T90 cod ends and their greater differences from the 140-mm T90 cod end (Figure 4). As was observed for Rex Sole, the mean L_{50} value for Dover Sole was smallest with the 114-mm T90 cod end. For both flatfish species, the 114-mm and 140-mm T90 cod ends showed narrower SRs and steeper selectivity curves than the 114-mm diamond cod end.

TABLE 3. Mean selection results for models describing the size selectivity of the three cod end types evaluated (114-mm T90 mesh; 140-mm T90 mesh; and 114-mm diamond mesh [DM]) for the West Coast groundfish bottom trawl fishery (Efron bootstrap 95% confidence intervals are shown in parentheses; SSTH = Shortspine Thornyhead; L_{50} = length at which 50% of fish have the probability of being retained; SR = selection range; SF = selection factor). For a given species, lowercase letters (z, y, x) indicate whether the L_{50} is significantly different among cod end types (at the $\alpha = 0.05$ level); the magnitude of the L_{50} value increases from z to x. The model that best described the data is presented (DLogit = double logistic).

Species	Cod end type	L_{50}	SR	SF	Model	P-value	Deviance	df
Rex Sole	114 DM	33.1 (32.3–34.9) y	6.5 (5.0–8.7)	0.28	Logit	0.4338	20.4	20
	114 T90	31.8 (31.2–32.4) z	3.8 (3.1–4.8)	0.27	DLogit	0.0051	38.5	19
	140 T90	36.4 (35.8–37.4) x	4.7 (3.8–5.8)	0.26	Logit	0.1827	24.4	19
Dover Sole	114 DM	34.9 (33.9–35.9) y	4.5 (3.0–7.8)	0.29	DLogit	0.1125	40.8	31
	114 T90	33.6 (33.0–34.2) z	3.5 (3.2–4.0)	0.28	Probit	0.9959	15.5	33
	140 T90	39.2 (38.3–40.2) x	3.6 (3.0–4.2)	0.28	Probit	0.9780	21.0	36
SSTH	114 DM	28.4 (27.6–30.5) z	8.0 (5.9–11.7)	0.24	DLogit	0.9521	28.8	43
	114 T90	30.0 (28.8–31.8) z	6.4 (5.1–8.2)	0.25	DLogit	0.1317	50.1	40
	140 T90	36.3 (34.9–37.4) y	6.7 (5.4–7.9)	0.26	Richard	0.9563	36.8	53
Sablefish	114 DM	42.2 (31.9–44.9) z	2.6 (0.1–14.5)	0.35	DLogit	0.9815	23.6	40
	114 T90	43.9 (42.3–45.4) zy	5.1 (4.1–6.5)	0.37	Gompertz	0.8082	34.8	43
	140 T90	46.5 (42.9–48.5) y	7.8 (4.4–51.5)	0.33	DLogit	0.9998	17.9	44

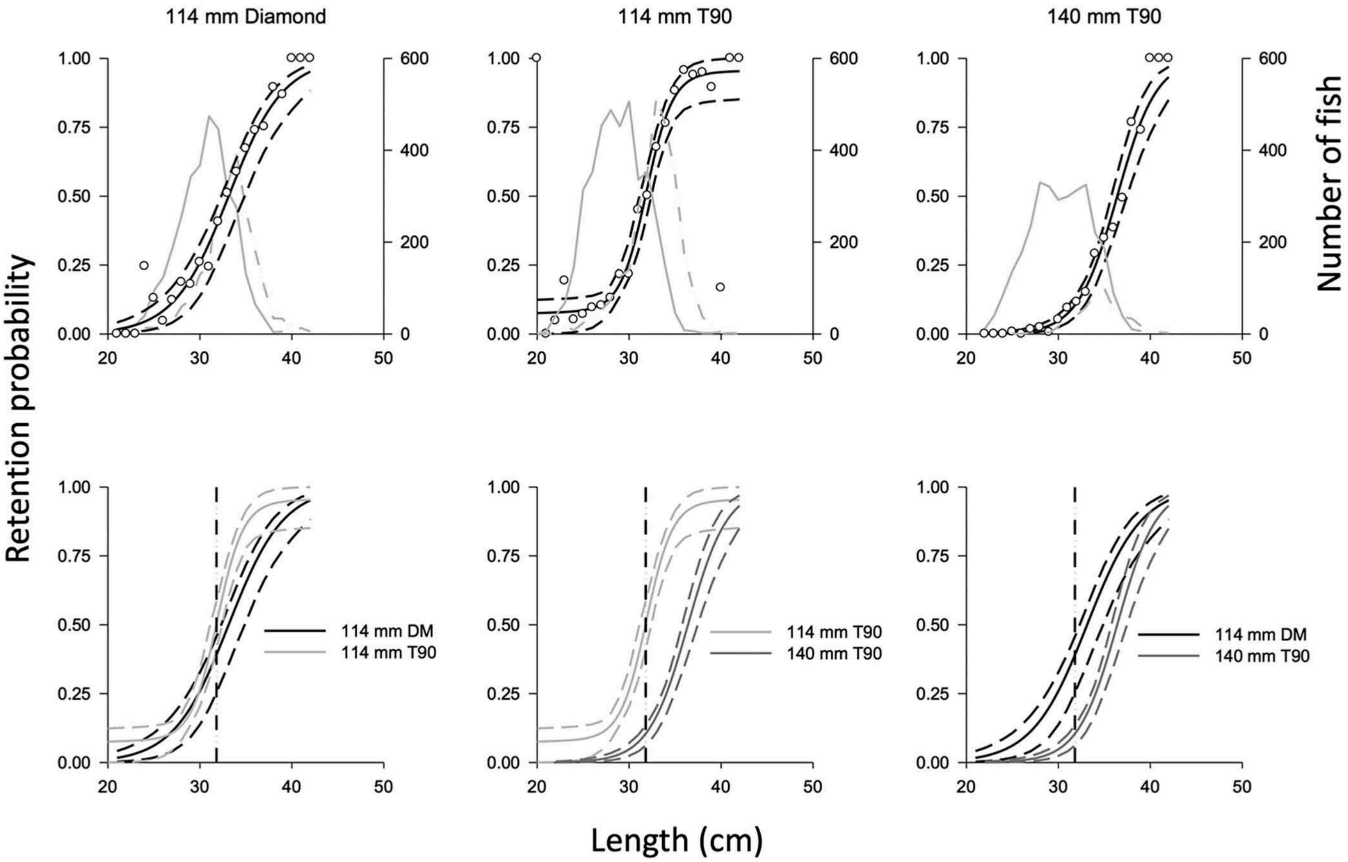

FIGURE 3. Mean selectivity curves (upper panels) modeled for Rex Sole in each cod end type examined (DM = diamond mesh; black solid line = the modeled value; black dashed lines = 95% confidence interval; open circles = experimental data; gray solid line = number of fish caught in the cod end cover; gray dashed line = number of fish caught in the cod end). Lower panels present comparisons of mean selectivity curves for the three cod end types (solid line = the modeled value; dashed lines = 95% confidence interval; vertical black dashed line = minimum market size).

Shortspine Thornyhead

The mean L_{50} for Shortspine Thornyheads caught in the 140-mm T90 cod end was significantly larger than the mean L_{50} values for the 114-mm diamond and 114-mm T90 cod ends (Table 3). Although the mean L_{50} value for the 114-mm T90 cod end was larger than that for the 114-mm diamond cod end, the two means did not differ statistically, as suggested by their substantially overlapping 95% CIs at L_{50} (Table 3; Figure 5). Mean selectivity curves for Shortspine Thornyheads illustrated the similarity in selectivity between the 114-mm diamond and 114-mm T90 cod ends and their differences in selectivity relative to the 140-mm T90 cod end (Figure 5). The 114-mm and 140-mm T90 cod ends exhibited narrower SRs and steeper selectivity curves than the 114-mm diamond cod end.

Sablefish

The mean L_{50} value for Sablefish that were caught in the 140-mm T90 cod end was significantly larger than the mean L_{50} for those caught in the 114-mm diamond cod end (Table 3). For Sablefish, mean L_{50} values did not differ significantly between the two 114-mm cod ends tested or between the two T90 cod ends tested, as too few fish were caught in the cover for the models to detect any significant differences (Figure 6). Overall, the 114-mm T90 cod end had a greater mean L_{50} value and a narrower SR 95% CI than the 114-mm diamond cod end. The 140-mm T90 cod end had a larger mean L_{50} and a wider SR 95% CI than the 114-mm T90 cod end (Table 3). As occurred in Shortspine Thornyheads, the mean L_{50} value for Sablefish was smallest with the 114-mm diamond cod end. Mean selectivity curves for Sablefish captured in the three cod ends are presented in Figure 6.

DISCUSSION

Turning diamond mesh 90° in orientation (i.e., T90 mesh) can affect the selection properties of a cod end. In this study, mean L_{50} values for Rex Sole and Dover Sole were significantly smaller in the 114-mm T90 cod end than in the 114-mm diamond cod end.

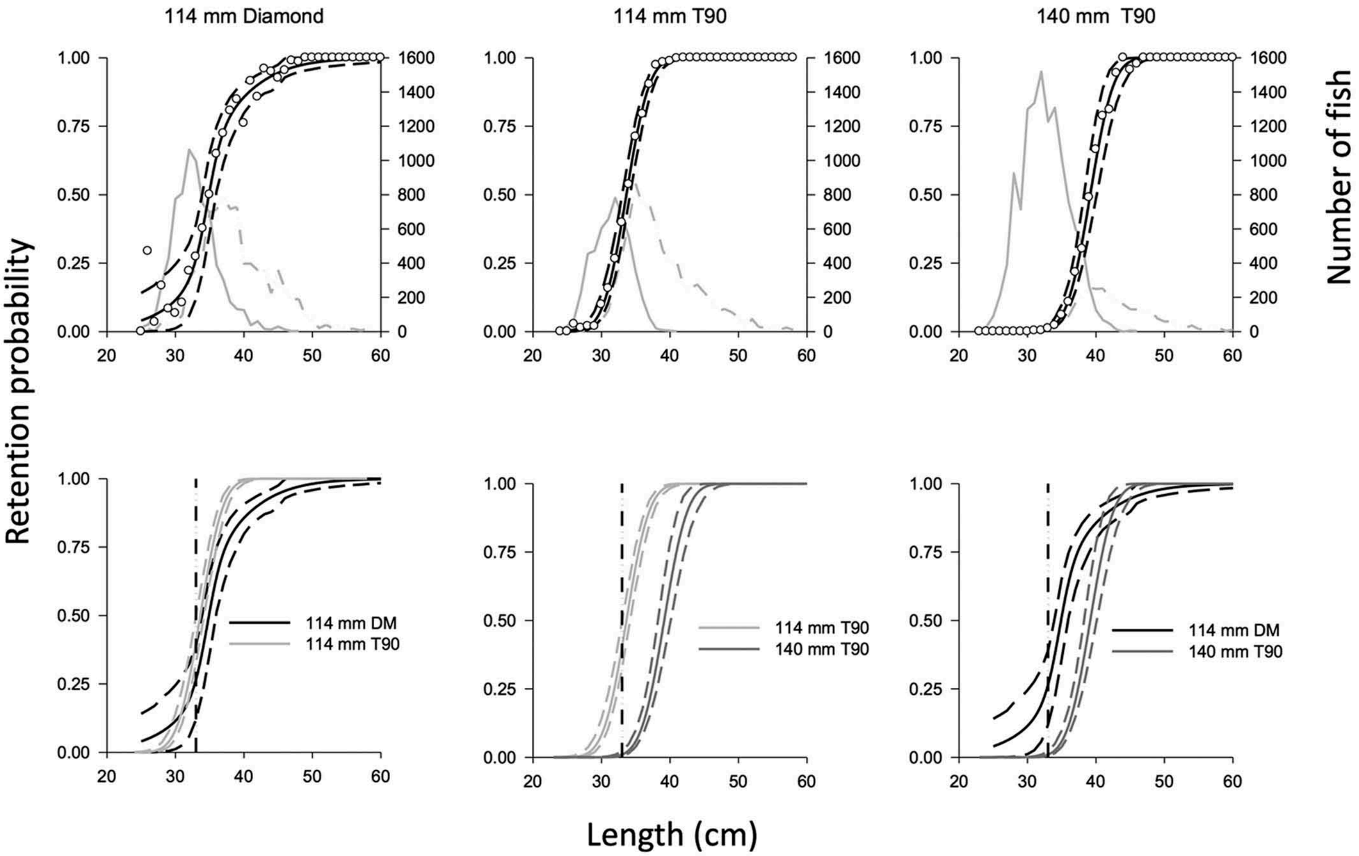

FIGURE 4. Mean selectivity curves (upper panels) modeled for Dover Sole in each cod end type examined (DM = diamond mesh; black solid line = the modeled value; black dashed lines = 95% confidence interval; open circles = experimental data; gray solid line = number of fish caught in the cod end cover; gray dashed line = number of fish caught in the cod end). Lower panels present comparisons of mean selectivity curves for the three cod end types (solid line = the modeled value; dashed lines = 95% confidence interval; vertical black dashed line = minimum market size).

For Shortspine Thornyheads and Sablefish, the opposite trend was consistently seen (Table 3), with larger mean L_{50} values occurring in the 114-mm T90 cod end than in the 114-mm diamond cod end. In our analyses of Rex Sole, Dover Sole, and Shortspine Thornyheads, selectivity values for the 140-mm T90 cod end were significantly different from those of the other two cod end types. The mean L_{50} value for Sablefish was largest in the 140-mm T90 cod end, and that mean was significantly different from the mean L_{50} associated with the 114-mm diamond cod end but not from the mean obtained with the 114-mm T90 cod end. However, the small number of Sablefish in the cover reduced the power of comparison tests for Sablefish relative to those conducted for the other three species. Our general findings of smaller mean L_{50} values for flatfishes but larger means for roundfishes occurring in the 114-mm T90 cod end relative to those in the 114-mm diamond cod end are similar to previous studies that have compared diamond cod ends to T90 cod ends (Wienbeck et al. 2011; Herrmann et al. 2013; Tokaç et al. 2014; Bayse et al. 2016) and square-mesh cod ends (Wallace et al. 1996; Perez-Comas et al. 1998; He 2007) with similar mesh sizes.

The selection factor (SF) parameter represents the ratio between L_{50} and mean mesh size. This parameter can be used to estimate L_{50} values (SF value × mesh size = L_{50}) for a species across different mesh sizes and is useful for comparing results within and/or between studies in which slightly different mesh sizes are used (Herrmann et al. 2016). In the present study, there was a slight difference in the mean mesh size between the nominal 114-mm cod ends (118.5 mm versus 119.6 mm). Therefore, SF values were calculated (Table 3) and examined to determine whether the difference in mesh size affected the L_{50}. Inspection of the SFs showed that the difference in mean mesh size between the 114-mm cod ends had a minimal effect, as the results still showed smaller mean L_{50} values for flatfishes but larger mean L_{50} values for roundfishes in the nominal 114-mm T90 cod end than in the 114-mm diamond cod end.

Prior to this study, cod end selectivity research off the U. S. West Coast had focused on diamond-mesh and square-mesh cod ends. Wallace et al. (1996) and Perez-Comas et al. (1998) examined the selection properties of 114-, 127-, and

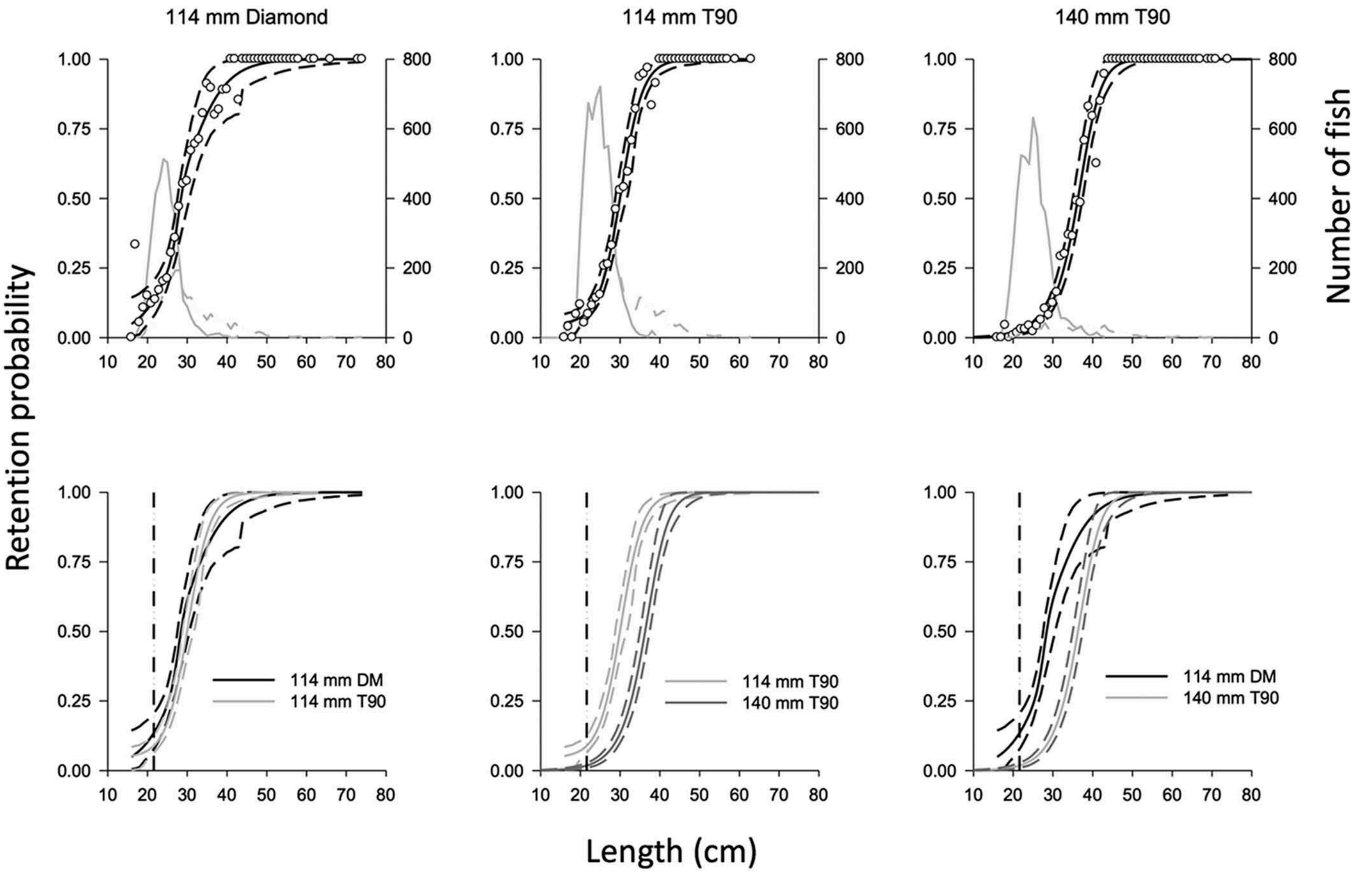

FIGURE 5. Mean selectivity curves (upper panels) modeled for Shortspine Thornyheads in each cod end type examined (DM = diamond mesh; black solid line = the modeled value; black dashed lines = 95% confidence interval; open circles = experimental data; gray solid line = number of fish caught in the cod end cover; gray dashed line = number of fish caught in the cod end). Lower panels present comparisons of mean selectivity curves for the three cod end types (solid line = the modeled value; dashed lines = 95% confidence interval; vertical black dashed line = minimum market size).

140-mm diamond-mesh cod ends and 114- and 127-mm square-mesh cod ends. In general, their results indicated that total discard rates decreased with increasing mesh sizes for both diamond and square-mesh cod ends. A decline in catch utilization also corresponded to increasing mesh size, with the highest loss occurring in the 140-mm diamond cod end. In the present study, where the size-selection properties of 114-mm T90, 140-mm T90, and 114-mm diamond-mesh cod ends were evaluated, the 114-mm T90 cod end showed a consistent trend of increasing the retention of flatfishes while lowering the catches of smaller-sized Shortspine Thornyheads and Sablefish relative to the 114-mm diamond and 140-mm T90 cod ends. Perez-Comas et al. (1998) observed a similar result when comparing a 114-mm square-mesh cod end to a 114-mm diamond cod end, with more immature and unmarketable-sized flatfishes (e.g., Rex Sole and Dover Sole) retained in the square-mesh cod end. They observed the opposite for roundfishes. Wallace et al. (1996) presented similar findings in the outer nearshore fishery (91–183-m depth), where the percentage of roundfishes is typically higher; the 114-mm square-mesh cod end performed better than the 114-mm diamond cod end at reducing roundfish discards. In the inner nearshore fishery (0–91-m depth), where the proportion of flatfishes is generally higher, Wallace et al. (1996) found that the 114-mm diamond cod end performed better at limiting discards. Results from the current study indicate that the 114-mm T90 cod end may perform better at reducing catches of smaller-sized roundfishes than the similar-sized diamond cod end. For the DTS fishery, in which the Sablefish has become a constraining species, the 114-mm T90 cod end could potentially benefit fishermen by reducing their catch rate of smaller-sized Sablefish and Shortspine Thornyheads while allowing them more opportunities to catch their Dover Sole IFQs. Although the 140-mm T90 cod end was effective at reducing catches of smaller-sized flatfishes and roundfishes (as indicated by the mean L_{50} values), this cod end would be economically unfeasible for use under current management regulations and market fish sizes because it exhibited a considerable loss of the catch of marketable-sized fishes.

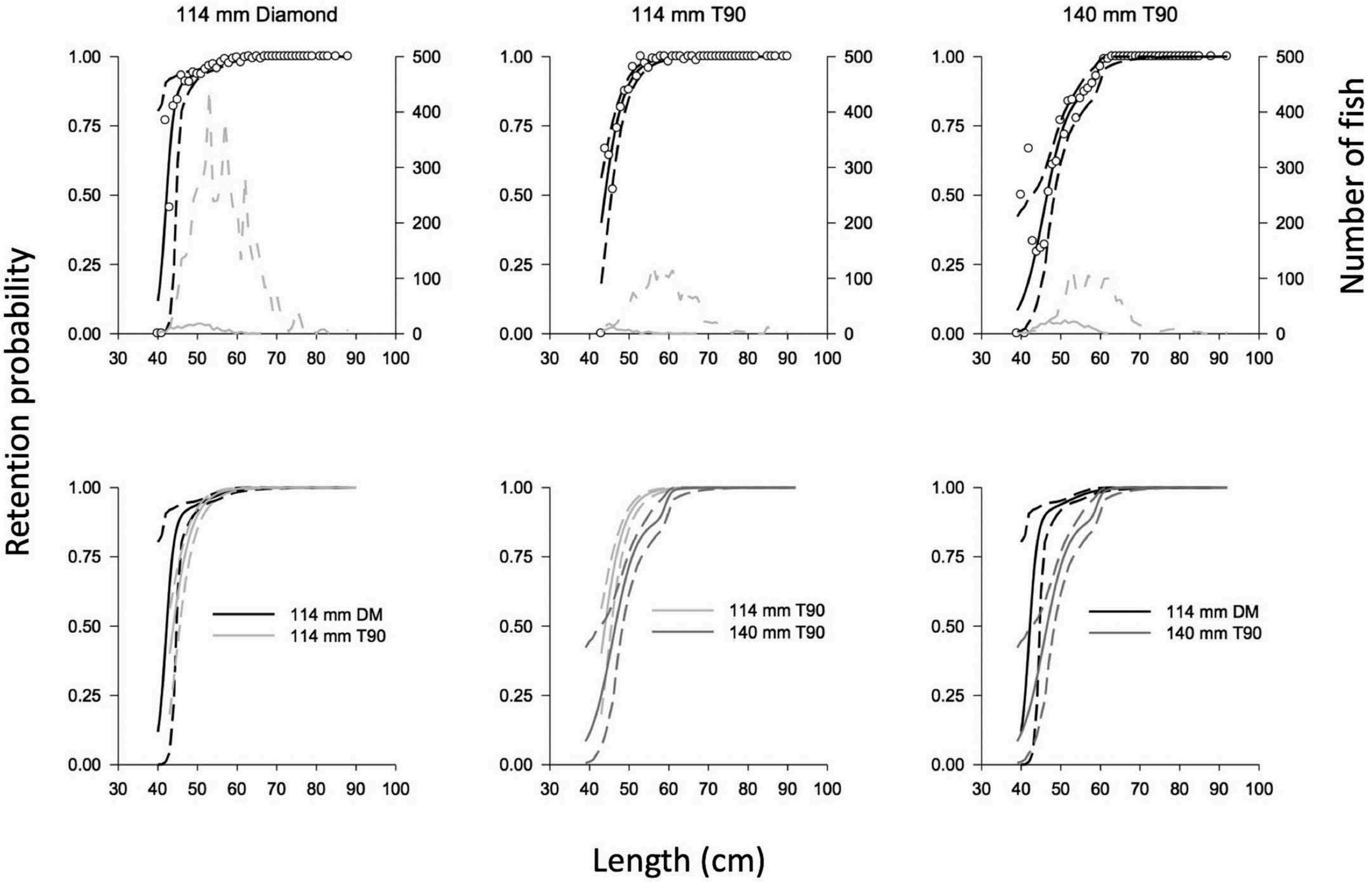

FIGURE 6. Mean selectivity curves (upper panels) modeled for Sablefish in each cod end type examined (DM = diamond mesh; black solid line = the modeled value; black dashed lines = 95% confidence interval; open circles = experimental data; gray solid line = number of fish caught in the cod end cover; gray dashed line = number of fish caught in the cod end). Lower panels present comparisons of mean selectivity curves for the three cod end types (solid line = the modeled value; dashed lines = 95% confidence interval).

Although there may be clear benefits to using T90 cod ends in the LE groundfish bottom trawl fishery, the use of cod end circumferences, twine thicknesses, and twine numbers (e.g., single or double) other than those employed in this study may improve results for trawl fishermen. In a simulated study on Haddock *Melanogrammus aeglefinus* (Herrmann et al. 2007) and a field study of Atlantic Cod in the Baltic trawl fishery (Wienbeck et al. 2011), reducing the number of meshes in the circumference of T90 and diamond-mesh cod ends improved size-selection characteristics (i.e., increased the mean L_{50} values). Both studies demonstrated that T90 and diamond cod ends with reduced circumferences improved selectivity, but the best selection results were achieved by using the T90 cod ends with reduced circumferences. Herrmann et al. (2013) examined the effects of twine characteristics (e.g., thickness, number, and orientation [T90 versus diamond]) on size selectivity for Atlantic Cod and Plaice *Pleuronectes platessa* in the Baltic trawl fishery. For the same mesh size, results showed that T90 cod ends increased the mean L_{50} values for Atlantic Cod. However, as twine thickness in the double-twine T90 cod ends increased, the mean L_{50} values for Atlantic Cod decreased. Increasing the twine thickness, increasing the twine number, and turning the diamond mesh 90° in orientation had a negative effect on Plaice size selectivity. Improvements in size selection of Atlantic Cod from reducing the cod end circumference and twine thickness and turning the diamond mesh 90° in orientation have also been demonstrated (Herrmann et al. 2016).

Identifying a particular cod end mesh size and mesh configuration that can effectively reduce discards while limiting catch losses in multispecies groundfish bottom trawl fisheries has been a challenge for researchers (Wallace et al. 1996; Perez-Comas et al. 1998; He 2007; Herrmann et al. 2013). In several cases, the selectivity for some species has improved, whereas the selectivity for other species has decreased. In these fisheries, where the composition of flatfishes and roundfishes can change spatially and temporally, the use of different cod end mesh sizes and mesh configurations as fishing operations change would most likely improve the ability of fishermen to enhance trawl selectivity relative to use of a single cod end mesh size and a single configuration across the whole fishery. Wallace et al. (1996) provided a good example of how the use of different cod end mesh sizes and configurations could improve trawl selectivity in the nearshore bottom trawl fishery for groundfish along the U.S. West Coast. In their study, square-mesh cod ends were found to perform best at reducing total discard rates in the outer nearshore fishery (91–183-m depth), where assemblages of Arrowtooth Flounder *Atheresthes stomias*, Pacific Cod *Gadus macrocephalus*, Sablefish, Lingcod *Ophiodon elongatus*, and Dover Sole were targeted, whereas diamond-mesh cod ends with a mesh size of at least 114 mm performed better in the inner nearshore fishery (0–91-m depth), where Pacific Sanddab *Citharichthys sordidus*, English Sole *Parophrys vetulus*, Rex Sole, and rockfishes were the main targeted species. Helping fishermen to identify more selective trawl gear that can reduce the retention of unmarketable-sized fishes as well as species with relatively low ACLs or allocations will allow the fishermen to more effectively utilize their IFQs and increase their economic benefits; furthermore, benefits will accrue to coastal communities, management, and the resource.

In conclusion, the size-selection characteristics of 114-mm T90, 140-mm T90, and 114-mm diamond-mesh cod ends were evaluated for two flatfish species and two roundfish species that are commonly caught over the continental shelf break and upper slope of the U.S. West Coast. Although there may be clear benefits to using T90 cod ends in this mixed-stock groundfish fishery, mesh sizes, cod end circumferences, twine thicknesses, and twine numbers other than those used here may improve results for trawl fishermen. Further evaluation of T90 cod ends over a range of mesh sizes and circumferences and under various fishing conditions would provide important information to better determine their potential efficacy in this fishery.

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Paper V

“Illuminating the Headrope of a Selective Flatfish Trawl: Effect on Catches of Groundfishes, Including Pacific Halibut”

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ARTICLE

Illuminating the Headrope of a Selective Flatfish Trawl: Effect on Catches of Groundfishes, Including Pacific Halibut

Mark J. M. Lomeli*
Pacific States Marine Fisheries Commission, 2032 Southeast OSU Drive, Newport, Oregon 97365, USA

W. Waldo Wakefield
Northwest Fisheries Science Center, Fishery Resource Analysis and Monitoring Division, 2032 Southeast OSU Drive, Newport, Oregon 97365, USA

Bent Herrmann
SINTEF Fisheries and Aquaculture, Willemoesvej 2DK-9850, Hirtshals, Denmark

Abstract

This study evaluated how illuminating the headrope of a selective flatfish trawl can affect catches of groundfishes, including Pacific Halibut *Hippoglossus stenolepis*, in the U.S. West Coast limited-entry (LE) groundfish bottom trawl fishery. Over the continental shelf, fishermen engaged in the LE bottom trawl fishery target a variety of flatfishes, roundfishes, and skates. Green LED fishing lights (Lindgren-Pitman Electralume) were used to illuminate the headrope. The lights were grouped into clusters of three, with each cluster attached ~1.3 m apart along the 40.3-m-long headrope. Catch comparisons and ratios of mean fish length classes were compared between tows conducted with (treatment) and without (control) LEDs attached along the trawl headrope. Fewer Rex Sole *Glyptocephalus zaphirus*, Arrowtooth Flounder *Atheresthes stomias*, and Lingcod *Ophiodon elongatus* were caught in the treatment than in the control trawl, though not at a significant level. Pacific Halibut catches differed between the two trawls, with the treatment trawl catching an average of 57% less Pacific Halibut. However, this outcome was not significant due to a small sample size. For Dover Sole *Microstomus pacificus* 31–44 cm in length and Sablefish *Anoplopoma fimbria* 43–61 cm in length, significantly fewer fish were caught in the treatment than in the control trawl. On average, the treatment trawl caught more rockfishes *Sebastes* spp., English Sole *Parophrys vetulus*, and Petrale Sole *Eopsetta jordani*, but not at a significant level. These findings show that illuminating the headrope of a selective flatfish trawl can affect the catch comparisons and ratios of groundfishes, and depending on fish length and species the effect can be positive or negative.

The U.S. West Coast limited-entry (LE) groundfish bottom trawl fishery operates under a catch share program that allocates individual fishing quotas (IFQs) and establishes annual catch limits (ACLs) for 29 managed units of groundfish (stocks, stock complexes, and geographical subdivisions of stocks; PFMC and NMFS 2011, 2015). Over the continental shelf, fishermen engaged in the LE bottom trawl fishery target a variety of flatfishes (e.g.,

Subject editor: Donald Noakes, Vancouver Island University, Nanaimo, British Columbia

*Corresponding author: mlomeli@psmfc.org
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English Sole *Parophrys vetulus*, Dover Sole *Microstomus pacificus*, Petrale Sole *Eopsetta jordani*), roundfishes (e.g., Yellowtail Rockfish *Sebastes flavidus*, Sablefish *Anoplopoma fimbria*, Lingcod *Ophiodon elongatus*), and skates (Rajidae). Fully utilizing the ACL for many of these groundfishes, however, have been affected in recent years by stocks with restrictive harvest limits (i.e., Darkblotched Rockfish *S. crameri*, and Yelloweye Rockfish *S. ruberrimus* [an overfished stock]), and bycatch of Pacific Halibut *Hippoglossus stenolepis* (a prohibited species). Hence, it is increasingly important for fishermen and managers to develop techniques that minimize the catches of constraining species, allowing for increased utilization of the catch share quotas of healthier fish stocks.

Low-rise trawls with either a cut back headrope or a top panel constructed of large mesh are often used in flatfish fisheries (King et al. 2004; Madsen et al. 2006; Krag and Madsen 2010). These trawls are designed to allow nontarget species that tend to rise when encountered an opportunity to escape before trawl entrainment. In the LE groundfish bottom trawl fishery, fishermen are required under current regulations to use a two-seam low-rise selective flatfish trawl when fishing north of 40°10′N latitude in bottom depths less than 183 m to reduce catches of overfished and rebuilding rockfishes (NOAA 2014). This trawl, with a mean headrope height of ~1.3 m (King et al. 2004; Hannah et al. 2005), is effective at reducing catches for many benthopelagic groundfishes, but has been less effective at reducing catches of some of the more benthic groundfishes, such as Darkblotched Rockfish, and smaller-sized Pacific Halibut (King et al. 2004).

Studies have demonstrated that light can affect the behavior of fish in and around trawl gear (Walsh and Hickey 1993; Ryer and Olla 2000; Ryer and Barnett 2006; Lomeli and Wakefield 2012; Hannah et al. 2015) and that vision is the primary sense affecting fish behavior in relation to trawl gear (Glass and Wardle 1989; Olla et al. 1997, 2000; Kim and Wardle 1998, 2003; Ryer et al. 2010). Using a Pacific Hake *Merluccius productus* midwater trawl, research tested whether artificial illumination could attract Chinook Salmon *Oncorhynchus tshawytscha* to specific escape windows of a bycatch reduction device (BRD) equipped with multiple escape windows. Video observations of 438 Chinook Salmon were made, with 299 individuals being observed to exit out the BRD. Of the Chinook Salmon that escaped, 243 (81.3%) exited out a window that was illuminated (Pacific States Marine Fisheries Commission, unpublished data). This result was highly significant ($P < 0.0001$). On an ocean shrimp *Pandalus jordani* trawl, Hannah et al. (2015) examined whether placing artificial illumination along the trawl fishing line could reduce Eulachon *Thaleichthys pacificus* bycatch by illuminating escape openings between the groundline contacting the seafloor and the fishing line. Eulachon bycatch was reduced 91% by weight. This work also noted catch reductions of 82% by weight for Darkblotched Rockfish and 56% by weight for other juvenile rockfishes. In the LE groundfish bottom trawl fishery, where species such as Darkblotched Rockfish and Pacific Halibut are affecting some fishermen's ability to maximize their IFQs of healthier groundfish stocks, enhancing the visibility of the selective flatfish trawls low-rise headrope using artificial illumination could prove effective at reducing bycatch and improving trawl selectivity.

The objective of this study was to evaluate how illuminating the headrope of a selective flatfish trawl could affect catches of groundfishes, including Pacific Halibut, in the West Coast LE groundfish bottom trawl fishery.

METHODS

Sea trials and sampling.— Sea trials occurred aboard the FV *Miss Sue*, a 24.7-m-long, 640-hp (1 hp = 746 W) trawler out of Newport, Oregon. Tows were conducted off central Oregon between 44°10′N and 44°59′N and between 124°17′W and 124°58′W in May 2016. Towing occurred over the continental shelf and shelf break during daylight hours at bottom fishing depths from 95 to 402 m (Table 1). The average bottom fishing depth was 203 m. Towing speed over ground ranged from 2.2 to 2.6 knots. Tow durations were set to 1 h. The trawl was fished using the vessel's forward net reel. The trawl was fished with (treatment) and without (control) LEDs in an alternate-tow randomized block design with the tows in each block occurring next to each other and in the same direction (but without overlapping their trawl paths). After each tow, all fish were identified to species and weighed using a motion-compensated platform scale. Total length (cm) was used to measure flatfish and Lingcod, while fork length (cm) was used for Sablefish and rockfishes.

The trawl used for this study was a two-seam Eastern 400 low-rise selective flatfish trawl with a cutback headrope (King et al. 2004; Hannah et al. 2005). The headrope was 40.3 m in length, and the chain footrope was 31.2 m in length. The chain footrope was covered with rubber discs 20.3 cm in diameter and outfitted with rubber rockhopper discs 35.6 cm in diameter placed approximately every 58.4 cm over the footrope length. This trawl also lacks floats along the central portion of the headrope to reduce any diving behavior by fish in reaction to floats. The trawl cod end was a four-seam tube of 116-mm diamond netting (6.0-mm double twine) that was 88 meshes in circumference, excluding the meshes in each selvedge.

Green LED fishing lights (Lindgren-Pitman Electralume, centered on 540 nm; ≥0.5–2.0 lx) were used to illuminate the trawl's headrope. The lights were grouped into clusters of three (Figure 1), with each cluster of lights

TABLE 1. Mean ambient and artificial light levels per tow at the center of the trawl belly and headrope. Asterisks denote treatment trawls (with LEDs); time = Pacific standard time.

Tow	Block	Date	Time (hours)	Depth (m)	Light level (μmol photons m^{-2} s^{-1})		Tow	Block	Date	Time (hours)	Depth (m)	Light level (μmol photons m^{-2} s^{-1})	
					Belly	Headrope						Belly	Headrope
1	1	May 10	0618	256	7.85×10^{-9}		25	13	May 18	1515	146	2.58×10^{-5}	3.32×10^{-3}
2	1*	May 10	1020	256	2.44×10^{-6}		26	13*	May 18	1652	148	7.94×10^{-6}	1.37×10^{-3}
3	2*	May 10	1327	220	2.72×10^{-4}		27	14	May 19	0646	150	3.28×10^{-6}	4.89×10^{-4}
4	2	May 10	1525	220	7.14×10^{-8}		28	14*	May 19	0937	150	2.58×10^{-5}	1.45×10^{-2}
5	3*	May 10	0611	155	4.40×10^{-6}		29	15*	May 19	1227	176	1.43×10^{-5}	2.13×10^{-3}
6	3	May 11	0851	155	1.43×10^{-5}		30	15	May 19	1504	176	4.40×10^{-6}	3.65×10^{-4}
7	4*	May 11	1144	154	4.01×10^{-5}		31	16*	May 20	0625	238	9.59×10^{-8}	7.61×10^{-4}
8	4	May 11	1338	155	4.64×10^{-5}		32	16	May 20	0825	238	1.29×10^{-7}	1.07×10^{-5}
9	5	May 12	0600	117	3.15×10^{-4}		33	17	May 20	1037	192	4.40×10^{-6}	3.65×10^{-4}
10	5*	May 12	0743	117	1.37×10^{-3}		34	17*	May 20	1149	192	4.41×10^{-6}	4.22×10^{-4}
11	6*	May 12	0933	146	3.65×10^{-4}		35	18*	May 24	0901	256	5.32×10^{-8}	1.30×10^{-4}
12	6	May 12	1319	154	3.15×10^{-4}		36	18	May 24	1106	256	3.42×10^{-8}	1.01×10^{-6}
13	7	May 13	0606	402	1.41×10^{-8}		37	19	May 24	1328	329	1.41×10^{-8}	2.95×10^{-8}
14	7*	May 13	0810	402	1.49×10^{-7}		38	19*	May 24	1532	329	1.42×10^{-8}	1.51×10^{-4}
15	8*	May 13	1113	187	3.11×10^{-7}		39	20	May 25	0706	238	1.41×10^{-8}	8.28×10^{-8}
16	8	May 13	1330	187	2.95×10^{-8}		40	20*	May 25	1025	238	1.36×10^{-6}	2.34×10^{-4}
17	9*	May 17	0745	95	5.44×10^{-2}		41	21	May 25	1305	311	7.14×10^{-8}	7.53×10^{-7}
18	9	May 17	1001	95	6.64×10^{-1}		42	21*	May 25	1555	311	7.94×10^{-6}	1.75×10^{-4}
19	10	May 17	1310	135	1.30×10^{-4}	1.20	43	22*	May 26	0658	338	1.82×10^{-6}	3.15×10^{-4}
20	10*	May 17	1615	135	8.37×10^{-5}	6.64×10^{-1}	44	22	May 26	0917	338	9.10×10^{-9}	3.42×10^{-8}
21	11*	May 18	0645	130	1.43×10^{-5}	1.18×10^{-3}	45	23*	May 26	1311	274	2.44×10^{-6}	1.37×10^{-3}
22	11	May 18	0900	130	2.99×10^{-5}	5.16×10^{-3}	46	23	May 26	1516	274	3.96×10^{-8}	4.84×10^{-7}
23	12*	May 18	1120	143	1.43×10^{-5}	3.32×10^{-3}	47	24*	May 27	0600	229	2.32×10^{-7}	2.34×10^{-4}
24	12	May 18	1330	143	4.40×10^{-6}	1.84×10^{-3}	48	24	May 27	0749	229	1.90×10^{-8}	1.01×10^{-6}

attached ~1.3 m apart on center along the length of the headrope. A total of 29 light clusters were used, with the LEDs facing port or starboard depending on the side of the trawl they were placed (Figure 1). Given the catenary shape of the trawl headrope, the LEDs faced increasingly forward moving along the headrope from its apex toward the leading edge of the wings. The lights were attached to the trawl on deployment and then removed on retrieval to avoid damaging them when winding the trawl onto the net reel. Attachment points were marked with twine along the headrope to assure that the tow-to-tow attachment point of each cluster was at the same location. A Wildlife Computers TDR-MK9 archival tag was attached, facing upward, to the middle of the trawl belly to measure the ambient and artificial light levels and temperature in the net on all tows. After tow 18, an additional MK9 tag was attached, facing upward, to the center of the headrope to collect further light data. Prior to field sampling, the MK9 tags were calibrated using an International Light IL1700 light meter and PAR sensor. The calibration function used to convert the MK9 relative light units to irradiance units was

$$y = 1\times10^{-9}e^{0.1472x} \tag{1}$$

where x is the relative light unit from the MK9 and y is the corresponding irradiance unit in μmol photons m^{-2} s^{-1}.

Statistical analysis.— We used the statistical analysis software SELNET (SELection in trawl NETting) to analyze the data (Sistiaga et al. 2010; Herrmann et al. 2012, 2016) and conducted a length-dependent catch comparison and catch ratio analyses. Table 2 summaries the data that was used in each analysis. The analysis was conducted separately by species following the procedure described below.

Using the catch information (numbers and sizes of fish for each of the tows), we wanted to determine whether there was a significant difference in catch efficiency between the control trawl (without LEDs) and the treatment trawl (with LEDs). We also wanted to determine whether a difference between the trawls could be related to the size of the fish. Specifically, to assess the relative length-dependent catch efficiency effect of changing from the control trawl to treatment trawl, we used the method described in Herrmann et al. (2017) based on comparing

FIGURE 1. Images of an LED cluster attached **(A)** near the center of the trawl headrope on the starboard side and **(B)** along the wing tip on the port side, and their orientations.

TABLE 2. Length data used for the catch comparison and catch ratio analyses. The values in parentheses are the percentages of the total catch that were sampled for length measurements. Rockfishes* includes Rougheye *Sebastes aleutianus*, Redbanded *S. babcocki*, Widow *S. entomelas*, Yellowtail *S. flavidus*, and Yelloweye rockfishes, Pacific Ocean Perch *S. alutus*, Chilipepper *S. goodei*, and Bocaccio *S. paucispinis*.

	Control		Treatment	
Species	No. measured	Length range (cm)	No. measured	Length range (cm)
Pacific Halibut	185 (1.0)	69–112	79 (1)	53–119
English Sole	1,096 (0.39)	20–42	1,276 (0.27)	20–44
Rex Sole *Glyptocephalus zachirus*	1,614 (0.27)	20–51	1,484 (0.48)	16–47
Arrowtooth Flounder *Atheresthes stomias*	1,145 (0.55)	25–70	1,050 (0.66)	25–70
Dover Sole	2,468 (0.30)	27–61	1,961 (0.54)	24–59
Petrale Sole	2,298 (0.36)	23–57	2,335 (0.26)	23–57
Darkblotched Rockfish	242 (1.0)	21–46	404 (1.0)	22–45
Greenstriped Rockfish	281 (0.77)	20–38	317 (1.0)	20–42
Canary Rockfish	82 (1.0)	34–57	130 (0.90)	33–56
Rockfishes*	148 (1.0)	24–53	144 (1.0)	25–53
Sablefish	593 (.038)	38–86	276 (1.0)	34–90
Lingcod	285 (0.69)	43–100	208 (0.61)	45–100

the catch data for tows with the control and treatment trawls. This method models the length-dependent catch comparison rate (CC_l) summed over tows, namely,

$$CC_l = \frac{\sum_{j=1}^{mt}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\sum_{i=1}^{mc}\left\{\frac{nc_{li}}{qc_i}\right\}+\sum_{j=1}^{mt}\left\{\frac{nt_{lj}}{qt_j}\right\}} \tag{2}$$

where nc_{li} and nt_{lj} are the numbers of fish measured in each length class l for the control and treatment trawls, respectively, in tows i and j, qc_i and qt_j are the related subsampling factors (fractions of the caught fish measured for length), while mc and mt are the numbers of tows carried out with the control and treatment trawls. The functional form catch comparison rate $CC(l,\mathbf{v})$ (the experimental being expressed by equation 2) was obtained using maximum likelihood estimation by minimizing the following equation:

$$-\sum_l \left\{ \begin{array}{c} \sum_{i=1}^{mc}\left\{\frac{nc_{li}}{qc_i}\times \ln(1.0 - CC(l,\mathbf{v}))\right\} \\ +\sum_{j=1}^{mt}\left\{\frac{nt_{lj}}{qt_j}\times \ln(\mathrm{CC}(l,\mathbf{v}))\right\} \end{array} \right\} \tag{3}$$

where $\mathbf{v}$ represents the parameters describing the catch comparison curve defined by $CC(l,\mathbf{v})$. The outer summation in the equation is the summation over the length classes l. When both the catch efficiency of the control and treatment trawls and the number of tows are equal ($mc = mt$), the expected value for the summed catch comparison rate would be 0.5. Therefore, this baseline can be applied to judge whether or not there is a difference in catch efficiency between the two trawls. The experimental CC_l was modelled by the function $CC(l,\mathbf{v})$, on the following form:

$$CC(l,\mathbf{v}) = \frac{\exp(f(l, v_0, \ldots, v_k))}{1+\exp(f(l, v_0, \ldots, v_k))} \tag{4}$$

where f is a polynomial of order k with coefficients v_0 to v_k. The values of the parameters $\mathbf{v}$ describing $CC(l,\mathbf{v})$ are estimated by minimizing equation (3), which is equivalent to maximizing the likelihood of the observed data. We considered f s of up to an order of 4 with parameters v_0, v_1, v_2, v_3, and v_4. Leaving out one or more of the parameters $v_0 \ldots v_4$ led to 31 additional models that were also considered as potential models for the catch comparison $CC(l,\mathbf{v})$. Among these models, estimations of the catch comparison rate were made using multimodel inference to obtain a combined model (Burnham and Anderson 2002; Herrmann et al. 2017).

The ability of the combined model to describe the experimental data was evaluated based on the *P*-value, which quantifies the probability of obtaining by coincidence at least as big a discrepancy between the experimental data and the model as observed, assuming that the model is correct. Therefore, this *P*-value, which was calculated based on the model deviance and the degrees of freedom, should not be <0.05 for the combined model to describe the experimental data sufficiently well except in cases in which the data are overdispersed (Wileman et al. 1996; Herrmann et al. 2017). Based the estimated catch comparison function $CC(l,\mathbf{v})$, we obtained the relative catch efficiency (also called the catch ratio) $CR(l,\mathbf{v})$ between fishing with the two trawls by the general relationship

$$CR(l,\boldsymbol{v}) = \frac{mc \times CC(l,\boldsymbol{v})}{mt \times (1 - CC(l,\boldsymbol{v}))} \qquad (5)$$

The catch ratio provides a direct relative value of the catch efficiency between fishing with the control and treatment trawls. If the catch efficiency of both trawls is equal, $CR(l,\boldsymbol{v})$ would be 1.0. Thus, $CR(l,\boldsymbol{v}) = 1.5$ would mean that the treatment trawl is catching (on average) 50% more fish with length l than the control trawl. In contrast, $CR(l,\boldsymbol{v}) = 0.8$ would mean that the treatment trawl is only catching 80% of the fish with length l that the control trawl is catching.

The confidence limits for the catch comparison curve and catch ratio curve were estimated using a double bootstrapping method (Herrmann et al. 2017). This bootstrapping method accounts for the uncertainty in the estimation resulting from tows' variation in catch efficiency and the availability of fish as well as uncertainty about the size structure of the catch for the individual tows. By employing multimodel inference in each bootstrap iteration, the method also accounts for the uncertainty due to uncertainty in model selection. We performed 1,000 bootstrap repetitions and calculated the Efron 95% (Efron 1982) confidence limits. To identify sizes of fish with significant differences in catch efficiency, we checked for length classes in which the confidence limits for the catch ratio curve did not contain 1.0.

A length-integrated average value for the catch ratio was also estimated directly from the experimental catch data by means of the equation

$$CR_{average} = \frac{\frac{1}{mt}\sum_{l}\sum_{j=1}^{mt}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\frac{1}{mc}\sum_{l}\sum_{i=1}^{mc}\left\{\frac{nc_{li}}{qc_i}\right\}} \qquad (6)$$

where the outer summation covers the length classes in the catch during the experimental fishing period.

Based on equation (6), the percentage change in average catch efficiency by shifting from the control trawl to the treatment trawl was estimated by

$$\Delta CR_{average} = 100 \times \left(CR_{average} - 1.0\right) \qquad (7)$$

By incorporating $\Delta CR_{average}$ into each of the bootstrap iterations described above, we were able to assess the 95% confidence limits for $\Delta CR_{average}$. We used $\Delta CR_{average}$ to provide a length-averaged value for the effect of changing from the control to the treatment trawl on the catch efficiency. In contrast to the length-dependent evaluation of the catch ratio, $\Delta CR_{average}$ is specific for the population structure encountered during the experimental sea trials. Therefore, its value is specific for the size structure in the fishery at the time the trials were carried out, and it cannot be extrapolated to other scenarios in which the size structure of the fish population may be different.

RESULTS

We completed 48 tows (24 blocks; Table 1). The combined catch of English Sole, Rex Sole, Arrowtooth Flounder, Dover Sole, and Petrale Sole ranged from 52 to 2,063 kg per tow in the treatment and from 48 to 2,062 kg per tow in the control trawl. Catches of Pacific Halibut per tow ranged from 0 to 137 kg in the treatment and from 0 to 604 kg in the control trawl (Table 3). Catch of rockfishes (11 species; Table 4) overall ranged from 0 to 144 kg per tow in the treatment and from 0 to 86 kg per tow in the control trawl. Darkblotched, Greenstriped, and Canary *S. pinniger* rockfishes were the most frequently encountered rockfishes. Other rockfishes caught, but in small numbers, included Rougheye, Redbanded, Widow, Yellowtail, and Yelloweye rockfishes, and Pacific Ocean Perch, Chilipepper, and Bocaccio. Sablefish catches per tow ranged from 0 to 128 kg in the treatment and from 0 to 441 kg in the control trawl. Catches of Lingcod per tow ranged from 0 to 484 kg in the treatment and from 0 to 477 kg in the control trawl (Table 4).

Flatfishes

The catch comparisons and ratios of flatfishes between the treatment and control trawls varied across length classes. In general, the treatment trawl on average caught more English Sole and Petrale Sole but fewer Rex Sole and Arrowtooth Flounder than the control trawl (Figure 2). These catch differences, however, were not significant, as the 95% CIs for the mean $CC(l,\boldsymbol{v})$ and $CR(l,\boldsymbol{v})$ for these species extend above and below the $CC(l,\boldsymbol{v})$ rate of 0.5 and the $CR(l,\boldsymbol{v})$ ratio of 1.0 (Figures 3 and 4). For Dover Sole, the treatment trawl caught significantly fewer fish 31–44 cm in length than the control trawl. Over this size-class range, the treatment trawl on average caught only 40–44% of the Dover Sole caught by the control trawl. Catches of Pacific Halibut were substantially lower in the treatment trawl, with the control trawl catching an average of 57% more Pacific Halibut. However, this outcome was not significant due to a small sample size (264 individuals). With the exception of Pacific Halibut, P-values <0.05 were observed in the $CC(l,\boldsymbol{v})$ models for flatfishes, which required further assessment to determine whether the models were adequately describing the experimental data for these species

TABLE 3. Catch data (kg) for flatfishes by experimental block; CTRL = control (without LEDs), TRMT = treatment (with LEDs).

	Pacific Halibut		English Sole		Rex Sole		Arrowtooth Flounder		Dover Sole		Petrale Sole	
Block	CTRL	TRMT	CTRL	TRMT	CTRL	TRMT	CTRL	TRMT	CTRL	TRMT	CTRL	TRMT
1	0	0	3.1	1.5	200.1	69.0	184.0	132.8	756.8	243.6	1.9	0
2	5.1	0	1.6	4.4	19.3	13.8	93.9	69.9	108.4	49.4	2.1	4.5
3	47.9	0	136.7	234.2	19.9	14.6	12.1	8.8	9.5	7.9	204.8	284.0
4	12.8	4.9	80.9	97.5	7.6	11.3	12.3	3.1	5.6	16.9	262.7	158.1
5	119.3	31.7	2.4	5	6.5	5.2	0	0	1.0	0.5	38.5	41.1
6	34.0	0	288.5	716.3	26.6	25.3	2.8	0.3	10.1	3.8	1,045.6	1,317.6
7	0	0	0	0	10.5	15.0	8.5	23.4	359.2	154.1	0	0
8	16.8	0	27.5	15.6	513.7	149.2	49.7	29.1	1,376.9	291.8	93.9	54.3
9	17.3	5.5	2.5	5.7	2.1	5.1	0	0	1.2	0.4	64.4	74.4
10	100.3	30.8	17.3	11.1	2.8	0.5	25.5	20.0	38.3	31.1	523.1	421.2
11	27.3	75.6	17.0	30.1	1.2	1.4	11.4	12.9	45.5	44.1	201.7	326.6
12	20.2	26.0	18.1	24.4	2.3	4.2	22.3	25.3	112.0	192.3	158.1	209.3
13	51.4	35.6	17.4	16.3	8.7	6.3	59.4	34.2	30.5	29.2	742.8	1,048.3
14	51.4	38.6	15.3	8.4	7.6	8.6	55.2	53.2	70.3	68.7	486.5	578.9
15	13.8	23.9	5.4	10.8	26.8	21.6	148.3	157.1	155.2	224.9	375.4	687.6
16	0	0	0	0	19.1	6.6	48.0	68.9	84.6	19.4	0	0
17	603.7	137.1	1.6	1.0	19.6	24.3	85.8	68.9	135.1	310.2	176.4	249.5
18	0	5.4	0.5	0	42.9	13.2	87.2	77.4	311.9	96.6	2.0	0
19	0	0	0	0	5.6	4.6	74.5	85.3	39.3	39.7	0	0
20	20.5	0	325.2	107.0	109.4	19.3	289.5	117.1	235.9	59.0	6.5	5.5
21	5.5	0	232.6	133.3	132.9	91.6	161.0	94.7	54.7	33.2	0	0
22	7.9	0	7.0	9.1	146.3	117.4	58.2	51.3	523.4	154.4	0	0
23	0	0	55.8	25	27.4	10.2	153.4	122.7	300.3	65.2	1.6	0
24	0	0	1.5	1.89	76.8	29.2	272.2	222.7	377.4	137.8	23.1	3.1
Total	1,155.2	415.1	1,257.9	1,458.6	1,435.7	667.5	1,915.2	1,479.1	5,143.1	2,274.2	4,411.1	5,464.0

(Table 5). Inspecting the fit between the experimental catch comparison data and the modeled mean curve for these species indicated *P*-values <0.05 were due to overdispersion of the data rather than the model's inability to adequately describe the data.

Roundfishes

The catch comparisons and ratios of roundfishes between the treatment and control trawls also varied across length classes. In general, the treatment trawl on average led to larger catches of rockfishes than the control trawl. Between the two trawls, mean catches of Lingcod were lower in the treatment trawl (Figure 2). These catch differences were not significant, as the 95% CIs of the mean $CC(l,\boldsymbol{v})$ and $CR(l,\boldsymbol{v})$ for these species extend above and below the $CC(l,\boldsymbol{v})$ rate of 0.5 and $CR(l,\boldsymbol{v})$ ratio of 1.0 (Figures 5 and 6). The large 95% CIs for these selectivity curves were partly a result of small sample sizes within length classes. For Sablefish, the treatment trawl caught significantly fewer fish 43–61 cm in length than the control trawl. Over these size-classes, the treatment trawl on average caught only 15–19% of the Sablefish caught by the control trawl. $CC(l,\boldsymbol{v})$ model *P*-values <0.05 were noted for Darkblotched Rockfish and Sablefish (Table 5). As was observed in the flatfish $CC(l,\boldsymbol{v})$ models, this result was due to overdispersion of the data rather than the model's inability to adequately describe the experimental data.

Light Levels and Temperature

The mud cloud created by the footrope contacting the seafloor was often detected in the MK9 tag data. Within each block, the mean light levels at the headrope were substantially higher than those at the trawl belly in both the treatment and control trawls. Within most (but not all) blocks, the treatment trawl exhibited higher mean light levels than the control trawl at both the belly and headrope (Table 1). The most reasonable explanation for this is the mud cloud obstructing the MK9 tags' ability to detect the LEDs. Bottom temperatures ranged from 5.4°C to 8.0°C, though the majority of temperature readings were between 5.5°C and 7°C.

TABLE 4. Catch data (kg) for rockfishes, Sablefish, and Lingcod by each experimental block; CTRL = control (without LEDs), TRMT = treatment (with LEDs). See Table 2 for the species included in Rockfishes*.

	Darkblotched Rockfish		Greenstriped Rockfish		Canary Rockfish		Rockfishes*		Sablefish		Lingcod	
Block	CTRL	TRMT	CTRL	TRMT	CTRL	TRMT	CTRL	TRMT	CTRL	TRMT	CTRL	TRMT
1	71.3	69.6	0	0	0	0	10.9	6.8	72.1	20.1	15.4	6.6
2	3.6	0.5	10.2	9.5	3.0	0	0.4	0.7	72.4	2.9	10.6	0
3	0	0	48.2	3.5	11.4	57.0	10.4	21.5	3.8	0	44.2	12.3
4	0	0	36.3	41.4	29.8	3.1	7.6	6.5	8.2	0	44.2	14.0
5	0	0	0	0	0	0	0	0	0	0	4.2	0
6	0	0	0	0	9.1	29.2	1.9	50.5	0	0	257.4	49.0
7	0	0	0	0	0	0	0	0	24.8	127.6	0	0
8	0	0	1.4	0.9	14.4	23.8	5.5	62.0	10	3.9	21.0	22.0
9	0	0	0	0	0	0	0	0	0	0	17.9	2.4
10	0	0	0.2	0	1.1	0	0	0	0	0	6.7	23.5
11	0	0	0	0.3	0.8	2.4	0	0	0.5	0	7.4	14.6
12	0.3	0	0	0	0	0	0	0.8	0.2	0	22.4	11.4
13	0	0	0	0.8	3.8	1.4	3.2	0	0.8	3.3	120.8	81.4
14	0	0	0.5	0	9.3	4.9	1.4	6.6	0.8	0	158.2	392.5
15	0	0	14.2	10.9	44.9	105.9	0	0	0	6.0	476.8	484.3
16	6.5	137.4	0.4	0	0	1.7	0	5.6	164.1	30.0	0	4.9
17	0	0.4	2.2	12.4	2.1	0	0	0	4.0	4.4	43.5	141.2
18	19.4	12.9	1.3	0	0	0	0.7	1.0	132.7	56.3	12.7	8.6
19	0	1.6	0	0	0	0	0	0	59.4	82.7	0	0
20	1.0	36.9	0.6	0	7.7	0	3.9	5.4	376.5	50.5	70.9	15.7
21	79.4	24.3	0	0	0	0	7.5	0.6	392.2	12.7	5.3	0
22	4.3	13.0	0	0	0	0	0	0.9	22.0	38.5	0	3.7
23	3.0	22.7	0	0	0	0	1.8	1.8	153.5	27.3	34.9	40.3
24	0.7	0	3.3	3.6	2.3	5.4	1.4	2.6	441.0	22.6	10.3	5.3
Total	189.5	319.3	118.8	83.3	139.7	234.8	56.6	173.3	1,939.0	488.8	1,384.8	1,333.7

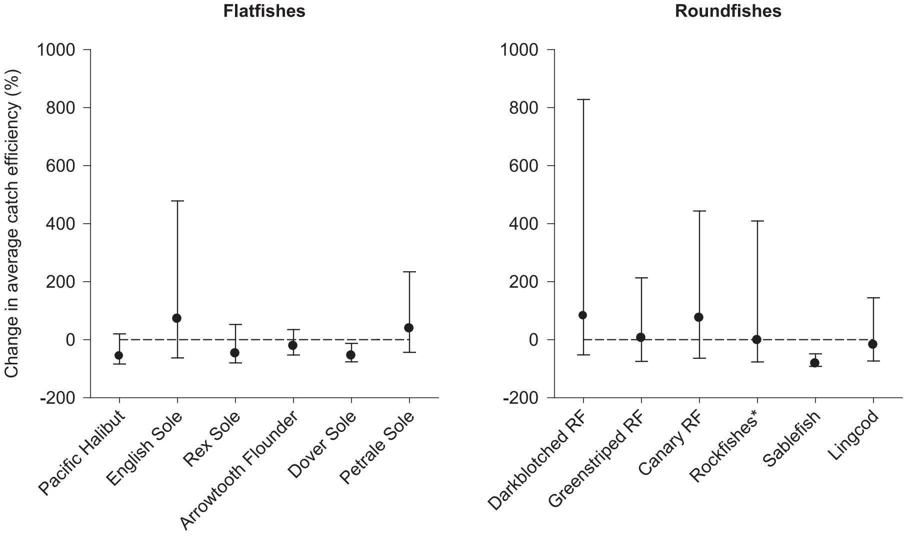

FIGURE 2. Change in average catch efficiency between the treatment and control trawls. Values below zero indicate that more fish were caught in the control trawl than in the treatment trawl, and conversely for values above zero. The abbreviation RF stands for rockfish; rockfishes* includes Rougheye, Redbanded, Widow, Yellowtail, and Yelloweye rockfishes, Pacific Ocean Perch, Chilipepper, and Bocaccio.

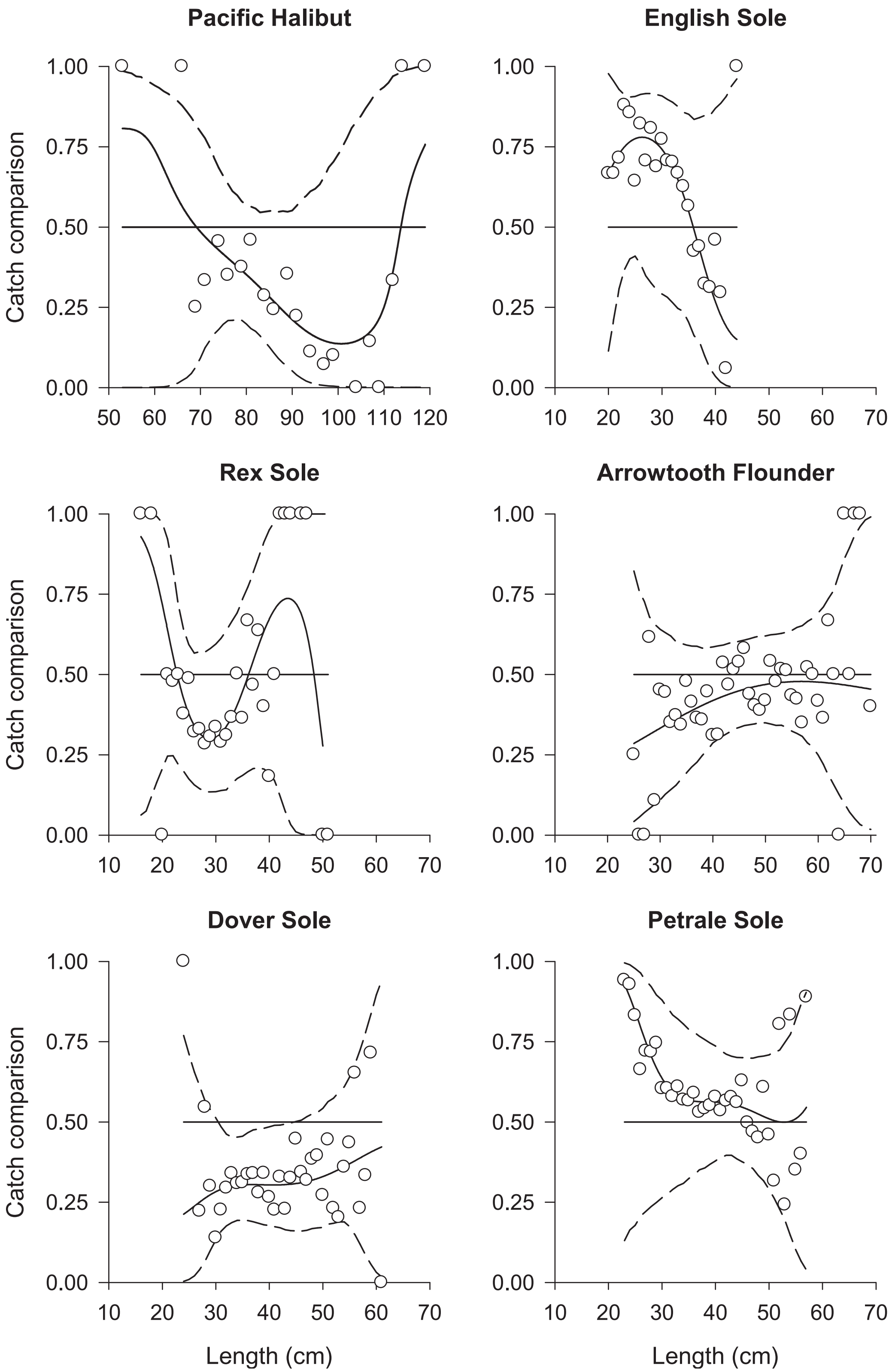

FIGURE 3. Mean catch comparison curves for flatfishes per size-class. Circles denote the experimental data; solid curves are the modeled values; dashed lines represent the 95% confidence interval limits; horizontal lines depict the baseline catch comparison rate of 0.5, indicating equal catch rates between the treatment and control trawls.

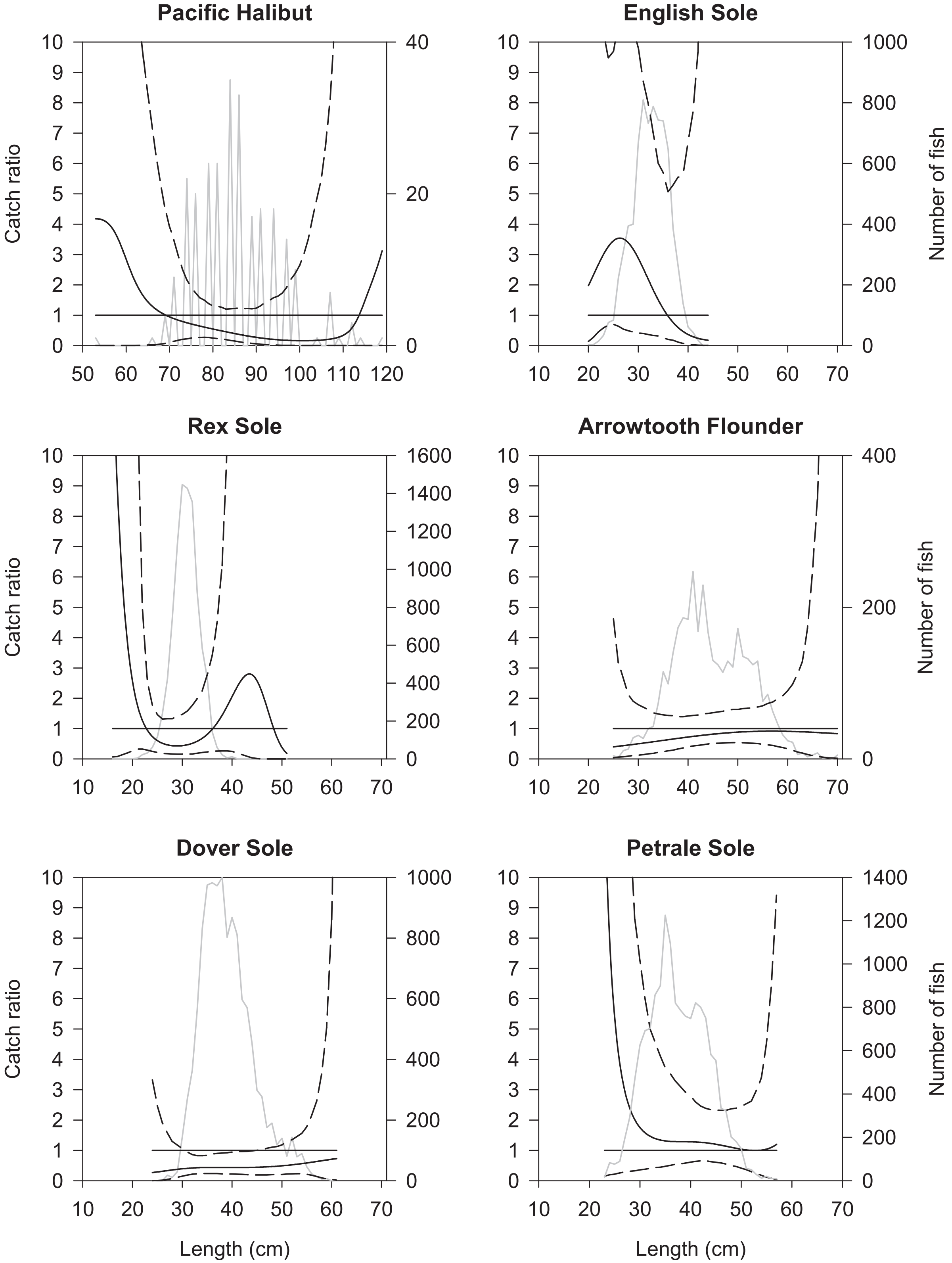

FIGURE 4. Mean catch ratio curves for flatfishes per size-class. The light gray lines denote the number of fish caught; solid curves are the modeled values; dashed lines represent the 95% confidence interval limits; horizontal lines depict the baseline catch ratio rate of 1.0, indicating equal catch efficiencies between the treatment and control trawls.

TABLE 5. Catch comparison curve fit statistics. See Table 2 for the species included in Rockfishes*.

Species	*P*-value	Deviance	df
Pacific Halibut	0.971	7.1	16
English Sole	0.011	36.0	19
Rex Sole	0.001	55.4	26
Arrowtooth Flounder	<0.001	77.4	40
Dover Sole	<0.001	75.3	30
Petrale Sole	0.037	45.2	30
Darkblotched Rockfish	<0.001	50.9	18
Greenstriped Rockfish	0.194	19.5	15
Canary Rockfish	0.528	17.9	19
Rockfishes*	0.278	26.5	23
Sablefish	0.043	56.6	40
Lingcod	0.056	59.8	44

DISCUSSION

Depending on the species and length of the fish, illuminating the headrope of the selective flatfish trawl could have positive or negative effects on catch. While the differences in the catch rates and catch efficiencies were not significant, there was a general tendency to catch fewer Rex Sole, Arrowtooth Flounder, and Lingcod when the headrope was illuminated. The catches of Pacific Halibut was also reduced, with an average of 57% fewer Pacific Halibut being caught when the headrope was illuminated. However, the small sample size of Pacific Halibut prevented the catch analysis models from detecting a significant difference between the treatment and control trawls. The opposite trend was observed for rockfishes, English Sole, and Petrale Sole, for which mean catches increased when the headrope was illuminated. Further data collection would improve the model's ability to detect significant differences, as comparisons of alternative tow designs often require large numbers of tows and length samples to detect significant effects.

The catches of Dover Sole and Sablefish differed significantly between the two trawls, with fewer fish being caught when the headrope was illuminated. While it is unclear whether these species avoid trawl entrainment by passing under the footrope or over the low-rise headrope, artificial illumination appears to enhance their optomotor response to the approaching trawl gear and thus their ability to escape capture. In a laboratory study in which juvenile Pacific Halibut, English Sole, and Northern Rock Sole *Lepidopsetta polyxystra* were exposed to a simulated trawl footrope under dark and light conditions, Ryer and Barnett (2006) found that these species exhibited a dominant "run" response (of four behavioral responses evaluated [hop, rise, run, and under]) when encountering the footrope under ambient light conditions. Under dark settings, the behavioral responses were more evenly distributed across the four categories, indicating a diminished optomotor response. In a midwater trawl, Olla et al. (2000) examined the swimming and orientation behaviors of Walleye Pollock *Gadus chalcogrammus* under light and dark conditions. Under lights conditions, Walleye Pollock swam actively and oriented themselves parallel to the principal axis of the trawl, whereas under dark conditions they showed little to no swimming activity and were unable to orient themselves parallel to the principal axis of the trawl. Further research using video or imaging sonar systems would identify the behavioral patterns exhibited by Dover Sole and Sablefish encountering the selective flatfish trawl.

When testing the effect of artificial illumination along the fishing line of an ocean shrimp trawl, Hannah et al. (2015) noted significant reductions in the catch of Darkblotched Rockfish when illumination was present. The authors speculated that these fish were most likely diving under the fishing line in response to the illumination and passing under the trawl through restricted openings (spaces of ~35–70 cm in height) made visible between the drop chains connecting the groundline to the fishing line. In the present study, in which we evaluated how illuminating the headrope of a selective flatfish trawl would affect fish catches, there was a general trend of catching more rockfishes, including Darkblotched Rockfish, when the headrope was illuminated. Coupled with Hannah et al. (2015), these results suggest that Darkblotched Rockfish exhibit a diving behavior in response to artificial illumination. While illuminating the headrope of the selective flatfish trawl did not reduce Darkblotched Rockfish catches, the findings from this study provide useful information on behavioral responses to illumination that could prove beneficial in developing selective fishing gear to reduce the catches of this species.

In summary, this study shows that illuminating the headrope of the selective flatfish trawl can affect the catch rates of several groundfish species, including Pacific Halibut, and that the effect varies by species and size. For example, fishermen concerned about Pacific Halibut bycatch when targeting English Sole and Petrale Sole could benefit from an illuminated headrope, whereas fishermen seeking to target Dover Sole and/or Sablefish but avoid Darkblotched Rockfish, would not. As fishermen in West Coast and Alaska fisheries experiment with artificial illumination in their efforts to improve gear selectivity, better understanding of the mechanisms affecting fish behavior in response to artificial illumination on mobile fishing gear becomes increasingly important to gear researchers, fishermen, management, and the resource.

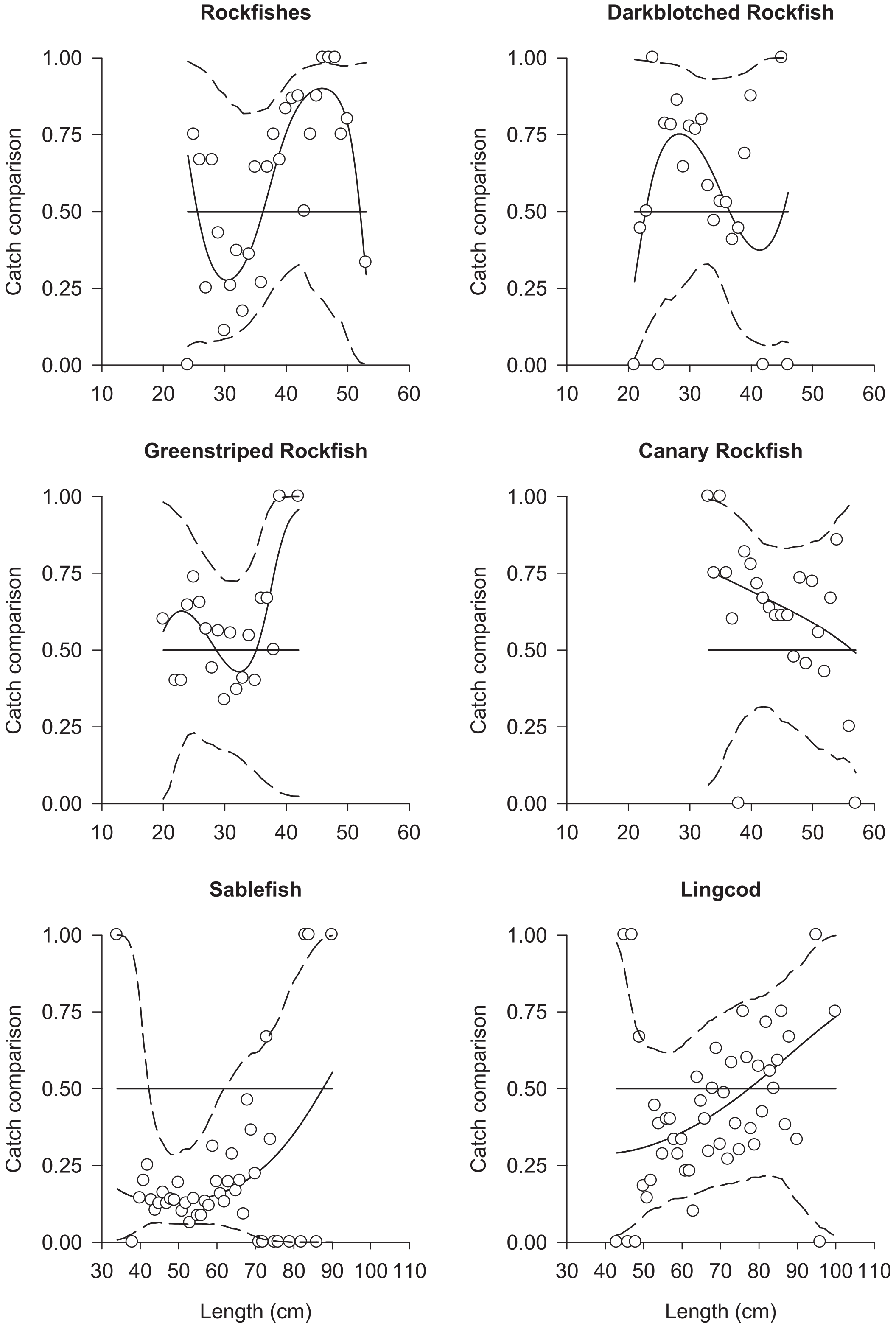

FIGURE 5. Mean catch comparison curves for rockfishes (Rougheye, Redbanded, Widow, Yellowtail, and Yelloweye rockfishes, Pacific Ocean Perch, Chilipepper, and Bocaccio), Darkblotched, Greenstriped, and Canary rockfishes, Sablefish, and Lingcod per size-class. Circles denote the experimental data; solid curves are the modeled value; dashed lines represent the 95% confidence interval limits; horizontal lines depict the baseline catch comparison rate of 0.5, indicating equal catch rates between the treatment and control trawls.

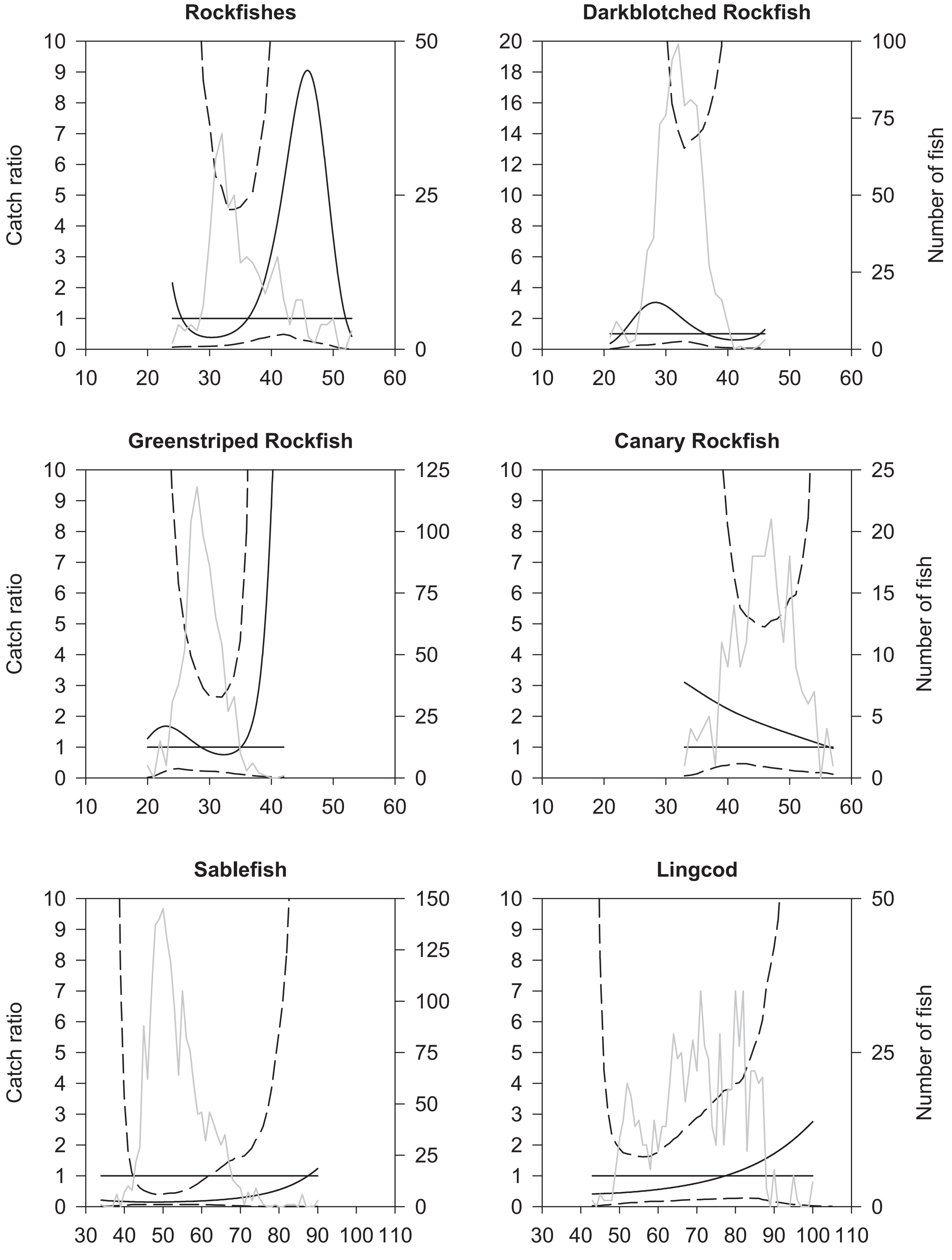

FIGURE 6. Mean catch ratio curves for rockfishes (Rougheye, Redbanded, Widow, Yellowtail, and Yelloweye rockfishes, Pacific Ocean Perch, Chilipepper, and Bocaccio), Darkblotched, Greenstriped, and Canary rockfishes, Sablefish, and Lingcod per size-class. The light gray lines denote the number of fish caught; solid curves are the modeled value; dashed lines represent the 95% confidence interval limits; horizontal lines depict the baseline catch ratio rate of 1.0, indicating equal catch efficiencies between the treatment and control trawls.

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Paper VI

“Effects on the bycatch of eulachon and juvenile groundfish by altering the level of artificial illumination along an ocean shrimp trawl fishing line”

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Original Article

Effects on the bycatch of eulachon and juvenile groundfish by altering the level of artificial illumination along an ocean shrimp trawl fishing line

Mark J. M. Lomeli[1],*, Scott D. Groth[2], Matthew T. O. Blume[3], Bent Herrmann[4], and W. Waldo Wakefield[5]

[1]Pacific States Marine Fisheries Commission, 2032 SE OSU Drive, Newport, OR 97365, USA
[2]Oregon Department of Fish and Wildlife, 63538 Boat Basin Drive, Charleston, OR 97420, USA
[3]Oregon Department of Fish and Wildlife, 2040 SE Marine Science Drive, Newport, OR 97365, USA
[4]SINTEF Fisheries and Aquaculture, Willemoesvej 2, Hirtshals DK-9850, Denmark
[5]Fishery Resource Analysis and Monitoring Division, Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 2032 SE OSU Drive, Newport, OR 97365, USA

**Corresponding author: tel: +1 541 867 0544; e-mail: mlomeli@psmfc.org.*

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We examined how catches of ocean shrimp (*Pandalus jordani*), eulachon (*Thaleichthys pacificus*), and juvenile groundfish could be affected by altering the level of artificial illumination along the fishing line of an ocean shrimp trawl. In the ocean shrimp trawl fishery, catches of eulachon are of special concern, as the species' southern Distinct Population Segment is listed as "threatened" under the US Endangered Species Act. Using a double-rigged trawl vessel, with one trawl illuminated and the other unilluminated, we compared the catch efficiencies for ocean shrimp, eulachon, and juvenile groundfish between an unilluminated trawl and trawls illuminated with 5, 10, and 20 LED fishing lights along their fishing line. The addition of artificial illumination along the trawl fishing line significantly affected the average catch efficiency for eulachon, rockfish (*Sebastes* spp.), and flatfish, with the three LED configurations each catching significantly fewer individuals than the unilluminated trawl without impacting ocean shrimp catches. For Pacific hake (*Merluccius productus*), the ten LED-configured trawl caught significantly more fish than the unilluminated trawl. For the five and 20 LED configurations, mean Pacific hake catches did not differ from the unilluminated trawl. This study contributes new data on how artificial illumination can affect eulachon catches (and other fish) and contribute to their conservation.

Keywords: artificial illumination, bycatch reduction, eulachon, fish behaviour, groundfish, LEDs, ocean shrimp.

Introduction

The ocean shrimp (*Pandalus jordani*) trawl fishery is an economically important fishery along the US west coast. From 2010 to 2017, annual landings of ocean shrimp averaged 28 635 tonnes resulting in an average annual ex-vessel value of $35.5 million (PacFIN, 2018). This fishery is managed by the states of Washington, Oregon, and California, with each state having jurisdiction of fishing operations for catches delivered to their ports. The mandatory use of rigid sorting grid bycatch reduction devices (BRDs), similar to the Nordmøre grate, with 19.1-mm maximum bar spacings are required off Washington and Oregon to minimize fish bycatch (WDFW, 2017; ODFW, 2018). Off California, fishers are required to use either a rigid sorting grid BRD with 50.8-mm maximum bar spacings, a soft-panel BRD made of netting no >15.2 cm, or a fisheye excluder (CDFW, 2017).

Fish bycatch in the ocean shrimp trawl fishery has been significantly reduced by using sorting grid BRDs (Hannah and Jones, 2007; Hannah *et al.*, 2011). However, bycatch of juvenile groundfish, such as Pacific hake (*Merluccius productus*), rockfish (*Sebastes* spp.), and flatfish, and eulachon (*Thaleichthys pacificus*) and whitebait smelt (*Allosmerus elongatus*) can still occur at considerable levels as these fish can pass through the bar spacings of the BRDs. For eulachon, an anadromous smelt species endemic to the eastern North Pacific, bycatch is of special concern, as the species' southern Distinct Population Segment (DPS) is listed as "threatened" under the US Endangered Species Act (ESA; DOC, 2011; Gustafson *et al.*, 2012). An ESA recovery plan has been implemented to protect and recover the southern DPS of eulachon; however, there are many uncertainties in forecasting their recovery (NMFS, 2017). As ocean distributions of eulachon and ocean shrimp often overlap, interactions between ocean shrimp trawl gear and eulachon are likely to continue to be an issue facing the fishery and the conservation of eulachon.

A typical ocean shrimp trawl consists of a bottom-tending groundline (steel cable covered with rubber discs) connected by drop chains to a fishing line (the leading edge of the trawl) that operates 30–70 cm off bottom (Hannah *et al.*, 2013). Hannah *et al.* (2015) tested if placing ten green LED fishing lights along an ocean shrimp trawl fishing line could enhance the ability of eulachon and other fish to perceive the space between the groundline and the fishing line (that they may not see as readily under normal seabed light levels) and allow them an opportunity to pass through the gap and avoid trawl entrainment. Findings showed that catches (by weight) of eulachon, juvenile rockfish, such as darkblotched rockfish (*Sebasres crameri*), and flatfish, such as slender sole (*Lyopsetta exillis*) were substantially reduced, while not affecting ocean shrimp catches. When testing whether adding illumination around the sorting grid could achieve the same effect, the opposite result was observed, as bycatch of eulachon and slender sole significantly increased. The authors speculated that the presence of illumination influenced fish to dive in a threatened response and pass through the spaces between the sorting grid bars and the groundline and fishing line at rates higher than would occur in the absence of artificial illumination. Following the Hannah *et al.* (2015) study, fisheries managers for the state of Oregon considered implementing the required use of LED fishing lights along ocean shrimp trawl fishing lines to minimize the fisheries impact on eulachon, groundfish, and other fish. However, further research examining the number of LEDs necessary to achieve optimal bycatch reduction was recognized as data needed before implementing the required use of footrope lighting (ODFW, Marine Resources Shellfish Program, pers. comm.).

Our study objectives were to (i) compare how catches of ocean shrimp, eulachon, and juvenile groundfish are affected by testing various configurations (quantity and spacing) of LED fishing lights along an ocean shrimp trawl fishing line compared to a simultaneous, identically configured, but unilluminated trawl, (ii) examine if the catch efficiencies between the three LED configurations differ from each other, (iii) provide fisheries managers quantitative information for making decisions when developing and implementing the required use of footrope lighting, and (iv) enhance our knowledge about the use of LED fishing lights as a technique to improve trawl selectivity in the ocean shrimp trawl fishery and contribute to the conservation of ESA-listed eulachon.

Material and methods

Sea trials and sampling

Sea trials occurred aboard the double-rigged ocean shrimp trawler FV "Miss Yvonne," an 18.6-m, 350-HP vessel. Tows were conducted off Oregon between 43°18′N and 45°29′N and between 124°13′W and 124°34′W during July and September 2017 (Figure 1). Towing occurred over the continental shelf during daylight hours at bottom fishing depths averaging 124 m. Towing speed ranged from 3.3 to 3.9 km h^{-1} (1.8–2.1 knots). Tow durations averaged 66 min and ranged from 60 to 105 min.

We used the trawl gear components of the FV "Miss Yvonne" for this study. The port and starboard gear components were identical in material and design. Wood and steel combination doors, 1.8×2.1 m (length × height), were used to spread each trawl. The trawl sweeps and bridles were 19-mm steel cable and 4.5 m in length. The headropes and fishing lines were 22 m in length. Drop chains measuring 39 cm in length attached the fishing line to the groundline at 1.2-m separations. The groundlines were 22 m in length, with the centre 7.3-m section covered with 7.6-cm diameter rubber disks. Rigid sorting-grid BRDs with 19.1-mm bar spacing were used in each trawl. Both trawls had a codend mesh size of 35 mm.

Lindgren-Pitman Electralume® green LED fishing lights, centred on 519 nm (Nguyen *et al.*, 2017), were used to illuminate the trawl groundgear components (e.g. fishing line, drop chains, groundline). While the spectral sensitivity has not been empirically determined for all the species examined in this study, the species that have been examined possess maximal sensitivity to blue-green light, the predominant spectral component of coastal waters (Bowmaker, 1990; Britt, 2009). Therefore, we selected green LEDs for two reasons: (i) to allow for a comparison of results with the Hannah *et al.* (2015) study, and (ii) this colour somewhat matches the ambient light environment encountered in our study area and transmits well through coastal and continental shelf waters. For this study, when we refer to an LED, we are referring to a single Lindgren-Pitman fishing light. For the illuminated trawl, quantities of 5, 10, and 20 LEDs were fished in an alternate tow randomized design, with each LED configuration fished for two or three tows per day. Under the 5- and 10-LED configurations, the LEDs were placed 1.2 m apart from the centre section of the fishing line and moving outward (Figure 2). In the 20-LED configuration, the LEDs were placed 0.6 m apart. The LEDs were attached to the trawl fishing line using zip ties, with the light-emitting end pointing progressively forward moving towards the wing tips. The LED configurations were switched between the port and starboard sides throughout the study, with one trawl serving as the illuminated and the other as the unilluminated.

After each tow, the catch from the illuminated and unilluminated trawls were dumped into a divided hopper where fish catches were then separately sorted to species as they came across the hopper conveyor belt, weighed, and then selected species were measured. Eulachon, whitebait smelt, and rockfish were measured to fork length (FL), whereas Pacific hake and flatfish were measured to total length (TL). For ocean shrimp, catches were collected in baskets as they came off the conveyor

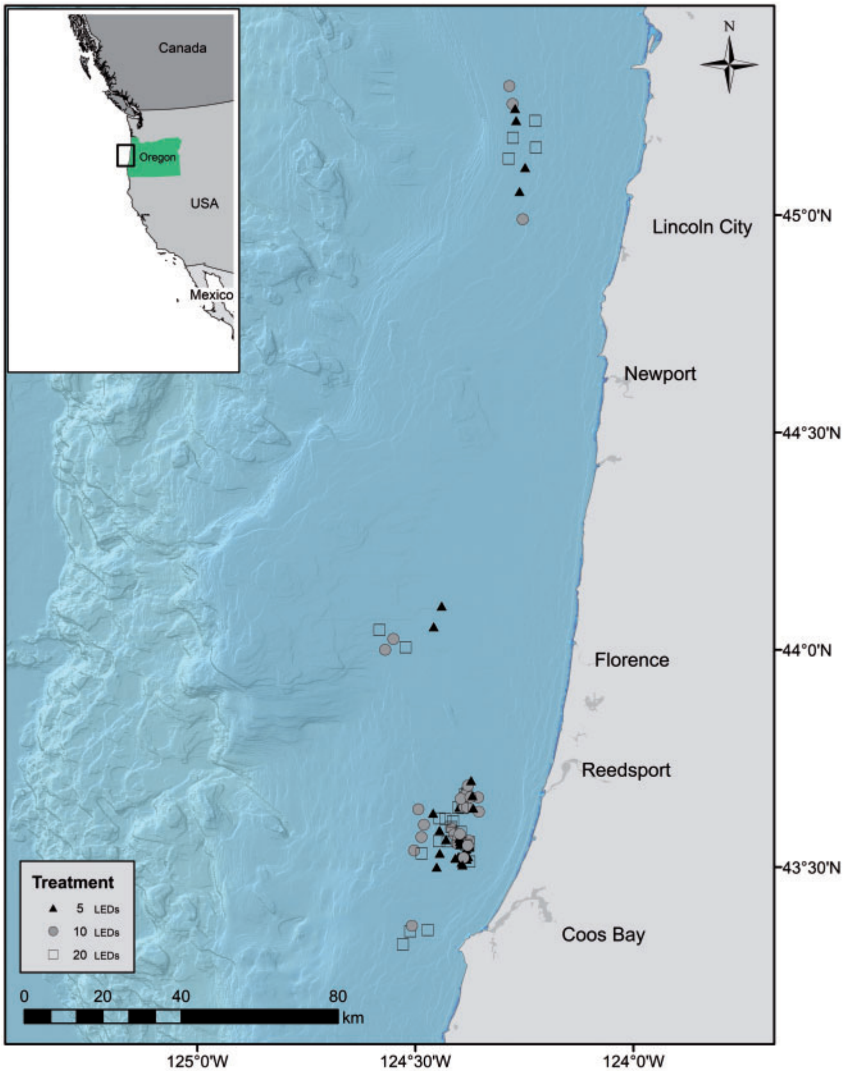

Figure 1. Map of the area off the Oregon coast where sea trials were conducted. Symbols represent trawl locations by LED configuration.

belt and set aside until sorting was completed. Following, a basket(s) of ocean shrimp was randomly selected to obtain length samples. From the selected basket(s), a 9.5-l plastic bag was filled with ocean shrimp and frozen for measurement at a laboratory. From this subsample, 100 individuals per net per tow were randomly selected for measurement (carapace length, CL). Given the small length class structure of ocean shrimp encountered (mainly 14–20 mm CL) and our random collection of ocean shrimp samples, measuring 100 individuals per net per tow was considered an adequate representation of the trawl catch. Further, this sampling rate has been found to accurately characterize mean sizes by age, used in distinguishing growth patterns by month and area, which is used in the ocean shrimp virtual population estimate (ODFW, Marine Resources Shellfish Program, pers. comm.).

Fishing line height was measured using Star-Oddi *DST tilt* sensors (0.05° tilt resolution, ±3° tilt accuracy) attached to the centre of the fishing line of each trawl to ensure uniformity between the trawls. Each tag was placed in a customized aluminium bracket outfitted with a rod that extended from the fishing line to the seabed (Supplementary Figure S1). The mean tilt angle for the *x*-axis was converted to height using the following formula:

$$\text{Fishing line height} = y \times \text{SIN}[\text{Radians}(x^\circ)] \qquad (1)$$

where y is the length of the aluminium bracket (86.4 cm, Supplementary Figure S1) and x° is the tilt *x*-axis degree angle. The vessel was not equipped to measure wing spread or door spread, but we assumed any differences that may occur in these measurements would be minimal and not affect our results as identical trawl components were used.

In each net, a Wildlife Computers TDR-MK9 archival tag was used (attached to the belly of the net directly behind the centre of the fishing line and facing upward) to measure the amount of light available. The MK9 tags were calibrated using an International Light IL1700 light meter and PAR sensor. Both MK9 tags had similar responses to the calibration. Therefore, the tag values were pooled and one calibration function was

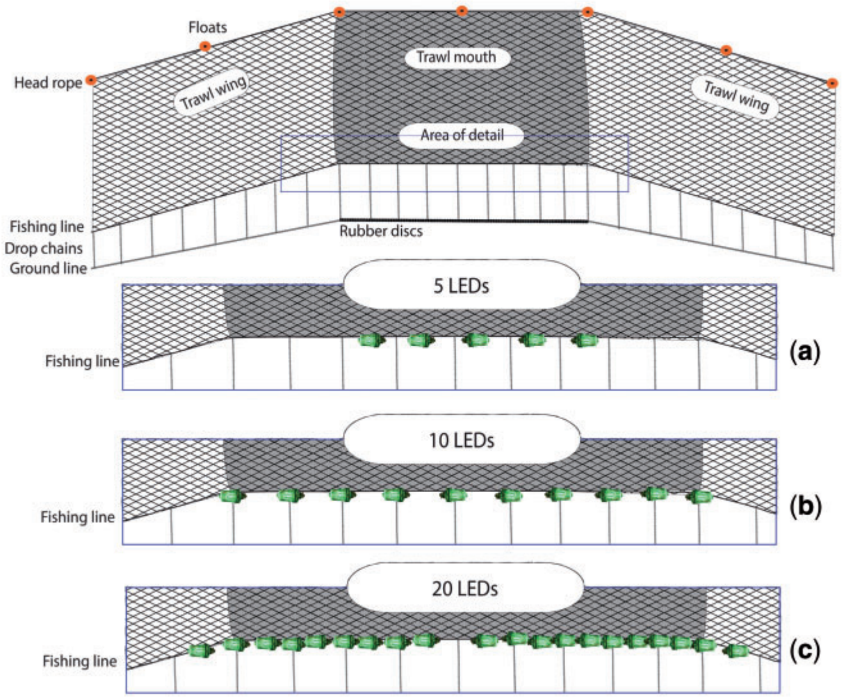

Figure 2. Schematic of an ocean shrimp trawl viewed from the front (top image) and diagrams depicting the placement and orientation of the LEDs along the trawl fishing line for the 5- (a), 10- (b), and 20-LED (c) configurations. Note: diagram not to scale.

Table 1. Length data used for the catch comparison and catch ratio analyses.

	5-LED configuration		10-LED configuration		20-LED configuration	
	No. measured		No. measured		No. measured	
Species	Illuminated trawl	Unilluminated trawl	Illuminated trawl	Unilluminated trawl	Illuminated trawl	Unilluminated trawl
Ocean shrimp	1 500 (0.01)	1 500 (0.01)	1 300 (0.004)	1 300 (0.005)	1 300 (0.005)	1 300 (0.004)
Eulachon	27 (1.0)	147 (1.0)	55 (1.0)	138 (1.0)	82 (1.0)	155 (1.0)
Whitebait smelt	134 (1.0)	460 (0.70)	27 (1.0)	253 (1.0)	33 (1.0)	47 (1.0)
Pacific hake	2 920 (0.26)	3 041 (0.24)	3 066 (0.21)	2 950 (0.16)	2 605 (0.28)	3 086 (0.26)
Rockfishes	109 (1.0)	318 (1.0)	62 (1.0)	189 (1.0)	119 (1.0)	414 (1.0)
Pacific sanddab	164 (1.0)	464 (1.0)	65 (1.0)	258 (1.0)	50 (1.0)	217 (1.0)
Rex sole	68 (1.0)	222 (1.0)	71 (1.0)	222 (1.0)	58 (1.0)	209 (1.0)
Slender sole	657 (0.83)	1 109 (0.65)	283 (1.0)	821 (0.82)	253 (1.0)	760 (0.78)

Values in parentheses are the length measurement subsample ratio from the total catch.

generated. The calibration function used to convert the MK9 relative light units to irradiance units was:

$$y = 1 \times 10^{-9} e^{0.1476x} \tag{2}$$

where x is the relative light unit from the MK9 and y is the corresponding irradiance unit in μmol photons $\mathrm{m}^{-2}\,\mathrm{s}^{-1}$. The r^2 value from our calibration curve was 0.9867.

Method for estimating relative catch efficiency between illuminated and unilluminated trawls

We used the statistical analysis software SELNET (SELection in trawl NETting) to analyse the catch data (Sistiaga *et al.*, 2010; Herrmann *et al.*, 2012, 2016) and conducted length-dependent catch comparison and catch ratio analyses. Table 1 summarizes the data used in each analysis. The analysis was conducted separately for each species following the procedure described below. For ocean shrimp, only tows with $\geq$10 kg of total catch (combined catch between the port and starboard trawls) were used in the catch analyses.

Using the catch information (numbers and length of ocean shrimp or a given species of fish for each of the tows), we wanted to determine whether there was a significant difference in catch efficiency between the unilluminated and illuminated trawls. We also wanted to determine if a potential difference between the trawls could be related to the size of the ocean shrimp or a given species of fish. Specifically, to assess the relative length-dependent catch efficiency effect of changing from unilluminated to illuminated trawl, we used the method described in Herrmann *et al.* (2017) based on comparing the catch data between the two trawls. This method models the length-dependent catch comparison rate (CC_l) summed over tows:

$$CC_l = \frac{\sum_{j=1}^{m}\{nt_{lj}/qt_j\}}{\sum_{j=1}^{m}\{(nt_{lj}/qt_j) + (nc_{lj}/qc_j)\}} \tag{3}$$

where nc_{lj} and nt_{lj} are the numbers of ocean shrimp or a given species of fish measured in each length class l for the unilluminated and illuminated trawl, respectively, in tows l and j, qc_j and qt_j are the related subsampling factors (fraction of the ocean shrimp or a given species of fish caught being length measured), and m is the number of tows carried out with the unilluminated and illuminated trawl for the specific LED configuration. The functional form of the catch comparison rate $CC(l, \boldsymbol{v})$ [the experimental being expressed by Equation (3)] was obtained using maximum likelihood estimation by minimizing the following equation:

$$-\sum_{l}\left\{\sum_{j=1}^{m}\left\{\frac{nc_{lj}}{qc_j}\times\ln[1.0-CC(l,\boldsymbol{v})]\right\}+\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j}\times\ln[CC(l,\boldsymbol{v})]\right\}\right\} \tag{4}$$

where $\boldsymbol{v}$ represents the parameters describing the catch comparison curve defined by $CC(l, \boldsymbol{v})$. The outer summation in the equation is the summation over the length classes l. When the catch efficiency of the unilluminated and illuminated trawls are equal, the expected value for the summed catch comparison rate would be 0.5. Therefore, this baseline can be applied to judge if there is a difference in catch efficiency between the two trawls. The experimental CC_l was modelled by the function $CC(l, \boldsymbol{v})$, on the following form:

$$CC(l, \boldsymbol{v}) = \frac{\exp\left[f(l, v_0, \ldots, v_k)\right]}{1 + \exp\left[f(l, v_0, \ldots, v_k)\right]} \tag{5}$$

where f is a polynomial of order k with coefficients v_0 to v_k. The values of the parameters $\boldsymbol{v}$ describing $CC(l, \boldsymbol{v})$ are estimated by minimizing Equation (4), which is equivalent to maximizing the likelihood of the experimental data. We considered f of up to an order of four with parameters v_0, v_1, v_2, v_3, and v_4. Leaving out one or more of the parameters $v_0 \ldots v_4$ led to 31 additional models that were also considered as potential models for the catch comparison $CC(l, \boldsymbol{v})$. Among these models, estimations of the catch comparison rate were made using multimodel inference to obtain a combined model (Burnham and Anderson, 2002; Herrmann *et al.*, 2017).

On the basis of the estimated catch comparison function $CC(l, \boldsymbol{v})$, we obtained the relative catch ratio $CR(l, \boldsymbol{v})$ between fishing with the two trawls by the general relationship:

$$CR(l, \boldsymbol{v}) = \frac{CC(l, \boldsymbol{v})}{[1 - CC(l, \boldsymbol{v})]} \tag{6}$$

The catch ratio provides a direct relative value of the catch efficiency between fishing with and without LEDs. Thus, if the catch efficiency of both trawls is equal, $CR(l, \boldsymbol{v})$ should always be 1.0. Thus, $CR(l, \boldsymbol{v}) = 1.5$ would mean that the illuminated trawl is catching on average 50% more ocean shrimp or a given species of fish with length l than the unilluminated trawl. In contrast, $CR(l, \boldsymbol{v}) = 0.8$ would mean that the illuminated trawl is only catching 80% of the ocean shrimp or a given species of fish with length l that the unilluminated trawl is catching.

The confidence interval (*CI*) limits for the catch comparison and catch ratio curves were estimated using a double bootstrapping method (Herrmann *et al.*, 2017). This bootstrapping method accounts for the uncertainty in the estimation resulting from variation in catch efficiency among tows and availability of ocean shrimp or a given species of fish as well as uncertainty about the size structure of the catch for the individual tows. However, contrary to the method by Herrmann *et al.* (2017), the outer bootstrapping loop accounting for between-haul variation was performed paired for the illuminated and unilluminated trawl in the current study. By multimodel inference in each bootstrap iteration, the method also accounts for the uncertainty due to uncertainty in model selection. We performed 1000 bootstrap repetitions and calculated the Efron 95% (Efron, 1982) *CI* limits. To identify sizes of ocean shrimp or a given species of fish with significant differences in catch efficiency, we checked for length classes in which the *CI* limits for the catch ratio curve did not contain 1.0.

A length-integrated average value for the catch ratio was also estimated directly from the experimental catch data by:

$$CR_{average} = \frac{\sum_{l}\sum_{j=1}^{m}\{nt_{lj}/qt_j\}}{\sum_{l}\sum_{j=1}^{m}\{nc_{lj}/qc_{ij}\}} \tag{7}$$

where the outer summation covers the length classes in the catch during the experimental fishing period.

On the basis of Equation (6), the percentage change in average catch efficiency between fishing with the unilluminated trawl to the illuminated trawl was estimated by:

$$\Delta CR_{average} = 100 \times \left(CR_{average} - 1.0\right) \tag{8}$$

By incorporating $\Delta CR_{average}$ into each of the bootstrap iterations described above, we could assess the 95% *CI* limits for $\Delta CR_{average}$. We used $\Delta CR_{average}$ to provide a length-averaged value for the effect of changing from unilluminated to illuminated trawl on the catch efficiency. In contrast to the length-dependent evaluation of the catch ratio, $\Delta CR_{average}$ is specific to the size classes encountered during the experimental sea trials.

Small sample sizes of rockfish necessitated pooling data from 10 rockfish species. For whitebait smelt, too few length classes were caught to perform catch comparison and catch ratio analyses. Therefore, only the $\Delta CR_{average}$ analysis was conducted on whitebait smelt.

Method for estimating relative catch efficiency between the three LED configurations

With the approach described above, we can quantify by Equation (6) the length-dependent ratio in catch efficiency between the illuminated and unilluminated trawls. Considering that each of the illuminated trawl configurations (5, 10, or 20 LEDs) are compared to the same unilluminated trawl configuration, we can obtain an estimate for relative catch efficiency between the three LED trawl configurations by:

$$CR(l)_{10_5} = \frac{CR(l)_{10}}{CR(l)_5}$$
$$CR(l)_{20_5} = \frac{CR(l)_{20}}{CR(l)_5} \qquad (9)$$
$$CR(l)_{20_{10}} = \frac{CR(l)_{20}}{CR(l)_{10}}$$

where $CR(l)_5$, $CR(l)_{10}$, and $CR(l)_{20}$ are the length-dependent catch ratios [obtained by Equation (6)] for the illuminated and unilluminated trawls for the illuminated configuration with 5, 10, and 20 LEDs, respectively. For simplicity, we have omitted the parameter $\boldsymbol{v}$ in the notation. We obtained 95% *CI* limits for $CR(l)_{10_5}$, $CR(l)_{20_5}$, and $CR(l)_{20_{10}}$ based on the three bootstrap population of results (1000 bootstrap repetitions in each) for, respectively, $CR(l)_5$, $CR(l)_{10}$, and $CR(l)_{20}$ as they are obtained independently. Using these bootstrap results, we created new bootstrap populations of results by:

$$CR(l)_{10_5 i} = \frac{CR(l)_{10_i}}{CR(l)_{5_i}}$$
$$CR(l)_{20_5 i} = \frac{CR(l)_{20_i}}{CR(l)_{5_i}} \quad i \in [1 \ldots 1000] \qquad (10)$$
$$CR(l)_{20_{10} i} = \frac{CR(l)_{20_i}}{CR(l)_{10_i}}$$

where *i* denotes the bootstrap repetition index. Because sampling was random and independent for the three groups of results, it is valid to generate the bootstrap populations of results for the ratios based on Equation (10) using the three independent generated bootstrap files (Moore *et al.*, 2003). On the basis of the bootstrap populations, we can obtain Efron percentile 95% *CI* limits for $CR(l)_{10_5}$, $CR(l)_{20_5}$, and $CR(l)_{20_{10}}$.

Results

We completed 29, 25, and 24 paired tows with the 5-, 10-, and 20-LED configuration, respectively. The most abundant species caught were ocean shrimp, Pacific hake, slender sole, Pacific sanddab (*Citharichthys sordidus*), rockfish, whitebait smelt, rex sole (*Glyptocephalus zachirus*), and eulachon (Table 1).

The average fishing line height (FLH) for the port trawl during the 5-, 10-, and 20-LED treatment was 30.1 (s.e. ±0.03), 30.2 (±0.04), and 30.0 (±0.04) cm, respectively. The average FLH for the starboard trawl during the 5-, 10-, and 20-LED treatment was 31.5 (±0.03), 31.2 (±0.04), and 31.1 (±0.05) cm, respectively. Figure 3 depicts the mean FLH per tow and LED configuration for the port and starboard trawl.

The mean ambient light level measured in the unilluminated trawl during the 5-, 10-, and 20-LED treatment was $3.4e^{-04}$ (s.e. $\pm 2.5e^{-05}$), $5.5e^{-04}$ ($\pm 4.0e^{-05}$), and $8.0e^{-04}$ ($\pm 4.9e^{-05}$) μmol photons $m^{-2}\,s^{-1}$, respectively. In the 5-, 10-, and 20-LED configured trawl, the mean light level measured increased to $4.0e^{-04}$ ($\pm 2.4e^{-05}$), $6.4e^{-04}$ ($\pm 4.1e^{-05}$), and $1.1e^{-03}$ ($\pm 5.1e^{-05}$) μmol photons $m^{-2}\,s^{-1}$, respectively. Mean light levels per tow for the unilluminated and illuminated trawls are shown in Figure 4.

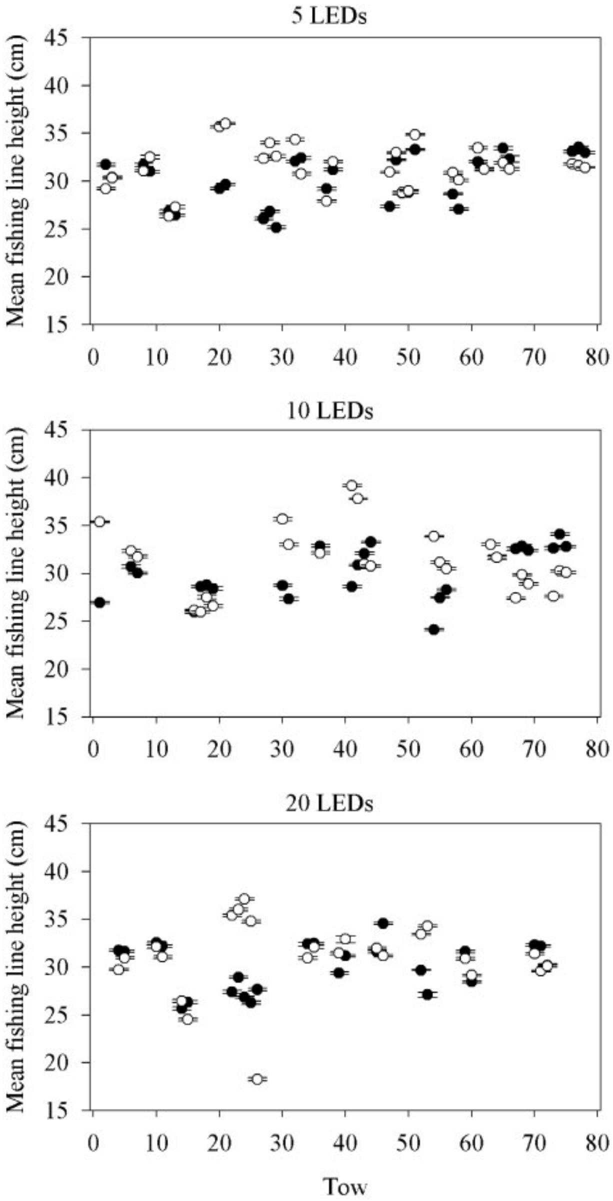

Figure 3. Mean fishing line height measured at the centre of the fishing line using Star-Oddi DST tilt sensors for the port (closed circles) and starboard (open circles) trawl per tow and LED configuration. ± bars are standard errors ($n = 300$ measurements per net per tow).

Relative catch efficiency

Ocean shrimp – The change in average catch efficiency of ocean shrimp for the three LED configurations did not differ significantly from the unilluminated trawl (Figure 5).

For each LED configuration, the catch comparison and ratio of ocean shrimp was not significantly different from the unilluminated trawl as depicted by the mean $CC(l, \boldsymbol{v})$ and $CR(l, \boldsymbol{v})$ 95% *CIs* extended above and below the $CC(l, \boldsymbol{v})$ rate of 0.5 and $CR(l, \boldsymbol{v})$ ratio of 1.0 (Supplementary Figure S2). Between the three LED configurations, the catch ratios did not differ significantly from each other for ocean shrimp of marketable-size, that is ocean shrimp >14.5 mm (Supplementary Figure S3).

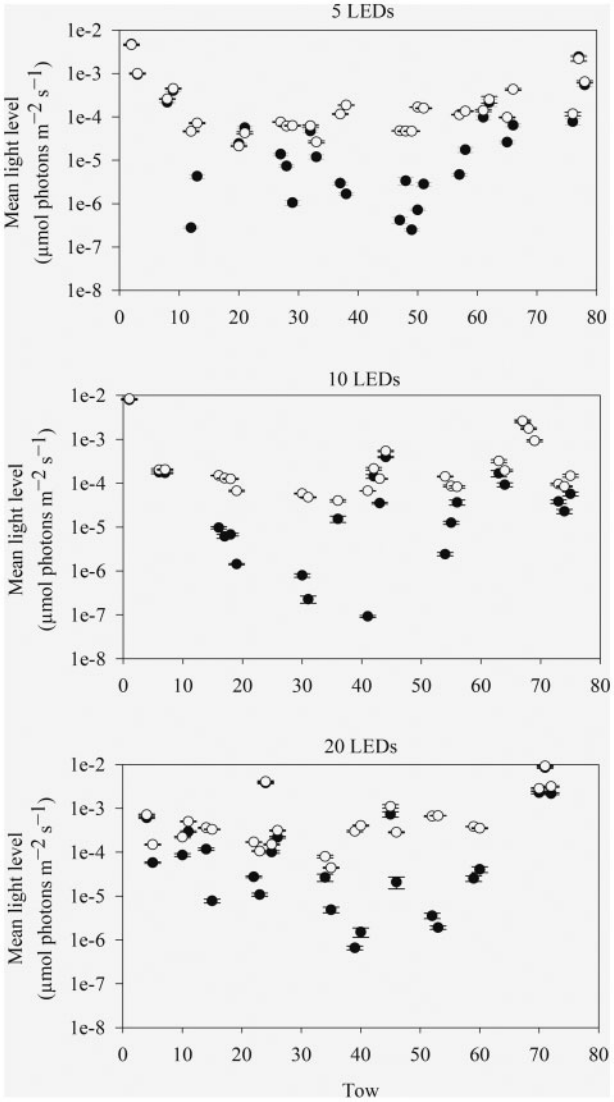

Figure 4. Mean light level measured at the centre of the fishing line for the unilluminated trawl (closed circles) and illuminated trawl (open circles) per tow and LED configuration. ± bars are standard errors ($n = 50$ measurements per net per tow).

Eulachon – The change in average catch efficiency results for eulachon showed the unilluminated trawl caught 81, 60, and 47% more eulachon than the 5-, 10-, and 20-LED configuration, respectively (Figure 5). These differences in average catch efficiency were significant.

Catch comparisons and ratios of eulachon between the three LED configurations and the unilluminated trawl varied across length classes (Supplementary Figure S4). For the 5-LED configuration, the illuminated trawl caught significantly fewer eulachon across all length classes. On average, the 5-LED configuration caught only 17% of the number of eulachon compared to the unilluminated trawl. For the 10- and 20-LED configurations, the illuminated trawls caught significantly fewer fish of 13.5–17.5 cm in length and 15.5–20.5 cm in length, respectively, than the unilluminated trawl. Over these size classes, the 10-LED configuration caught only 39% of the number of eulachon compared to the unilluminated trawl, while the 20-LED configuration caught only 51% of the number of eulachon compared to the unilluminated trawl (Supplementary Figure S4). Between the three LED configurations, the catch ratios of eulachon did not differ significantly from each other for fish >14.5 cm (Supplementary Figure S5).

Whitebait smelt – For the 5- and 10-LED configurations, there was a significant difference in average catch efficiency with the unilluminated trawls catching 79 and 89%, respectively, more whitebait smelt than the illuminated trawls (Figure 5). Under the 20-LED configuration, while the general trend shows higher average catches of whitebait smelt in the unilluminated trawl, the large 95% *CI*s generated from the limited sample size (Table 1) show that there is no significant difference in the average catch efficiency between the illuminated and unilluminated trawl.

Pacific hake – The change in average catch efficiency of Pacific hake between the 10-LED configured trawl and unilluminated trawl differed significantly, with the illuminated trawl catching 66% more Pacific hake than the unilluminated trawl (Figure 5). Under the 5- and 20-LED configurations, the change in average catch efficiency did not differ significantly from the unilluminated trawl.

The Pacific hake catch comparison and ratio results for the three LED configurations were similar to each other in that each configuration caught significantly fewer larger-sized fish (>20.5 cm in length) than the unilluminated trawl (Supplementary Figure S6). For smaller-sized fish (9.5–16.5 cm in length), the 10-LED configured trawl caught on average twofold more Pacific hake than the unilluminated trawl. The 20-LED configuration showed a similar trend; however, a significant difference was not detected. For the 5-LED configuration, the illuminated trawl caught fewer smaller-size Pacific hake. However, this result was not significant. The catch ratio of Pacific hake between the 5-, 10-, and 20-LED configurations differed significantly from each other for some length classes. The most pronounced difference was noted between the 5- and 10-LED configurations, with the 5-LED configuration catching significantly fewer Pacific hake of 10.5–19.5 cm in length than the 10-LED configuration (Supplementary Figure S5).

Rockfish – Stripetail (*S. saxicola*) and darkblotched rockfish were the most frequently caught rockfish. Stripetail and darkblotched rockfish comprised 66 and 22% of the total catch of rockfish by numbers, respectively. Greenstriped (*Sebastes elongatus*), shortbelly (*Sebastes jordani*), quillback (*Sebastes maliger*), redstripe (*Sebastes proriger*), halfbanded (*Sebastes semicinctus*), and sharpchin (*Sebastes zacentrus*) rockfish, and Pacific ocean perch (*Sebastes alutus*), and chilipepper (*Sebastes goodei*) comprised the remaining 12% of the total catch of rockfish by numbers.

For the three LED configurations, the change in average catch efficiency for rockfish differed significantly from the unilluminated trawl. Compared to the 5-, 10-, and 20-LED illuminated trawls, the unilluminated trawl caught 65, 67, and 71% more rockfish, respectively (Figure 5).

Results from the catch comparison and ratio analyses showed the 5-, 10-, and 20-LED configured trawls caught significantly fewer rockfish of 8.5–13.5, 9.5–14.5, and 7.5–14.5 cm, respectively, than the unilluminated trawl (Supplementary Figure S7). Over these size classes, the 5-, 10-, and 20-LED configured trawls caught on average only 30, 26, and 30%, respectively, of the number of rockfish compared to the unilluminated trawl. Between the three LED configurations, the catch ratios of rockfish did not differ significantly from each other (Supplementary Figure S5).

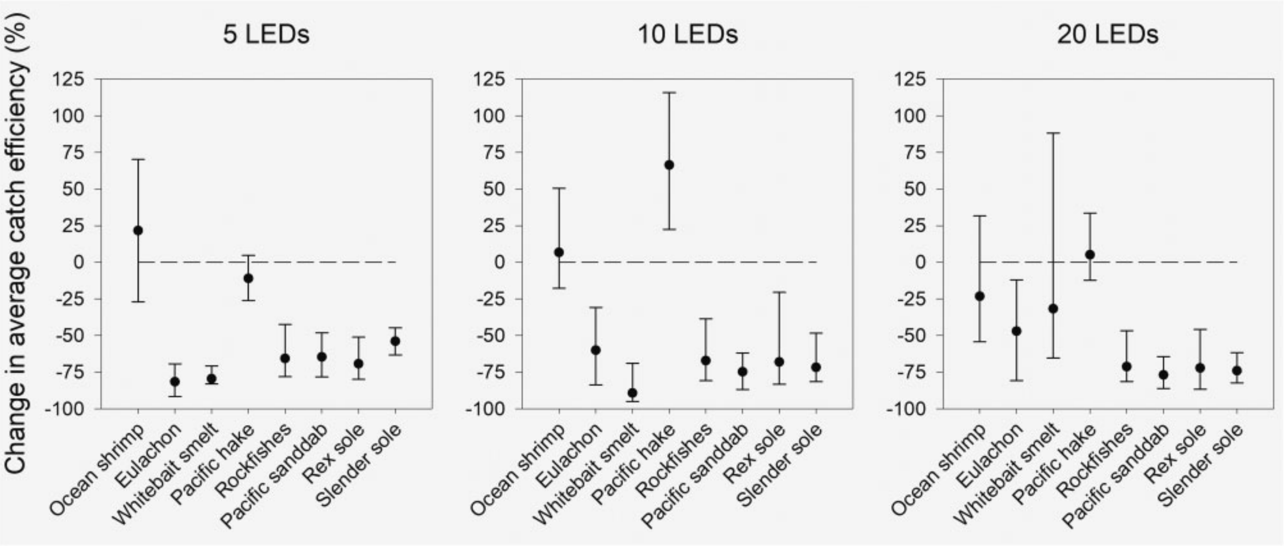

Figure 5. Change in average catch efficiency (%) between the three LED illuminated trawls and the unilluminated trawl. Values below zero indicate more ocean shrimp or a given species of fish were caught in the unilluminated trawl, and vice versa for values above zero.

Pacific sanddab – The change in average catch efficiency results show the unilluminated trawl caught 64, 74, and 76% more Pacific sanddab than the 5-, 10-, and 20-LED configurations, respectively (Figure 5). These differences in average catch efficiency were significant.

The Pacific sanddab catch comparison and ratio results showed the 5-LED configuration caught significantly fewer fish across all length classes compared to the unilluminated trawl (Supplementary Figure S8). On average, the 5-LED illuminated trawl caught only 33% of the number of Pacific sanddab compared to the unilluminated trawl. For the 10- and 20-LED configurations, the illuminated trawls caught significantly fewer fish <24.5 cm than the unilluminated trawl (Supplementary Figure S8). Of Pacific sanddab <24.5 cm, the 10- and 20-LED configurations caught on average only 24 and 23%, respectively, of the number of fish compared to the unilluminated trawl. The catch ratios of Pacific sanddab between the three LED configurations did not differ significantly from each other (Supplementary Figure S9).

Rex sole – The average catch efficiency of the unilluminated trawl was significantly higher for rex sole than the three LED configured trawls. Overall, the unilluminated trawl caught 69, 68, and 72% more rex sole than the 5-, 10-, and 20-LED configurations, respectively (Figure 5).

The catch comparisons and ratios of rex sole between the three LED configured trawls and the unilluminated trawl varied across length classes (Supplementary Figure S10). For the 5-LED configuration, the illuminated trawl caught significantly fewer 8.5–29.5 cm rex sole. Over these length classes, the 5-LED configuration caught only 29% of the number of rex sole compared to the unilluminated trawl. For the 10-LED configuration, the illuminated trawl caught significantly fewer 21.5–25.5 cm fish than the unilluminated trawl. Under the 20-LED configuration, the illuminated trawl caught significantly fewer fish of 10.5–21.5 cm and 25.5–31.5 cm than the unilluminated trawl. Between the three LED configurations, the catch ratios of rex sole did not differ significantly from each other (Supplementary Figure S9).

Slender sole – A significant difference in the change in average catch efficiency between the illuminated trawls and the unilluminated trawl was noted for slender sole, with the unilluminated trawl catching 54, 71, and 74% more fish than the 5-, 10-, and 20-LED configured trawls, respectively (Figure 5).

The slender sole catch comparison and ratio analyses showed that the 5-, 10-, and 20-LED configured trawls caught significantly fewer 11.5–23.5, 9.5–26.5, and 9.5–27.5 cm fish, respectively, than the unilluminated trawl (Supplementary Figure S11). Over these length classes, the 5-, 10-, and 20-LED illuminated trawls caught only 39, 28, and 22%, respectively, of the number of slender sole compared to the unilluminated trawl. Between the three LED configurations, the catch ratios of slender sole did not differ significantly from each other for fish >12.5 cm (Supplementary Figure S9).

Discussion

We demonstrated that the addition of illumination along the fishing line of an ocean shrimp trawl can significantly affect the catch efficiency for eulachon, whitebait smelt, and juvenile groundfish without affecting ocean shrimp catches. Overall, the average catch efficiency for eulachon, rockfish, and flatfish were significantly lower in the illuminated trawls than in the unilluminated trawl. The opposite was noted for Pacific hake under the 10-LED illuminated trawl. For the 5- and 20-LED illuminated trawls, the average catch efficiency for Pacific hake did not differ significantly from the unilluminated trawl.

Studies have shown that vision is the primary sense affecting fish behaviour when encountering trawl gear (Glass and Wardle, 1989; Olla *et al.*, 1997; Kim and Wardle, 1998; Olla *et al.*, 2000; Kim and Wardle, 2003; Ryer *et al.*, 2010) and that light can influence their behaviour (Ryer and Olla, 2000; Ryer and Barnett, 2006; Lomeli and Wakefield, 2012; Hannah *et al.*, 2015; Lomeli *et al.*, 2018). Prior to our study, we speculated that the 10- and 20-LED configurations would perform better at reducing bycatch than the 5-LED configuration because more illumination along the fishing line length would enhance fishes' visual perception of the approaching trawl gear and provide them increased opportunities to avoid trawl entrainment. However, our findings suggest that the light emitted by the 5-LED configuration provided sufficient illumination for most fishes to perceive the contrast between the trawl fishing line and the seabed and thus avoid capture, and that use of more illumination provides no clear added bycatch reduction benefit. The groundgear components herding and concentrating fish towards the centre of the trawl, where fish encounter the five LEDs and behaviourally respond by diving under the fishing line, is likely a contributing factor to the noted results as well.

While the catch efficiency analyses showed catch variability occurring across some length classes between the three LED configurations, the 95% *CI*s for the mean delta catch ratio curves extending above and below the ratio of 1.0 show that the three LED configurations do not differ significantly from each other at reducing catches of rockfish, Pacific sanddab, and rex sole across all length classes. The 95% *CI*s extended outside the ratio of 1.0 for ocean shrimp (5- vs. 20-LED), slender sole (5- vs. 10-, 20-LED), and eulachon (5- vs. 20-LED); however, the ratio difference was very minimal and only occurred over one or two length classes and was not considered to hold any meaningful significant difference. In contrast to the species above, the presence of illumination did not have a bycatch reduction effect on Pacific hake. Under the 10-LED configuration, catches of Pacific hake were found to significantly increase in the illuminated trawl. Compared to the 5- and 20-LED configurations, the mean delta catch ratio for the 10-LED illuminated trawl differed significantly from the 5-LED configuration across several length classes, but not from the 20-LED configuration to a degree that was considered significantly meaningful. While it is unclear why this catch variability occurred between the three LED configurations for Pacific hake, factors other than the presence of artificial illumination likely had an effect. As Pacific hake can often form large schools near the seabed, and juveniles and subadults have been described as weak swimmers when encountering a BRD in the extension section of a midwater trawl (Lomeli and Wakefield, 2012), it is possible that a schooling behavioural response to the approaching trawl, variability in school density and/or the rate that the school encountered the trawl throughout the tow, their swimming ability, and/or their ability to visually perceive the trawl gear had an effect. Unfortunately, we were unable to compare our results to Hannah *et al.* (2015) as they did not encounter this species.

The light levels measured in the illuminated trawls likely underestimate the amount of light occurring under the trawl fishing line (and across its length) as we positioned a single MK9 tag in the net directly behind the centre of the fishing line and facing upward to measure the amount light available inside the net. A more suitable method to capture the amount of light occurring near the seabed would have been to place multiple MK9 tags across the fishing line length and have them positioned on the underside of the net. While it is possible that light from an illuminated trawl could spread towards the unilluminated trawl, our catch results show no effect of this occurring between the three LED configurations to a degree that is detectable.

As a result of this study and the work by Hannah *et al.* (2015), the Oregon Fish and Wildlife Commission (the regulatory authority for the state of Oregon) has implemented the required use of lighting along ocean shrimp trawl fishing lines to reduce bycatch of eulachon and groundfishes (ODFW, 2018). The regulation requires fishers landing ocean shrimp off Oregon to use a minimum of five green LEDs (spaced 1.2 m apart starting from the centre section of the fishing line) within 15.2 cm of the forward leading edge of the bottom panel of the trawl netting. The state of Washington is in the process of applying similar regulatory requirements. At this current time, it is unknown if the state of California will pursue actions requiring ocean shrimp trawl fishers to use lighting devices along their trawl fishing lines.

To the best of our knowledge, the Hannah *et al.* (2015) research was the first peer-reviewed study presented where artificial illumination was successfully used to reduce bycatch in a trawl fishery. Because of their research, other studies have occurred in trawl fisheries where artificial illumination was used in efforts to affect fish behaviour and catchability. In the US west coast groundfish bottom trawl fishery, Lomeli *et al.* (2018) compared an unilluminated trawl to a trawl with an illuminated headrope and found that the illuminated trawl caught significantly fewer sablefish (*Anoplopoma fimbria*) and Dover sole (*Microstomus pacificus*). Catches of other groundfish did not differ between the two trawls. In the Barents Sea demersal trawl fishery, Grimaldo *et al.* (2018) placed LEDs in the centre of a square-mesh section (forward of the codend) in efforts to improve the release efficiency for smaller-sized cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) by startling them towards the trawl meshes. Findings suggested that haddock escapement could be improved using illumination, but not for cod. Further, Larsen *et al.* (2017, 2018) tested how placing LEDs along the escape exit above a Nordmøre grate and along the base of the grate in a northern prawn (*Pandalus borealis*) trawl could affect bycatch of fishes such as cod, haddock, and redfish (*Sebastes* spp.). They found the addition of illumination near and on the Nordmøre grate had no significant result on fish bycatch. In the Pacific hake fishery, Lomeli and Wakefield (2012) examined a Chinook salmon (*Oncorhynchus tshawytscha*) BRD (equipped with multiple escape windows) and observed that Chinook salmon tended to escape out windows that artificial illumination was directed towards. Based off these observations, a study was conducted to specifically test if illumination could be used to attract them towards and out specific escape windows. Findings showed that artificial illumination can influence where Chinook salmon exit out the BRD, but also that illumination can be used to enhance their escapement overall (PSMFC, unpubl. data). In our study, where we examined the effects on fish bycatch of altering the number of LEDs along an ocean shrimp trawl fishing line, our results contribute new data to the growing field of research exploring catch effects of artificial illumination on trawl gear (as described above) and has helped fisheries managers develop and implement the required use of LEDs in the ocean shrimp trawl fishery. While our results have regional impacts, our research findings could have potential applications in other trawl fisheries internationally; for example, the ocean shrimp trawl fishery off British Columbia, Canada where eulachon occur as bycatch (Hay and McCarter, 2000; NMFS, 2017), and northern prawn trawl fisheries in the North Atlantic (He and Balzano, 2013; Larsen *et al.*, 2017, 2018) where bycatch of marine fishes occur.

In conclusion, this study examined how catches of ocean shrimp, eulachon, and juvenile groundfish are affected by using 5, 10, and 20 LED fishing lights along an ocean shrimp trawl fishing line. In general, the three LED configurations performed similarly to each other at reducing catches of eulachon and juvenile rockfish and flatfish without impacting ocean shrimp catches. As the southern DPS of eulachon faces many uncertainties in their

ESA recovery, our study contributes new data on how artificial illumination along an ocean shrimp trawl fishing line can affect eulachon catches (and other fishes) and contribute to their conservation. Lastly, this study provided fisheries management with quantitative information used to implement the required use of an inexpensive and practical technique to improve trawl selectivity and reduce bycatch of an ESA-listed species.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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Paper VII

“The Efficacy of Illumination to Reduce Bycatch of Eulachon and Groundfishes Before Trawl Capture in the Eastern North Pacific Ocean Shrimp Fishery”

The Efficacy of Illumination to Reduce Bycatch of Eulachon and Groundfishes Before Trawl Capture in the Eastern North Pacific Ocean Shrimp Fishery

Mark J.M. Lomeli[1*], Scott D. Groth[2], Matthew T.O. Blume[3], Bent Herrmann[4,5], and W. Waldo Wakefield[6]

[1]Pacific States Marine Fisheries Commission, 2032 SE OSU Drive, Newport, OR 97365, USA
[2]Oregon Department of Fish and Wildlife, 63538 Boat Basin Drive, Charleston, OR 97420, USA
[3]Oregon Department of Fish and Wildlife, 2040 SE Marine Science Drive, Newport, OR 97365, USA
[4]SINTEF Fisheries and Aquaculture, Willemoesvej 2, DK-9850 Hirtshals, Denmark
[5]University of Tromsø, Breivika, N-9037 Tromsø, Norway
[6]Oregon State University, Cooperative Institute for Marine Resources Studies, Hatfield Marine Science Center, 2030 SE Marine Science Drive, Newport, OR 97365, USA

*Corresponding author: tel: +1 541 867 0544; e-mail: mlomeli@psmfc.org

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Abstract

This study examined the extent that eulachon (*Thaleichthys pacificus*) and groundfishes escape trawl entrainment in response to artificial illumination along an ocean shrimp (*Pandalus jordani*) trawl fishing line. Using a double-rigged trawler, we compared the catch efficiencies for ocean shrimp, eulachon, and groundfishes between an unilluminated trawl and a trawl illuminated with 5 green LEDs along its fishing line. Results showed a significant reduction in the bycatch of eulachon and yellowtail rockfish (*Sebastes flavidus*) in the presence of illumination. As eulachon are an Endangered Species Act listed species, this finding provides valuable information for fishery managers implementing recovery plans and evaluating potential fishery impacts on their recovery and conservation. For other rockfishes (*Sebastes* spp.) and flatfishes, however, we did not see the same effect as the illuminated trawl caught similarly or significantly more fishes than the unilluminated trawl. Prior to this research, the extent that eulachon and groundfishes escape trawl capture in response to illumination along an ocean shrimp trawl fishing line was unclear. Our study has provided results to fill that data gap.

1. Introduction

The ocean shrimp (*Pandalus jordani*) fishery is one of the largest trawl fisheries by ex-vessel value off the U.S. West Coast (PacFIN 2018). Semi-pelagic trawls and otter trawls equipped with small mesh codends (35 mm between knots [BK]) are used to harvest ocean shrimp over mud and mud-sand bottom habitats (Hannah et al. 2013). Since 2003, trawls outfitted with sorting grids, similar to the Nordmøre grid, have been required to minimize bycatch of groundfishes such as Pacific hake (*Merluccius productus*), darkblotched rockfish, (*Sebastes crameri*), canary rockfish, (*S. pinniger*), and Pacific halibut (*Hippoglossus stenolepis*). In 2012, sorting grids of 19.1 mm maximum bar spacing became required off Oregon and Washington to reduce eulachon (*Thaleichthys pacificus*) bycatch (Hannah et al. 2011). Prior to this regulation, fishers were using sorting grids with bar spacing ranging from 22.2 to 28.6 mm. In 2018, additional regulations were implemented requiring fishers landing ocean shrimp in Oregon and Washington to use lighting devices (e.g., LEDs) near the trawl fishing line to further reduce eulachon bycatch (ODFW 2018; Lomeli et al. 2018a; WDFW 2018).

In the ocean shrimp trawl fishery, bycatch of eulachon (an anadromous smelt species endemic to the eastern North Pacific) has been an issue facing the fishery as the species' southern Distinct Population Segment (DPS) was listed as "threatened" under the US Endangered Species Act (ESA) in 2010 (DOC 2011; Gustafson et al. 2012). Use of sorting grids with 19.1 mm bar spacing have been shown to be effective at minimizing catches of larger-sized eulachon (>13 cm in length) and adult groundfishes. However, the devices have been less effective at reducing bycatch of smaller-sized eulachon and juvenile groundfishes which can pass through the bar spacings (Hannah et al. 2011). When smaller-sized eulachon are abundant, their bycatch can occur in considerable quantities (Hannah et al. 2105) and impact fishing operations (e.g., sorting time). Consequently, techniques to reduce the bycatch of eulachon and groundfishes such as use of LEDs to illuminate escape areas around the trawls leading edge have recently been tested (Hannah et al. 2015; Lomeli et al. 2018a).

Use of artificial illumination to minimize fish bycatch in trawl fisheries has received considerable attention in recent years. Research has primarily used illumination as a method to enhance fishes' visual perception of trawl gear components and escape areas (Hannah et al. 2015; Larsen et al. 2017, 2018; Lomeli et al. 2018ab; Melli et al. 2018; Lomeli and Wakefield 2019), but also in efforts to startle fish towards selective mesh panels (Grimaldo et al. 2018a). In the ocean shrimp trawl fishery, work has demonstrated that illuminating the trawl fishing line can reduce bycatch of eulachon, and some other fishes, without impacting ocean shrimp catches. Hannah et al. (2015) placed 10 LEDs along the center section of an ocean shrimp trawl fishing line and observed a 91% reduction by weight of eulachon. Significant bycatch reductions of rockfishes (*Sebastes* spp.) and flatfishes were also noted. Following their study, Lomeli et al. (2018a) evaluated how catches of eulachon and other fishes could be affected by altering the quantity of LEDs (e.g., 5 vs 10 vs 20 LEDs) along the fishing line. Results showed each LED configuration caught significantly fewer eulachon than the unilluminated trawl and that the catch ratio of eulachon did not differ significantly from each other between the three LED configurations tested. Rockfish and flatfish catches were significantly reduced across each LED configuration as well. These results guided to fishery managers implementation of an effective footrope lighting regulation in Oregon and Washington (ODFW 2018; WFDW 2018). Although substantial catch reductions were noted in the Hannah et al. (2015) and Lomeli et al. (2018a) studies, data was collected from the residual bycatch of trawls fished with sorting grids with 19.1 mm bar spacing and hindered the authors ability to determine the degree that eulachon across all length classes (and other fishes) are escaping trawl entrainment in response to the illumination. Thus, determining the overall efficacy of LEDs placed along ocean shrimp trawl fishing lines and knowing the degree that eulachon and other fishes escape (or do not escape) trawl entrainment in response to illumination is essential for understanding potential trawl catch impacts (e.g., physical contact with the sorting grids and/or netting, post-release and unobserved mortality, etc.) on non-target species.

The objective of this study was to determine the degree to which eulachon, and other fishes, escape trawl entrainment in response to artificial illumination along an ocean shrimp trawl fishing line.

2. Materials and Methods

2.1. Sea trials and sampling

Sea trials occurred during daylight hours off Oregon (Fig. 1) in 2018 aboard the double-rigged ocean shrimp trawler *F/V Ms. Julie*, a 22.9 m, 400 HP vessel. Our study site (Fig. 1) was selected as it is an area where ocean shrimp are typically fished and eulachon often co-occur. Tow durations were set to 60 min. to avoid catches too large for sorting, weighing, and measuring. In this fishery, commercial tow durations often range between 30 and 180 min.

We used the trawl gear components of the *F/V Ms. Julie* for this study. The port and starboard gear components were identical in material and design. Wood and steel combination doors, 2.4 x 2.7 m (length x height), were used to spread each trawl. The trawl bridles were 19 mm steel cable and totaled 6.1 m in length and connected directly to the trawl doors. The headropes and fishing lines were 27.4 m in length (Fig. 2). Drop chains measuring 0.4 m in length attached the fishing line to the chain ground line at 0.9 m separations. The center 7.3 m section of the trawl groundgear consisted of only drop chains. Both trawls had a codend mesh size of 35 mm BK.

Five Lindgren-Pitman Electralume® green LED fishing lights, centered on a wavelength of 519 nm (Nguyen et al. 2017), were used to illuminate the central trawl fishing line area. While the spectral sensitivity has not been empirically determined for all the species examined in this study, the species that have been examined possess maximal sensitivity to blue-green light, expectedly, as this is the predominant spectral component of coastal waters (Jerlov, 1976; Bowmaker 1990; Britt 2009). Therefore, we selected green LEDs for two reasons: (1) to allow for a comparison of results with the Lomeli et al. (2018a) and Hannah et al. (2015) studies, and (2) this color best matches the ambient light environment encountered in our study area and transmits well through coastal and continental shelf waters. The LEDs were attached to the trawl fishing line using zip ties, with the diodes pointing progressively forward moving towards the trawl wing tips. The LEDs were switched between the port and starboard trawl throughout the study, with one trawl serving as the illuminated and the other as the unilluminated, to control for any trawl specific differences that may occur in the selectivity between the two trawls (Hannah et al. 2011, 2015; Lomeli et al. 2018a). Lastly, fishing occurred with the sorting grids removed from the trawls.

In each trawl, two Wildlife Computers TDR-MK9 archival tags were used to measure the amount of light available and water temperature. The tags were attached to the underside of the net five meshes (35 mm nominal mesh size) behind the midpoint of the fishing line with the light sensor positioned horizontally and looking forward. See Lomeli et al. (2018a) for the calibration function used to convert the MK9 relative light units to irradiance units.

A Sea-Bird Scientific ECO Scattering Sensor (set to a scattering wavelength of 650 nm) was centered on the starboard trawl headrope to measure the amount of backscatter present during our study. This scattering wavelength provides a measurement of the amount of turbid material from non-organic matter in the water. The backscatter value increases with increased turbidity levels. Further, this wavelength was selected as absorption by dissolved organic material is negligible at longer wavelengths such as 650 nm (Pegau et al. 1997). The calibration function used to convert the scattering sensor relative units to meter per steradian (m^{-1} sr^{-1}) units was:

$$m^{-1}\ sr^{-1} = \textit{scale factor} * (\textit{output} - \textit{dark counts}) \qquad (1)$$

where *scale factor* is $3.586e^{-06}$ (m^{-1} sr^{-1})/counts, *output* is the relative scattering sensor value, and *dark counts* is 40. The MK9 tags and ECO Scattering Sensor were used to capture the conditions that this study was conducted under. Collecting this data is recommended by the International Council for the Exploration of the Sea to improve comparability of results between light studies (ICES 2018).

Fishing line height (FLH) was measured using Star-Oddi DST tilt sensors (0.05° tilt resolution, ±3° tilt accuracy) attached to the center of the fishing line of each trawl to ensure uniformity between the trawls. Each tag was placed in a customized aluminum bracket outfitted with a rod that extended from the fishing line to the seabed (Lomeli et al. 2018a). The mean tilt angle for the x-axis was converted to height using the following formula:

$$\mathrm{FLH} = y \times \mathrm{SIN}(x) \qquad (2)$$

where y is the length of the bracket (86.4 cm, Lomeli et al. 2018a) and x is the mean tilt angle in the vertical plane perpendicular to the fishing line. Tows where the mean FLH value between the two trawls differed >8.5 cm were not included in the analysis. The vessel was not equipped to measure wing spread or door spread, but we assumed any differences that may occur in these measurements would be minimal and not affect our results as identical trawl components were used.

Overall, 47 paired tows were completed. Five tows were excluded from the analyses due to mean FLH differences of >8.5 cm. After each tow, the catch from the illuminated and unilluminated trawls were dumped into a divided hopper where fish catches were then separately sorted to species as they came across the hopper conveyor belt, weighed, and then measured. Eulachon and rockfishes were measured to fork length, while flatfishes were measured to total length. For ocean shrimp, catches were collected in baskets and then a basket(s) was randomly selected to obtain length samples. From the selected basket(s), a 9.5 L plastic bag was filled with ocean shrimp and frozen for measurement at a laboratory. From this subsample, 100 individuals per net per tow were randomly selected for carapace length measurement.

2.2. Modeling the relative catch efficiency between illuminated and unilluminated trawls

We used the statistical analysis software SELNET (SELection in trawl NETting) to analyze the catch data (Sistiaga et al. 2010; Herrmann et al. 2012, 2016) and conducted length-dependent catch comparison and catch ratio analyses (Lomeli et al. 2018ab, 2019).

Using the catch information (Table 1) we wanted to determine whether there was a significant difference in catch efficiency between the unilluminated and illuminated trawl. We also wanted to determine if a potential difference between the trawls could be related to the size of ocean shrimp or a given species of fish. Specifically, to assess the relative length-dependent catch efficiency effect of changing from unilluminated to illuminated trawl, we used the method described in Herrmann et al. (2017) based on comparing the catch data between the two trawls. This method models the length-dependent catch comparison rate (CC_l) summed over tows:

$$CC_l = \frac{\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j}+\frac{nc_{lj}}{qc_j}\right\}} \tag{3}$$

where nc_{lj} and nt_{lj} are the numbers of ocean shrimp or a given species of fish measured in each length class l for the unilluminated and illuminated trawl in tow j, respectively. Parameters qc_j and qt_j are the related subsampling factors (fraction of the ocean shrimp or a given species of fish caught being length measured), and m is the number of tows carried out with the unilluminated and illuminated trawl. As is common practice for fishing gear catch comparison investigations a functional form $CC(l,\boldsymbol{v})$ for the catch comparison rate was estimated from the experimental data (Grimaldo et al. 2018b; Karlsen et al. 2018; Lomeli et al. 2018a). The functional form provides a smooth curve for length dependency that is less influenced by the observation error for individual length classes than the experimental being expressed by equation 3 and it enables to interpolate over length classes with no experimental observations. The functional form of the catch comparison rate was obtained using maximum likelihood estimation by minimizing the following equation:

$$-\sum_{l}\left\{\sum_{j=1}^{m}\left\{\frac{nc_{lj}}{qc_j}\times ln[1.0-CC(l,\boldsymbol{v})]\right\}+\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j}\times ln[CC(l,\boldsymbol{v})]\right\}\right\} \qquad (4)$$

where $\boldsymbol{v}$ represents the parameters describing the catch comparison curve defined by $CC(l,\boldsymbol{v})$. The outer summation in the equation is the summation over the length classes l. When the catch efficiency of the unilluminated and illuminated trawl are equal, the expected value for the summed catch comparison rate would be 0.5. Therefore, this baseline can be applied to judge if there is a difference in catch efficiency between the two trawls. The experimental CC_l was modeled by the function $CC(l,\boldsymbol{v})$, on the following form:

$$CC(l,\boldsymbol{v})=\frac{exp[f(l,v_0,\ldots,v_k)]}{1+exp[f(l,v_0,\ldots,v_k)]} \qquad (5)$$

where f is a polynomial of order k with coefficients v_0 to v_k. The values of the parameters $\boldsymbol{v}$ describing $CC(l,\boldsymbol{v})$ are estimated by minimizing equation 4, which is equivalent to maximizing the likelihood of the experimental data. We considered f of up to an order of 4 with parameters v_0, v_1, v_2, v_3, and v_4 as our experience from former studies including Krag et al. (2015) Santos et al. (2016) and Sistiaga et al. (2018) have shown that this provides a model that is sufficiently flexible to describe the catch comparison curves between fishing gears well in the cases examined. Leaving out one or more of the parameters $v_0 \ldots v_4$ led to 31 additional models that were also considered as potential models for the catch comparison $CC(l,\boldsymbol{v})$. Among these models, estimations of the catch comparison rate were made using multimodel inference to obtain a combined model (Burnham and Anderson 2002; Herrmann et al. 2017). Specifically, the models were ranked and weighed in the estimation according to their AICc values (Burnham and Anderson 2002). The AICc is calculated as the AIC (Akaike, 1974), but it includes a correction for finite sample sizes in the data. Models that resulted in AICc values within +10 of the value of the model with lowest AICc value ($\mathrm{AICc_{min}}$) were considered for the estimation of *cc(l,**v**)* following the procedure described in Katsanevakis (2006) and in Herrmann et al. (2015). We use the name combined model for the result of this multi-model averaging and calculated it by:

$$cc(l,\boldsymbol{v}) = \sum_i w_i \times cc(l,\boldsymbol{v}_i) \quad \text{with} \quad w_i = \frac{exp(0.5 \times (AICc_i - AICc_{min}))}{\sum_j exp(0.5 \times (AICc_j - AICc_{min}))} \qquad (6)$$

where the summations are over the models with an AICc value within +10 of $\mathrm{AICc_{min}}$.

The ability of the combined model to describe the experimental data was evaluated based on the *p*-value, which quantifies the probability of obtaining by coincidence at least as big a discrepancy between the experimental data and the model as observed, assuming that the model is correct. Therefore, this *p*-value, which was calculated based on the model deviance (D) and the degrees of freedom (DF), should be >0.05. Specifically, D has approximate χ^2 distribution when the model is correct and the p-value is therefore calculated for a χ^2 distribution with D and DF as parameters (Wileman et al. 1996). For DF we use the number of length classes in the experimental data minus the number of parameters $\boldsymbol{v}$ in the model $cc(l,\boldsymbol{v})$. However, lack of fit as indicated by large D compared to DF which corresponds to p-value < 0.05 does not necessarily imply that the fitted combined catch comparison curve is not a good model for the length dependent catch comparison data (Wileman et al. 1996). If a plot of deviance residuals D_l versus length l shows no clear structure then the lack of fit can be assumed to be due to over-dispersion in the data (McCullagh and Nelder 1989). Therefore, in case of p-value < 0.05 we checked deviance residuals which for individual length classes is calculated by:

$$D_l = 2 \times sign(y_l - ym_l) \times \sum_l \left\{ nt_l \times ln\left(\frac{y_l}{ym_l}\right) + nc_l \times ln\left(\frac{1-y_l}{1-ym_l}\right) \right\} \quad (7),$$

where

$$
\begin{aligned}
y_l &= \frac{nt_l}{nt_l + nc_l} \\
ym_l &= \frac{qt_l \times cc(l,\boldsymbol{v})}{qt_l \times cc(l,\boldsymbol{v}) + qc_l \times (1 - cc(l,\boldsymbol{v}))} \\
nt_l &= \sum_{j=1}^{m} nt_{lj} \\
nc_l &= \sum_{j=1}^{m} nc_{lj} \\
qt_l &= \frac{nt_l}{\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j}\right\}} \\
qc_l &= \frac{nc_l}{\sum_{j=1}^{m}\left\{\frac{nc_{lj}}{qc_j}\right\}}
\end{aligned}
\qquad (8)
$$

The model deviance is based on equation 7 calculated by (Wileman et al 1996):

$$D = \sum_l D_l^2 \qquad (9)$$

Based on the estimated combined catch comparison function *CC(l,**v**)*, we obtained the relative catch ratio *CR(l,**v**)* between fishing with the two trawls by the general relationship:

$$CR(l,\boldsymbol{v}) = \frac{CC(l,\boldsymbol{v})}{[1 - CC(l,\boldsymbol{v})]} \qquad (10)$$

The catch ratio provides a direct relative value of the catch efficiency between fishing with and without illumination. Thus, if the catch efficiency of both trawls is equal, *CR(l,**v**)* should always be 1.0.

The 95% confidence interval (CI) limits for the catch comparison and catch ratio curves were estimated using a double bootstrapping method for paired trawl catch data in SELNET. The bootstrapping method accounts for uncertainty due to between haul variation by selecting *m* hauls with replacement from the *m* hauls available during each bootstrap repetition (equation 4). Within each resampled haul, the data for each length class were resampled in an inner bootstrap to account for the uncertainty in estimation of the catch comparison and catch ratio rates in the haul resulting from that only a limited number of ocean shrimp or a given species of fish were caught, and length measured in the specific haul. The inner resampling of the data in each length class were performed prior to the raising of the data with subsampling factors qc_j and qt_j to account for the additional uncertainty due to the subsampling (Eigaard et al. 2012). The resulting data set obtained from each bootstrap repetition was analyzed as described above and therefore also accounted for uncertainty in model selection and model averaging because the multimodel inference was included (Grimaldo et al. 2018a). Based on the bootstrap results we estimated the Efron percentile 95% confidence intervals (Efron 1982) for both the catch comparison and catch ratio curve. We performed 1,000 bootstrap repetitions.

A length-integrated average value for the catch ratio was also estimated directly from the experimental catch data by:

$$CR_{average} = \frac{\sum_l \sum_{j=1}^{m} \left\{ \frac{nt_{lj}}{qt_j} \right\}}{\sum_l \sum_{j=1}^{m} \left\{ \frac{nc_{lj}}{qc_{ij}} \right\}} \qquad (11)$$

where the outer summation covers the length classes in the catch during the experimental fishing period. Based on equation 11, the percent change in average catch efficiency between fishing with the unilluminated trawl to the illuminated trawl was estimated by:

$$\Delta CR_{average} = 100 \times (CR_{average} - 1.0) \qquad (12)$$

We used $\Delta CR_{average}$ to provide a length-averaged value for the effect of changing from unilluminated to illuminated trawl on the catch efficiency. When the percent change in catch efficiency of both trawls is equal, the expected value would be zero. The uncertainties for $CR_{average}$ and $\Delta CR_{average}$ were obtained by including their calculation according to equation 11 and 12 into the bootstrap procedure described above.

2.3. *Modeling the effect of artificial illumination level and backscatter value on catch comparison*

We performed regression analyses on tow data using the statistical software JMP® (version 14.2.0) to examine if $CC_{average}$ changed linearly with level of artificial illumination and degree of backscatter for ocean shrimp or a given species of fish. Linear regression was used to model level of artificial illumination and degree of backscatter against $CC_{average}$ as single model parameters, while a multiple regression model was used with level of artificial illumination and degree of backscatter as combined model parameters. Light level and backscatter values were log-transformed to achieve normality of model residuals. Because the regression analyses were performed on tow data, we were unable to use $CR_{average}$ as the response variable as some tows had zero catch in the control trawl (unilluminated trawl).

3. Results

3.1. *Sampling conditions*

Towing occurred at bottom fishing depths averaging 166 m (SE ±1.4). Towing speed ranged from 3.3 to 3.5 km h^{-1} (1.8–1.9 knots). The mean ambient light level measured in the unilluminated trawl was $2.4e^{-05}$ ($\pm1.0e^{-06}$) µmol photons m^{-2} s^{-1}. In the illuminated trawl, the mean light level measured increased to $3.2e^{-02}$ ($\pm8.4e^{-04}$) µmol photons m^{-2} s^{-1}. Mean light levels per tow for the unilluminated and illuminated trawl are shown in Figure 3. The mean temperature was 8.4^{o}C (±0.02) and ranged from 8.0-8.7^{o}C. The mean backscatter value was $1.66e^{-03}$ (SE $\pm9.13e^{-06}$) m^{-1} sr^{-1}. Figure S1 in the Supplementary material shows the mean backscatter value per tow. The mean FLH for the port trawl was 25.8 cm (SE ±0.10) while the starboard trawl was 27.6 cm (±0.09). The mean FLH for the illuminated trawl was 26.1 cm (±0.09) while the unilluminated trawl was 27.2 cm (±0.09). Figure S2 in the Supplementary material shows the mean FLH per tow for the port and starboard trawl.

3.2. *Relative catch efficiency between illuminated and unilluminated trawls*

The change in average catch efficiency of ocean shrimp did not differ significantly between the illuminated and unilluminated trawl (Fig. 4). Further, the catch comparison and catch ratio analyses detected no significant length-dependent catch efficiency effect of changing from unilluminated to illuminated trawl for ocean shrimp as indicated by the mean $CC(l,\boldsymbol{v})$ and $CR(l,\boldsymbol{v})$ 95% CIs extended above and below the $CC(l,\boldsymbol{v})$ rate of 0.5 and $CR(l,\boldsymbol{v})$ ratio of 1.0. (Figs. 5 and S3).

Eulachon 12.5-16.5 cm in length comprised 94% of the total eulachon catch by numbers. Over this size range, a significant difference in catch efficiency occurred (Fig. 5) with the illuminated trawl catching on average only 33% of the number of eulachon compared to the unilluminated trawl (Fig. S3). For yellowtail rockfish (*S. flavidus*), a similar effect was observed with the illuminated trawl catching significantly fewer fish 43.5-61.5 cm in length than to the unilluminated trawl (Fig. 6). Over these lengths, the illuminated trawl caught on average only 37% of the number of yellowtail rockfish compared to the unilluminated trawl (Fig. S4). In terms of change in average catch efficiency, results show the unilluminated trawl caught significantly more eulachon (66%) than the illuminated trawl (Fig. 4). For yellowtail rockfish, the change in average catch efficiency showed the illuminated trawl caught on average 51% more fish than the unilluminated trawl. This result was significant, however, moderate in effect as the mean $\Delta CR_{average}$ 95% CIs nearly extended above and below the $\Delta CR_{average}$ ratio of zero (Fig. 4).

In contrast to eulachon and yellowtail rockfish, the catch comparison and catch ratio analysis show the illuminated trawl caught significantly more stripetail rockfish (*S. saxicola*) (8.5-16.5 cm in length), other rockfishes (11.5-34.5 cm in length), arrowtooth flounder (*Atheresthes stomias*) (across all lengths), slender sole (*Lyopsetta exilis*) (13.5-27.5 cm in length), and other flatfishes (8.5-37.5 cm in length) than the unilluminated trawl (Figs. 6 and 7). Over these size classes, the illuminated trawl on average caught 3.6, 3.5, 2.8, 4.4, and 2.7 times more stripetail rockfish, other rockfishes, arrowtooth flounder, slender sole, and other flatfishes, respectively, than the unilluminated trawl (Figs. S4-S5). When evaluating the change in average catch efficiency (a length-averaged value), the same effect was noted with the illuminated trawl catching significantly more stripetail rockfish and flatfishes than to the unilluminated trawl (Fig. 4). For other rockfishes, the illuminated trawl on average caught 59% more fish than the unilluminated trawl, however, this change in average catch efficiency did not differ significantly from the unilluminated trawl (Fig. 4). The catch efficiency analyses (e.g., $CC(l,\boldsymbol{v})$, $CR(l,\boldsymbol{v})$, and $\Delta CR_{average}$) for darkblotched rockfish detected no significant difference in catch efficiencies between the illuminated and unilluminated trawl (Figs. 6 and S4).

With the exception to ocean shrimp, the combined $CC(l,\boldsymbol{v})$ models described the experimental data well for the species we evaluated as demonstrated by the fit statistics *p*-values >0.05 and the deviances within times of the degrees of freedom values (Table 2). For ocean shrimp, inspecting the fit between the experimental catch comparison data and the modeled mean curve for these species indicated the poor fit statistics were due to overdispersion of the data rather than the model's inability to adequately describe the data.

3.3. *Effect of artificial illumination level and backscatter value on catch comparison*

The regression analyses results showed $CC_{average}$ did not changed linearly with level of artificial illumination for ocean shrimp or a given species of fish (Table 3, Fig. 8, Supplementary Figs. S6-S9). For the degree of backscatter, the linear regression analysis showed this parameter effected the $CC_{average}$ for only ocean shrimp and arrowtooth flounder (Table 3, Supplementary Figs. S6-S9) with $CC_{average}$ decreasing as the degree of backscatter increased (Fig. 8). However, these results were moderate in effect. In the multiple regression analysis, results showed the degree of backscatter effected the $CC_{average}$ for only ocean shrimp (Table 4). This result was also moderate in effect.

4. Discussion

To determine the extent that eulachon and other fishes escape trawl entrainment in response to illumination along the trawl fishing line, we compared the catch efficiency between two simultaneously fished ocean shrimp trawls (one illuminated and the other unilluminated) without sorting grids installed. Our analyses showed eulachon (and yellowtail rockfish) escaped trawl capture in significant numbers when the fishing line was illuminated. As eulachon are an ESA-listed species, this finding provides critical information for fishery managers implementing ESA recovery plans and evaluating potential fishery impacts on their recovery and conservation (NMFS 2017). The clear reduction in eulachon bycatch before trawl capture in trawls outfitted with LEDs translates to significantly fewer fish exposed to capture-escape processes within the trawl. These processes can cause physiological stress, fatigue, injuries (from contact with sorting grids, webbing, and/or other fishes, etc.) and lead to unobserved and unaccounted post-release mortality (Chopin and Arimoto 1995; Davis and Olla 2001, 2002; Ryer 2004; Davis 2005). Depending on its magnitude, a reduction in eulachon bycatch mortality could have significant conservation benefits.

We found using illumination along the trawl fishing line significantly affected the catch rates of eulachon and several groundfishes, without impacting ocean shrimp catches. However, the effect was not consistent across species. Our data continues to support the hypothesis that there is a significant reduction in eulachon bycatch when artificial illumination is present. Research has shown that vision plays a major role in how fish respond to trawl gear (under conditions without artificial illumination present) (Glass and Wardle 1989; Olla et al. 1997, 2000; Kim and Wardle 1998, 2003; Ryer et al. 2000, 2010; Ryer and Barnett, 2006; Arimoto et al. 2010). However, it remains unknown whether eulachon's response is positive (moving towards), negative (moving away), or neutral (the presence of illumination simply allows them to perceive the trawl gear components and escape capture). Research on phototaxis and visual cues in eulachon is required to understand the behavioral response affecting their catch rates. For rockfishes and flatfishes, our results suggest their ability to escape trawl entrainment in response to illumination along the fishing line is not as strong as previously indicated (Hannah et al. 2015; Lomeli et al. 2018a). Compared to the unilluminated trawl, we found the illuminated trawl caught significantly more stripetail rockfish and flatfishes. The illuminated trawl also caught more darkblotched rockfish and other rockfishes (except yellowtail rockfish), but not at a significant level. These results differ from prior studies (which included the use of sorting grids) that demonstrated the ability to significantly reduce bycatch of those same species with the addition of illumination along the fishing line (Hannah et al. 2015; Lomeli et al. 2018a). It should also be mentioned, that the trawls used in the current study differed from the prior studies in that the central portion of the groundgear consisted of just drop chains as opposed to a continuous ground line (Hannah et al. 2011). This complicates our ability to further understand the efficacy of illumination along trawl fishing lines as trawls with central ground line sections removed have been shown to reduce the overall level of bycatch compared to trawls with continuous ground lines (Hannah and Jones, 2003; Hannah et al., 2011). In the ocean shrimp fishery, both groundgear configurations described above are commonly used. Further research investigating how changes in groundgear configuration may affect the efficacy of illumination along ocean shrimp trawl fishing lines is needed.

While the presence of artificial illumination was found to have a significant effect on the catch efficiency for eulachon, yellowtail and stripetail rockfishes, arrowtooth flounder, slender sole, and other flatfishes, our regression analyses showed the level of artificial illumination itself had no effect on the average catch comparison rate for ocean shrimp or a given species of fish. However, the linear regression analysis did show that degree of backscatter had a moderate effect (p=0.04) on the average catch comparison rate for ocean shrimp and arrowtooth flounder. For these two species, the catch efficiency analyses showed the illuminated trawl caught more individuals than the unilluminated trawl. This result was significant for arrowtooth flounder (across all size classes), but not significant for ocean shrimp. In the linear regression analysis, results showed the average catch comparison rate for ocean shrimp and arrowtooth flounder decreased towards 0.5 (which would indicate equal catch efficiency between the two trawls) as degree of backscatter increased towards 3.0 m^{-1} sr^{-1}. These findings make logical sense in terms that increased levels of backscatter (e.g., increased turbidity) would reduce the attenuation of light and either hinder a fishes or shrimps ability to perceive the illumination itself or the distance that a fish or shrimp can perceive and respond to the illumination; which could influence the effectiveness of the illumination. Why this result was only noted for ocean shrimp and arrowtooth flounder is unclear, but differences in their spectral sensitivity compared to the other species could be one plausible explanation. Lastly, as this research occurred under conditions representative of conditions fished by ocean shrimp fishers, our catch efficiency results reflect what would occur under normal fishing conditions with LEDs attached along the trawl fishing line.

In the U.S. West Coast groundfish bottom trawl fishery, Lomeli et al. (2018b) found illuminating the headrope of a low-rise selective flatfish trawl with LEDs tended to increase rockfish catches (i.e., darkblotched, greenstriped [*S. elongatus*], and canary rockfishes). For flatfishes, catch trends varied between species with the illuminated trawl catching on average more English sole (*Parophrys vetulus*) and petrale sole (*Eopsetta jordani*), but fewer rex sole (*Glyptocephalus zachirus*), arrowtooth flounder, and Dover sole (*Microstomus pacificus*). Catch trends from that previous study have some similarities to our current results. While our work and the prior studies presented above are not directly comparable to each other, they collectively present that specific species behavioral response to illumination stimuli can be widely variable (with perhaps the exception to eulachon). Results from our study suggest that factors beyond vision (i.e., size [Melli et al. 2018], innate behavior [Grimaldo et al. 2018a], fish density, fatigue, stress, time of day, placement of illumination [Hannah et al. 2015], groundgear configuration, etc.) may have a considerable effect on how some fishes respond to illumination on trawl gear. How these factors influence fishes behavioral response to illumination, however, is not well understood and requires further research.

Bycatch reduction research and implementation of findings have been key to the success of ocean shrimp management. In 2003, ocean shrimp trawls outfitted with sorting grids became mandatory to reduce canary rockfish bycatch (a stock declared overfished at that time). In 2016, the canary rockfish stock was declared fully rebuilt, and had been since 2006 (Thorson and Wetzel 2016). Further, because earlier studies (Hannah et al. 2015; Lomeli et al. 2018a) in the fishery have shown use of illumination along the trawl fishing line can result in codend catches comprised mainly of ocean shrimp, some may question whether the sorting grid requirement is still necessary (due to handling and safety concerns, loss of target catch that can occur at times, and the recovery of canary rockfish). Results from our study clearly demonstrate that sorting grids are still necessary as our study noted the illuminated trawl caught several size classes of fishes that the sorting grids would have released if present.

Prior to this study, the degree that fishes escaped trawl capture in response to illumination along an ocean shrimp trawl fishing line was unclear. Our research has provided results to help fill that data gap. For eulachon and yellowtail rockfish, we found they escaped trawl entrainment in significant numbers in response to illumination along the fishing line. As conservation of ESA-listed eulachon is an ongoing management priority, our research contributes new data on the efficacy of footrope illumination to reduce their bycatch before trawl capture. For other species, however, we did not see the same effect as the illuminated trawl caught similarly or significantly more fishes than the unilluminated trawl. These findings demonstrate that some fishes ability to escape trawl entrainment in response to illumination along the fishing line is not as strong as previous research (which included sorting grids) has suggested and that the combined use of footrope illumination and sorting grids (as is required in Oregon and Washington fisheries) is the most effective means for reducing bycatch across a larger suite of species and sizes. Further, our research shows that use of footrope illumination to reduce bycatch is a much more complex process than simply enhancing fishes' visual perception of trawl gear components and escape areas. Lastly, while our results have regional impacts, our study findings could provide useful information to other shrimp/prawn trawl fisheries internationally; for example, the ocean shrimp trawl fishery off British Columbia, Canada where fishers have requested management to allow use of illumination to reduce eulachon bycatch (DFO 2018), and northern prawn (*P. borealis*) trawl fisheries in the Northern Atlantic where illumination has been tested as a bycatch reduction technique for marine fishes (Larsen et al. 2017, 2018).

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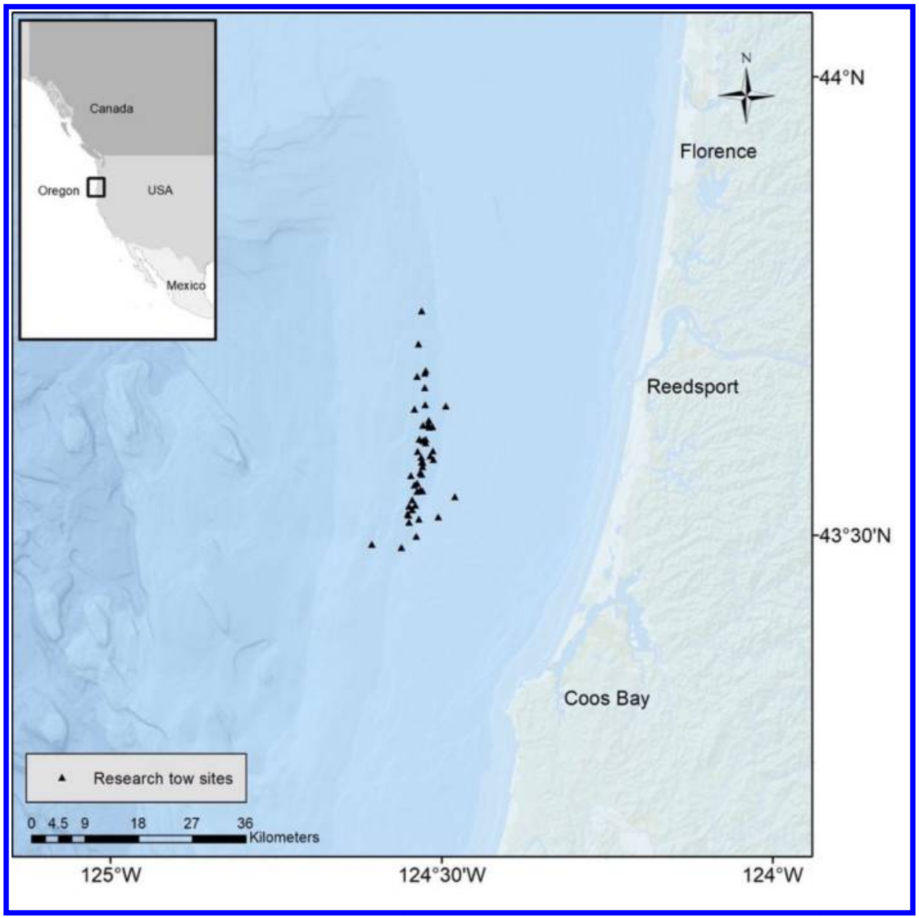

Figure 1. Map of the area off the Oregon coast where sea trials were conducted. Map source: ArcGIS, 2019.

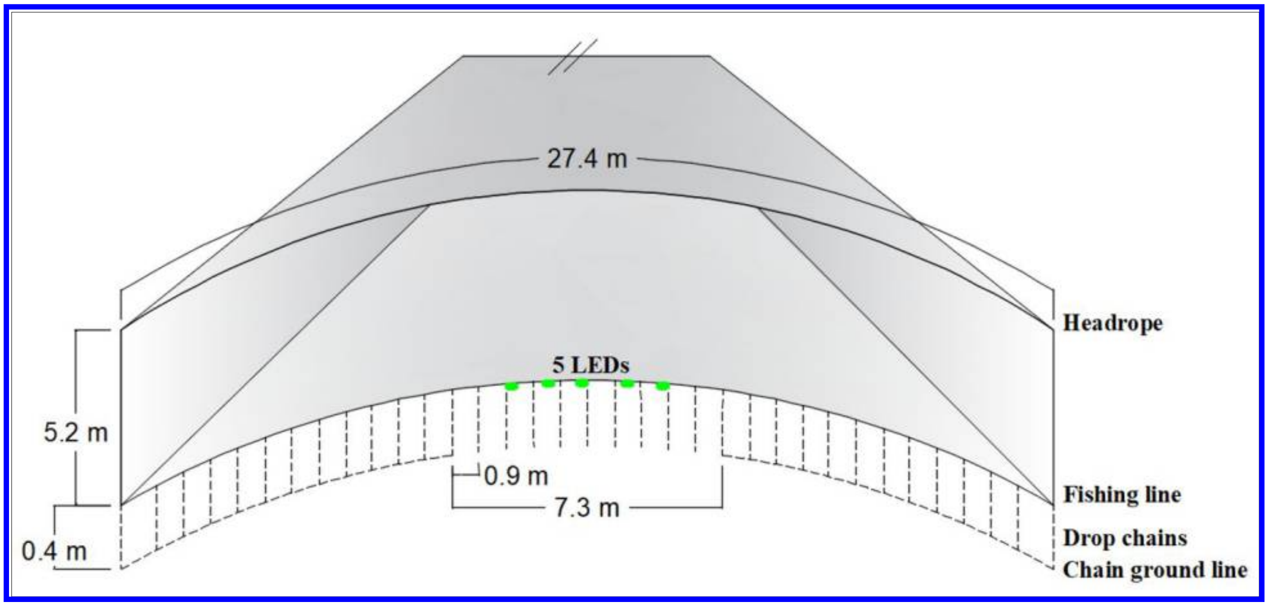

Figure 2. Schematic diagram of an ocean shrimp trawl and placement of LEDs along the trawl fishing line. Note: diagram not to scale.

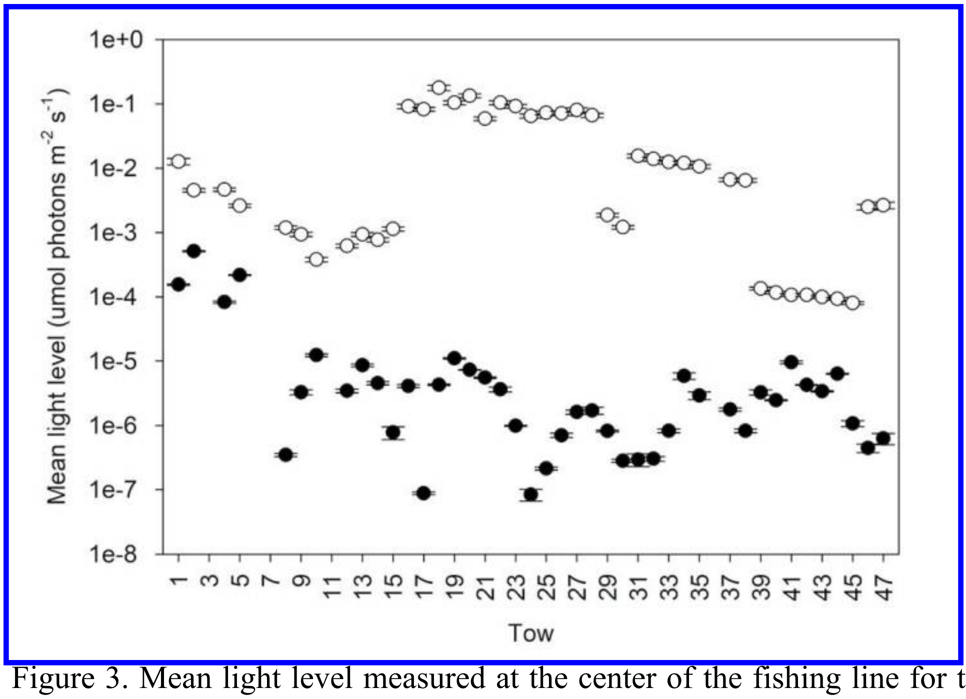

Figure 3. Mean light level measured at the center of the fishing line for the unilluminated trawl (closed circles) and illuminated trawl (open circles) per tow. ± bars are standard errors (n = 50 measurements per net per tow).

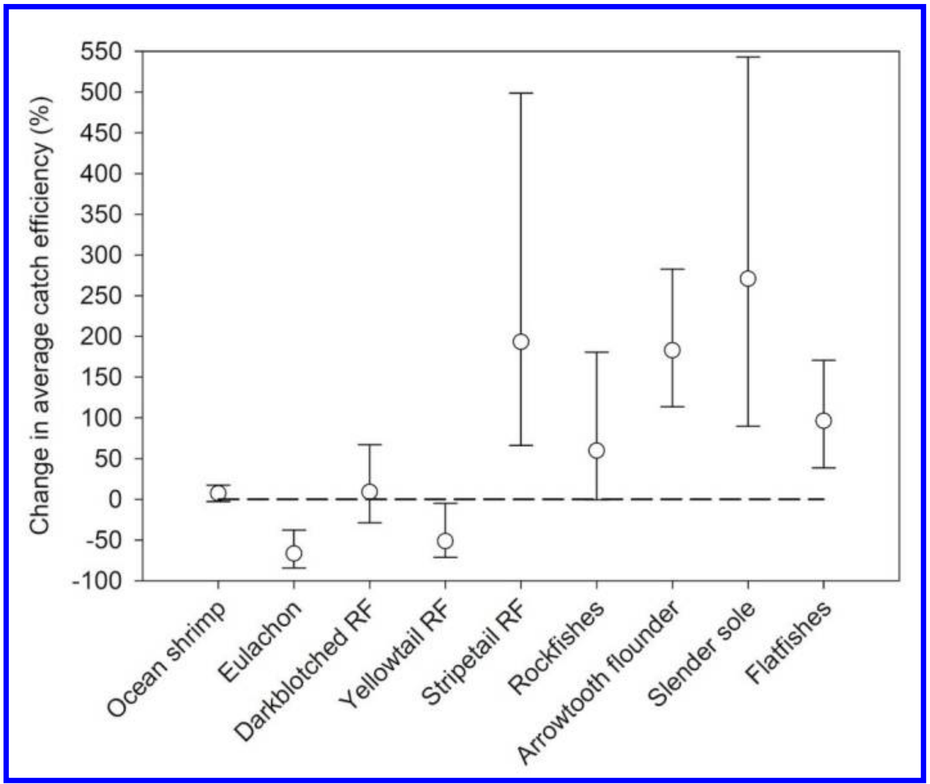

Figure 4. Change in average catch efficiency (%) between the illuminated trawl and the unilluminated trawl. Values below zero indicate more ocean shrimp or a given species of fish were caught in the unilluminated trawl, and vice versa for values above zero. ± bars are 95% CIs; RF = rockfish. See Table 1 for the species included in rockfishes and flatfishes.

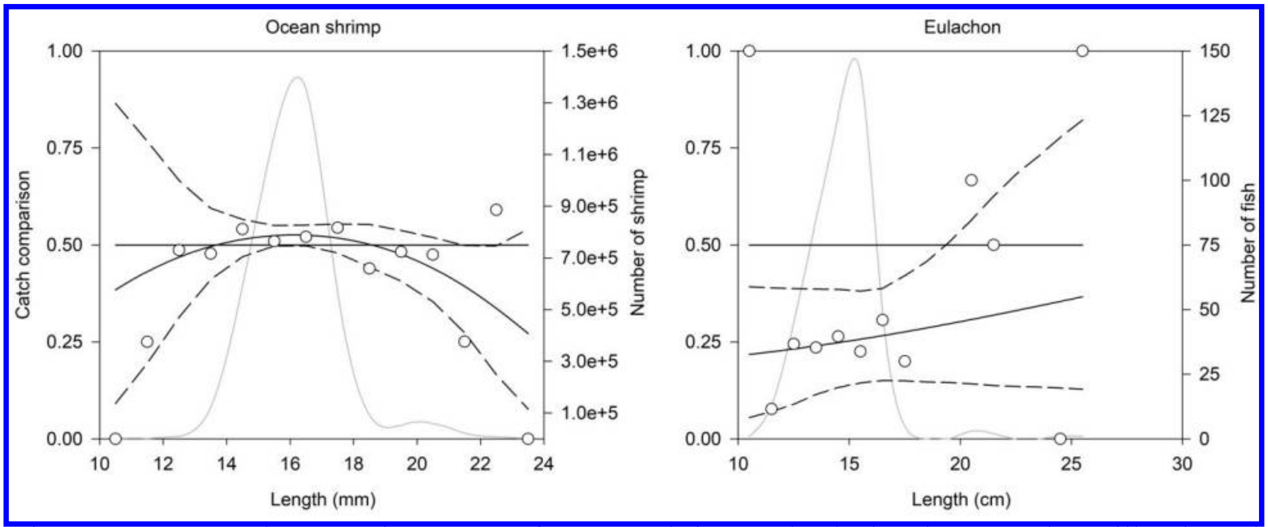

Figure 5. Mean catch comparison curves for ocean shrimp and eulachon between the unilluminated trawl and illuminated trawl. Circles are the experimental data; fitted lines are the modeled value; dashed lines are 95% CIs; grey lines are number of ocean shrimp and eulachon caught; straight lines depict the baseline catch comparison rate of 0.5 indicating equal catch rates between the illuminated and unilluminated trawl.

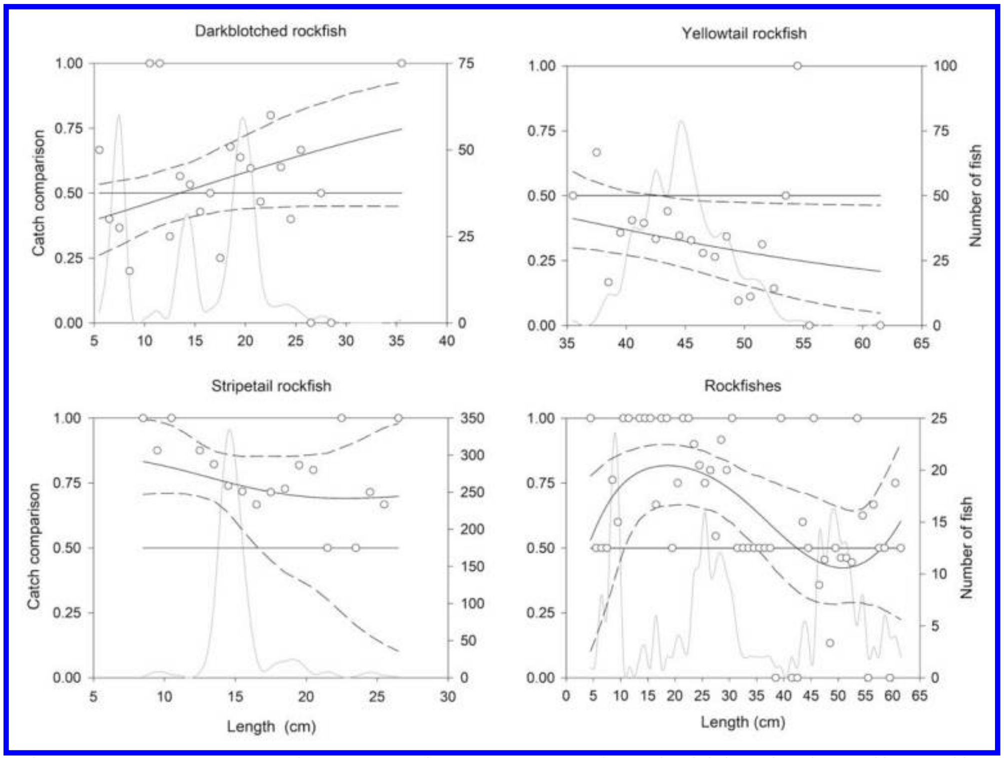

Figure 6. Mean catch comparison curves for darkblotched, yellowtail, stripetail, and other rockfishes between the unilluminated trawl and illuminated trawl. Circles are the experimental data; fitted lines are the modeled value; dashed lines are 95% CIs; grey lines are number of fish caught; straight lines depict the baseline catch comparison rate of 0.5 indicating equal catch rates between the illuminated and unilluminated trawl. See Table 1 for the species included in rockfishes.

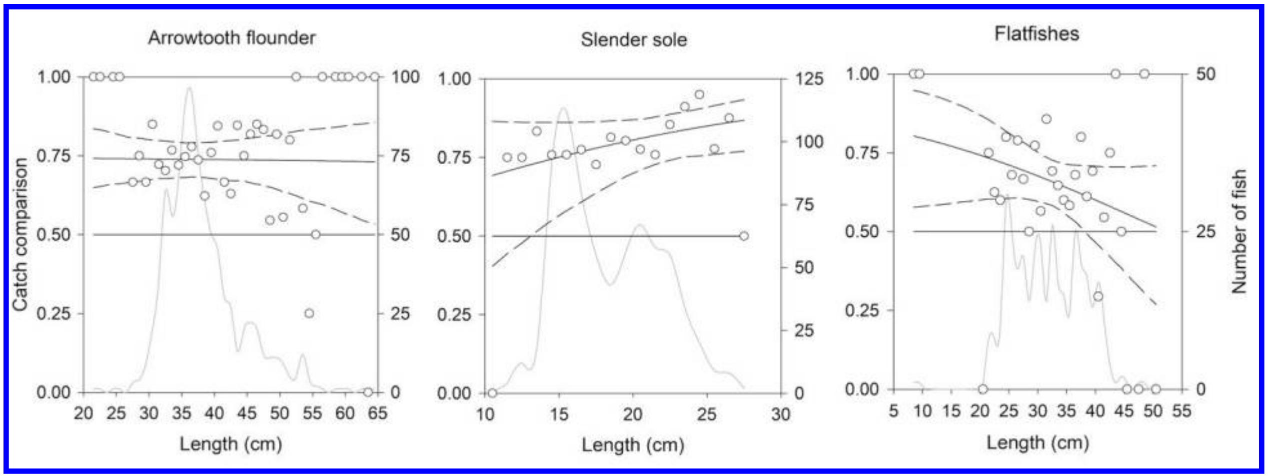

Figure 7. Mean catch comparison curves for arrowtooth flounder, slender sole, and other flatfishes between the unilluminated trawl and illuminated trawl. Circles are the experimental data; fitted lines are the modeled value; dashed lines are 95% CIs; grey lines are number of fish caught; straight lines depict the baseline catch comparison rate of 0.5 indicating equal catch rates between the illuminated and unilluminated trawl. See Table 1 for the species included in flatfishes.

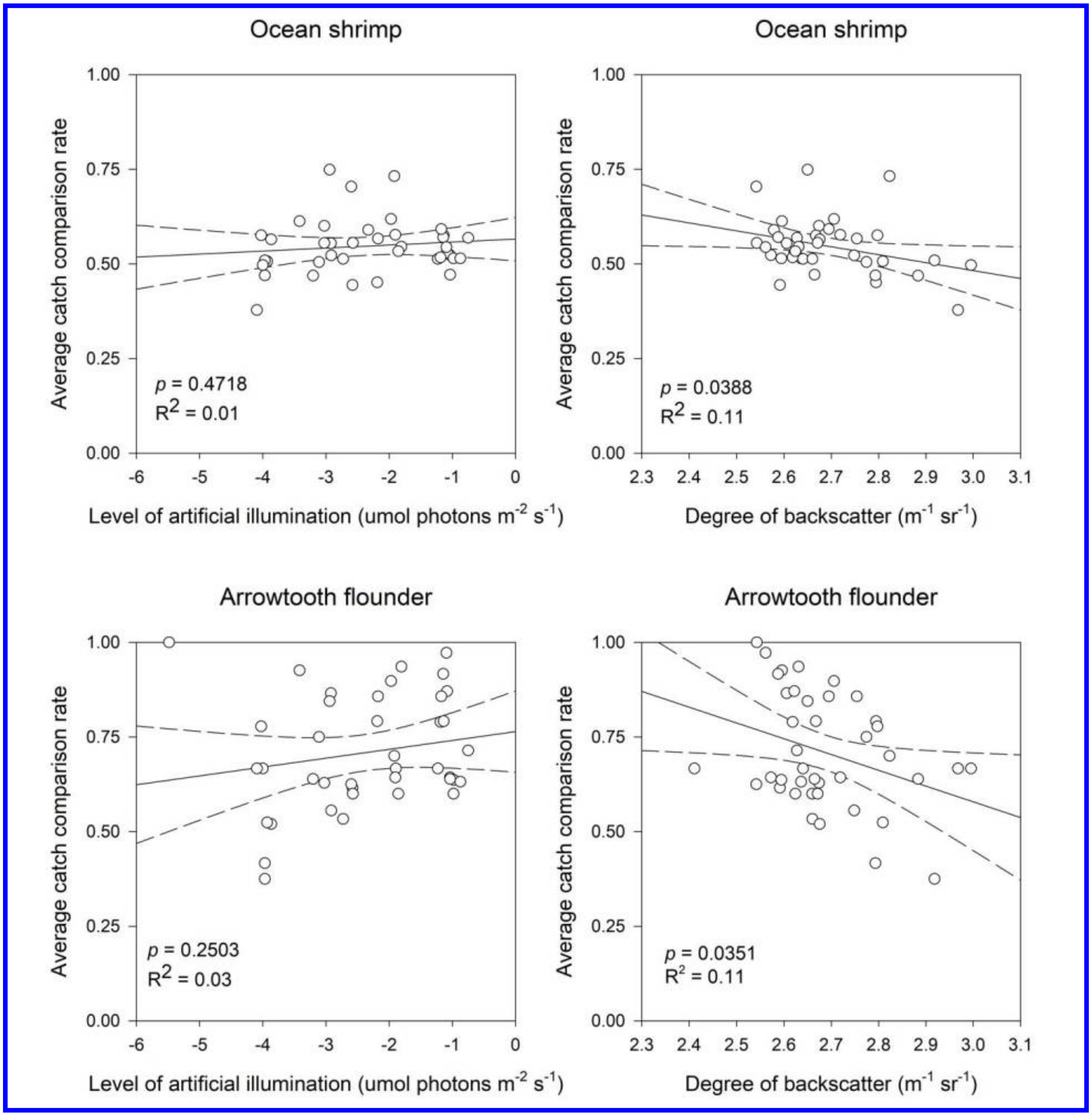

Figure 8. Linear regression model results examining if $CC_{average}$ changes linearly with level of artificial illumination or degree of backscatter for ocean shrimp and arrowtooth flounder. Circles are the experimental data; fitted lines are the regression lines; dashed lines are 95% CIs.

Table 1. Length data used for the catch comparison and catch ratio analyses. Values in parentheses are the length measurement subsample ratio from the total catch. Other rockfishes include widow (*Sebastes entomelas*, n=2), shortbelly (*S. jordani*, n=7), greenstriped (*S. elongatus*, n=114), splitnose (*S. diploproa*, n=62), redstripe (*S. proriger*, n=1), and canary (*S. pinniger*, n=140) rockfishes, chilipepper (*S. goodei*, n=5) and cowcod (*S. levis*, n=4); Other flatfishes include Pacific sanddab (*Citharichthys sordidus,* n=4), rex sole (*Glyptocephalus zachirus,* n=195), Dover sole (*Microstomus pacificus*, n=127), flathead sole (*Hippoglossoides elassodon*, n=49), petrale sole (*Eopsetta jordani*, n=7).

	No. measured	
Species	Illuminated trawl	Unilluminated trawl
Ocean shrimp	4,000 (0.002)	4,000 (0.002)
Eulachon	119 (1.0)	358 (1.0)
Darkblotched rockfish	182 (1.0)	167 (1.0)
Yellowtail rockfish	176 (1.0)	270 (0.75)
Stripetail rockfish	560 (1.0)	191 (1.0)
Other rockfishes	206 (1.0)	129 (1.0)
Arrowtooth flounder	664 (1.0)	236 (1.0)
Slender sole	492 (0.86)	147 (1.0)
Other flatfishes	253 (1.0)	129 (1.0)

Table 2. Catch comparison curve fit statistics. See Table 1 for the species included in other rockfishes and other flatfishes.

Species	*p*-value	Deviance	Degrees of freedom
Ocean shrimp	<0.0001	76.0	9
Eulachon	0.3740	10.8	10
Darkblotched rockfish	0.2295	26.5	22
Yellowtail rockfish	0.3257	21.2	19
Stripetail rockfish	0.8762	9.0	15
Other rockfishes	0.1246	63.9	52
Arrowtooth flounder	0.4695	38.0	38
Slender sole	0.7170	12.4	16
Other flatfishes	0.3403	31.5	29

Table 3. Fit statistics for linear regression model ($CC_{average} = \beta_0 + \beta_1 x_1 + e$) examining if $CC_{average}$ changed linearly with level of artificial illumination or degree of backscatter as single model effects. See Table 1 for the species included in other rockfishes and other flatfishes.

	Model parameter: Level of artificial illumination			Model parameter: Degree of backscatter		
Species	Estimate (95% CIs)	*p*-value	R^2	Estimate (95% CIs)	*p*-value	R^2
Ocean shrimp	0.0079 (-0.0142 – 0.0301)	0.4718	0.01	-0.2098 (-0.4083 – -0.0114)	0.0388	0.11
Eulachon	0.0069 (-0.0737 – 0.0877)	0.8585	<0.01	-0.1201 (-1.0393 – 0.7990)	0.7879	<0.01
Darkblotched rockfish	0.0014 (-0.0844 – 0.0871)	0.9746	<0.01	0.0741 (-0.7427 – 0.8909)	0.8550	<0.01
Yellowtail rockfish	0.1179 (-0.2215 – 0.4573)	0.4127	0.14	-1.5314 (-3.2733 – 0.2105)	0.0734	0.51
Stripetail rockfish	0.0550 (-0.0320 – 0.1420)	0.2026	0.08	-0.7045 (-1.5715 – 0.1625)	0.1059	0.12
Other rockfishes	0.0772 (-0.0470 – 0.2015)	0.2038	0.11	0.1343 (-1.3149 – 1.5835)	0.8453	<0.01
Arrowtooth flounder	0.0234 (-0.0172 – 0.6400)	0.2503	0.03	-0.4172 (-0.8037 – -0.0307)	0.0351	0.11
Slender sole	0.0151 (-0.0723 – 0.1024)	0.7262	<0.01	0.0701 (-0.7858 – 0.9260)	0.8678	<0.01
Other flatfishes	-0.0021 (-0.0665 – 0.0622)	0.9459	<0.01	-0.4211 (-1.0898 – 0.2476)	0.2069	0.06

Table 4. Fit statistics for the multiple regression model ($CC_{average} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + e$) examining if $CC_{average}$ changed linearly with level of artificial illumination and degree of backscatter and model parameters. See Table 1 for the species included in other rockfishes and other flatfishes.

	Model parameters					
	Level of illumination		Degree of backscatter		Whole model	
Species	Estimate (95% CIs)	*p*-value	Estimate (95% CIs)	*p*-value	R^2	Model *p*-value
Ocean shrimp	-0.0077 (-0.0338 – 0.0185)	0.5568	-0.2520 (-0.4989 – -0.0051)	0.0457	0.12	0.1023
Eulachon	0.0067 (-0.0763 – 0.0896)	0.8680	-0.1179 (-1.0638 – 0.8280)	0.7971	0.01	0.9518
Darkblotched rockfish	0.0053 (-0.0897 – 0.1004)	0.9102	0.0943 (-0.8106 – 0.9992)	0.8335	<0.01	0.9773
Yellowtail rockfish	0.1140 (-0.1531 – 0.3811)	0.3018	-1.5178 (-3.3280 – 0.2924	0.0804	0.63	0.1341
Stripetail rockfish	0.0166 (-0.0996 – 0.1328)	0.7688	-0.5922 (-1.7789 – 0.5945)	0.3103	0.12	0.2674
Other rockfishes	0.1054 (-0.0364 – 0.2473)	0.1324	0.6710 (-0.8899 – 2.2319)	0.3700	0.17	0.3029
Arrowtooth flounder	0.0054 (-0.0389 – 0.0497)	0.8071	-0.3928 (-0.8328 – 0.0472)	0.0786	0.11	0.1086
Slender sole	0.0203 (-0.0752 – 0.1158)	0.6653	0.1421 (-0.7919 – 1.0761)	0.7570	0.01	0.8968
Other flatfishes	-0.0158 (-0.0826 – 0.0509)	0.6292	-0.4737 (-1.1890 – 0.2416)	0.1847	0.07	0.4068

Paper VIII

"The effect of artificial illumination on Chinook salmon behavior and their escapement out of a midwater trawl bycatch reduction device"

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The effect of artificial illumination on Chinook salmon behavior and their escapement out of a midwater trawl bycatch reduction device

Mark J.M. Lomeli[a,*], W. Waldo Wakefield[b,1]

[a] Pacific States Marine Fisheries Commission (PSMFC), 2032 SE OSU Drive, Newport, OR 97365, USA
[b] Fishery Resource Analysis and Monitoring Division, Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 2032 SE OSU Drive, Newport, OR 97365, USA

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ABSTRACT

The Pacific hake (*Merluccius productus*) midwater trawl fishery is the largest groundfish fishery off the U.S. West Coast by volume. Catches comprise mainly Pacific hake, however, bycatch of Chinook salmon (*Oncorhynchus tshawytscha*) can be an issue affecting the fishery as Endangered Species Act (ESA) listed Evolutionarily Significant Units represent a portion of the total Chinook salmon bycatch. We conducted two separate experiments evaluating the influence of artificial illumination on Chinook salmon behavior and their escapement out a bycatch reduction device (BRD) in a Pacific hake midwater trawl. In Experiment 1, we tested whether Chinook salmon could be attracted out specific escape windows of a BRD equipped with multiple escape windows using artificial illumination. In Experiment 2, we compared Chinook salmon escapement rates out of the BRD between tows conducted with and without artificial illumination to determine if illumination can enhance their escapement. Our results show that artificial illumination can influence where Chinook salmon exit out of the BRD, but also demonstrate that illumination can be used to enhance their escapement overall. As conservation of ESA-listed Chinook salmon is an ongoing management priority, our research contributes new information on how artificial illumination can minimize adverse interactions between the Pacific hake fishery and Chinook salmon.

1. Introduction

Along the U.S. West Coast there are 17 Evolutionarily Significant Units (ESUs) identified for Chinook salmon (*Oncorhynchus tshawytscha*). Of these ESUs, two are listed as “endangered” and seven as “threatened” under the U.S. Endangered Species Act (ESA) (National Marine Fisheries Service, West Coast Region (NMFS WCR, 2017a). As these ESA-listed Chinook salmon ESUs intermix with other fish populations, commercial fisheries targeting healthy fish stocks can be restricted at times to ensure catches of ESA-listed Chinook salmon do not exceed conservation thresholds. Aside from a directed Chinook salmon troll fishery and a limited river gillnet fishery, Chinook salmon catches are prohibited in West Coast commercial fisheries.

The Pacific hake (*Merluccius productus*), also known as Pacific whiting or whiting, midwater trawl fishery is the largest groundfish fishery off the U.S. West Coast by volume. Over the past five years, annual landings of Pacific hake have averaged 259,805 MT (Pacific Fisheries Information Network (PacFIN, 2019). Catches comprise mainly Pacific hake (typically > 95% by volume), however, bycatch of Chinook salmon can be an issue affecting the fishery as ESA-listed ESUs represent a portion of the total Chinook salmon bycatch. The current ESA biological opinion issued for the West Coast groundfish fishery addresses the potential effects of Chinook salmon bycatch in the Pacific hake fishery by restricting the annual bycatch of Chinook salmon to 11,000 individuals (National Marine Fisheries Service, West Coast Region (NMFS WCR, 2017a). If this bycatch threshold is exceeded, then conservation measures such as the Ocean Salmon Conservation Zone (OSCZ) may be implemented. The OSCZ is a zone shoreward of a boundary line that approximates the 183 m (100 fathom) depth contour where Pacific hake fishing vessels are prohibited from trawling. In 2014, the fishery exceeded the 11,000 Chinook salmon bycatch threshold resulting in the implementation of the OSCZ (National Marine Fisheries Service, West Coast Region (NMFS WCR, 2014), which affected the fleet's access to the Pacific hake stock. As ocean distributions of Chinook salmon and Pacific hake can overlap, interactions between Pacific hake trawl gear and Chinook salmon are likely to remain an issue for the fishery. Hence, developing techniques that minimize Chinook salmon bycatch are important to fishers, management, and the

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[*] Corresponding author.
E-mail address: mlomeli@psmfc.org (M.J.M. Lomeli).
[1] Present affiliation: Oregon State University, Cooperative Institute for Marine Resources Studies, 2030 SE Marine Science Drive, Newport, OR 97365, USA.

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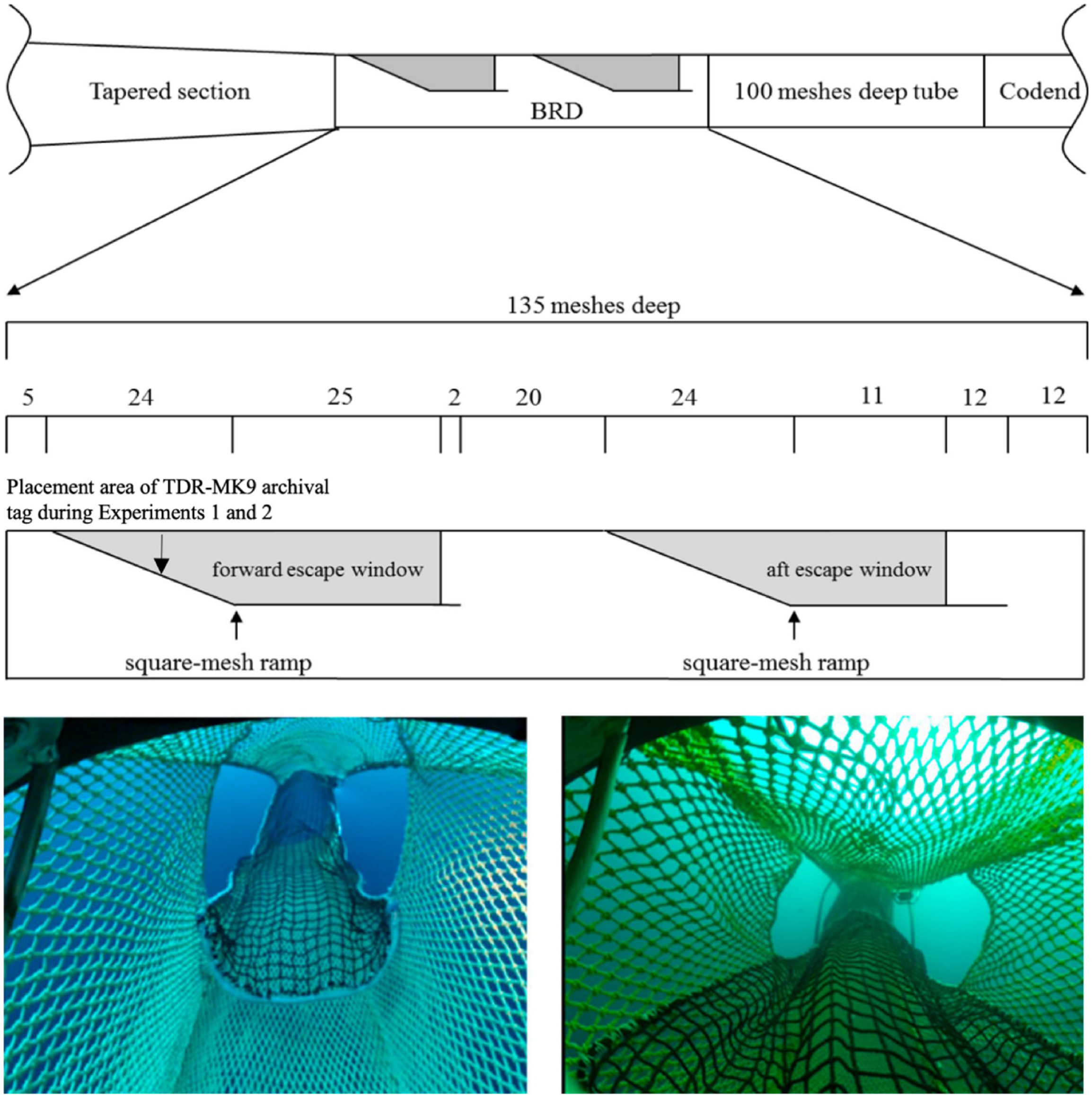

Fig. 1. Schematic diagram of the open escape window BRD tested in Experiment 1 and 2 (top); forward view of the forward set of escape windows under ambient light (left image); forward view of the aft set of escape windows under ambient light (right image). Note: diagram not to scale.

conservation of ESA-listed Chinook salmon.

Use of artificial illumination to reduce fish bycatch in trawl fisheries has recently received considerable attention (Hannah et al., 2015; Larsen et al., 2017, 2018; Grimaldo et al., 2018; Lomeli et al., 2018a,b; Melli et al., 2018). These studies have mostly used illumination as a technique to enhance fishes' visual perception of trawl gear components and escape areas. In the ocean shrimp (*Pandalus jordani*) trawl fishery, researchers have placed LEDs along trawl fishing lines to illuminate open spaces between the fishing line and groundline, and observed significant catch reductions for eulachon (*Thaleichthys pacificus*), juvenile rockfishes (*Sebastes* spp.), and flatfishes without impacting ocean shrimp catches (Hannah et al., 2015; Lomeli et al., 2018a). Comparing an unilluminated trawl to a trawl with an illuminated headrope in the U.S. West Coast groundfish bottom trawl fishery, Lomeli et al. (2018b) found that the illuminated trawl caught significantly fewer sablefish (*Anoplopoma fimbria*) and Dover sole (*Microstomus pacificus*). Catches of other groundfishes did not differ between the two trawls. Research has also used illumination in efforts to startle fish towards mesh sorting panels. For example, in the Barents Sea demersal trawl fishery, Grimaldo et al. (2018) positioned LEDs on lines with floats in the center of a square mesh section (creating a moving effect of the stimuli and a physical barrier) in efforts to improve the release efficiency for smaller-sized cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) by startling them towards the square mesh netting. Findings showed haddock displayed an erratic behavioral response to the illumination and reacted by swimming quickly either towards the square mesh netting or the codend. When interacting with the square mesh netting, however, they were not optimally oriented for escapement. Cod, on the other hand, did not display a noticeable behavioral response to the illumination and continued to move aft towards the codend.

In the Pacific hake fishery, Lomeli and Wakefield (2012) conducted research on a bycatch reduction device (BRD) that is similar to the design that is subject of the current study. Video camera systems outfitted with LED lights were used to measure fish escapement out the BRD. While the study was not focused on the effect of artificial illumination on fish behavior and escapement rates, they found that a significant proportion of Chinook salmon exited out of an escape window where artificial illumination was directed towards. These observations suggested that artificial illumination could potentially be used to reduce Chinook salmon bycatch.

The objectives of this study were to: 1) test whether artificial illumination can influence which escape window Chinook salmon utilize when exiting a BRD, and 2) determine if artificial illumination can enhance Chinook salmon escapement overall.

2. Materials and methods

We carried out two experiments aboard the *F/V Miss Sue*, a 24.7 m long, 640 horsepower trawler out of Newport, Oregon. Experiment 1 occurred off Oregon between 43°30′ and 45°09′N and between 124°17′ and 124°55′W in September 2015, whereas Experiment 2 occurred off Oregon between 43°37′ and 45°33′N and between 124°01′ and 124°57′W in May and November 2017. We used the commercial trawler's midwater trawl which had a headrope, footrope, and mouth opening measurement of 125, 164, and 36 m, respectively. Both experiments were conducted between sunrise and sunset hours at an average seafloor depth of 195 m and average headrope fishing depth of ca. 135 m (measured using a Wesmar TCS series trawl sonar). Towing speed ranged from 2.7 to 3.2 knots.

2.1. BRD design

The BRD was built around a four-seam tube of Euroline premium diamond netting 102 mm knot-to-knot nominal mesh size (6.0 mm single twine) that was 135 meshes long and 136 meshes in circumference, excluding meshes in each selvedge. This BRD design consisted of two Ultra Cross knotless square mesh netting ramps of 108 mm center-to-center nominal mesh size (800 ply) that were inserted inside the BRD tube of netting. The square mesh ramps are designed to guide actively swimming fish toward two large sets of escape windows cut out of each side of the net on the upper portions of the port and starboard side panels (Fig. 1).

In Experiments 1 and 2, we attempted to make several tows each day to increase the probability of encountering Chinook salmon and obtaining the data needed to answer our research questions. However, this created logistical difficulties for sampling catches of Pacific hake aboard a catcher vessel. Specifically, 1) single tow catches of Pacific hake often occur in volumes too large (e.g., > 30 MT) to weigh at sea using fish baskets (48 × 48 × 43 cm, L × W × H) and require delivering to a shore-side processing plant (a transit upwards to 8 h depending on fishing location) where the catch data can be quantified, and 2) the vessel's fish holds are typically not configured to separate catches beyond one or two tows. Considering these factors and vessel time, we elected not to retain and deliver Pacific hake to a shore-side processing plant for data processing. Further, not focusing on quantifying Pacific hake escapement in this study was based on prior gear trials (conducted by the current authors) that have shown Pacific hake lack the ability to escape out of this BRD design in meaningful numbers. When testing this BRD design in the absence of artificial illumination, the mean escapement of Pacific hake was found to be < 2% by weight (Table 1). Under conditions where this BRD design was tested in the presence of illumination, video observations showed Pacific hake rarely escaped (Lomeli and Wakefield, 2012; PSMFC unpubl. data 2014). Supplementary Video 1 shows footage of Pacific hake and their behavior as they encounter this BRD design in the presence of illumination (PSMFC, unpubl. data 2014).

2.2. Artificial illumination

Lindgren-Pitman Electralume® blue LED fishing lights, wavelength centered on 464 nm (Nguyen et al., 2017), were used as the artificial light source. Blue colored LEDs were selected as this wavelength transmits the furthest in water and the predominant spectral component of coastal and continental shelf waters in this region is blue-green light (Jerlov, 1976; Bowmaker, 1990; Schweikert et al., 2018). In both experiments, the lights were grouped into clusters of two andattached

Table 1
Pacific hake catch by weight (MT) from 2011 gear trials using a recapture net to evaluate the catch performance of the BRD presented in Fig. 1 under fishing conditions without LEDs on the BRD.

Trip	No. of tows	Pacific hake catch totals		
		Recapture net	Trawl codend	Codend retention (%)
1	2	1.35	111.35	98.8
2	1	1.86	99.49	98.2
3	2	0.95	100.32	99.1
4	1	1.51	87.83	98.3
5	1	0.86	96.05	99.1
6	2	0.86	104.39	99.2
7	1	0.21	36.61	99.4
8	1	0.86	44.49	98.1
9	2	1.01	113.36	99.1
Total	13	9.47	793.89	98.8

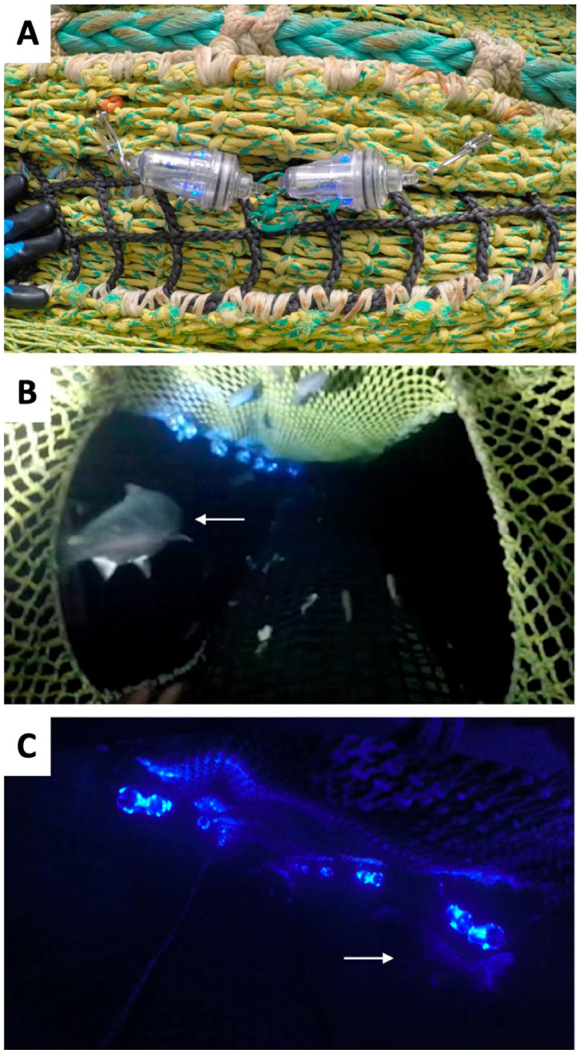

Fig. 2. Image of an LED cluster attached to the trawl netting in a horizontal position with the light-emitting end pointing forward (image A); forward view with LEDs attached along the port-side of the BRD of the forward escape window and a Chinook salmon exiting the BRD in Experiment 1 (image B); forward view with LEDs along port and starboard side forward escape windows and a Chinook salmon exiting the BRD in Experiment 2 (image C). Arrows depict Chinook salmon en route of exiting out of the BRD.

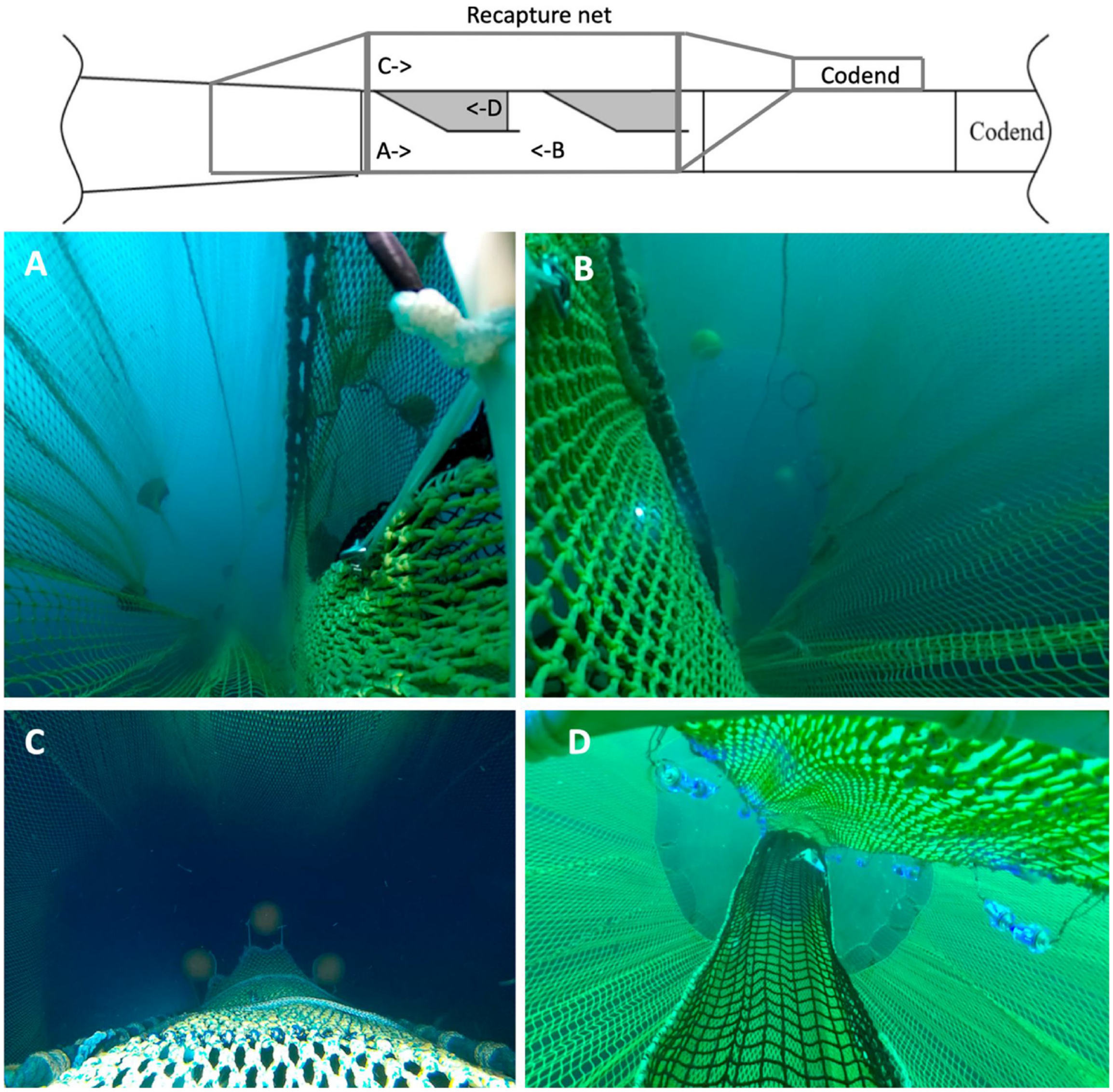

Fig. 3. Schematic diagram and images under ambient light examining the recapture net over the BRD in Experiment 2. Port-side aft view from outside of the BRD (image A); starboard-side forward view from outside of the BRD (image B); top panel aft view from outside the BRD (image C); forward view of the forward set of escape windows from within the BRD (image D). Note: diagram not to scale.

to the trawl netting in a horizontal position with the light-emitting end pointing forward (Fig. 2, image A) upon deployment and then removed upon retrieval to avoid damage when winding the trawl onto the net reel. Attachment points were marked with twine to assure that the placement of the LEDs was consistent on all tows.

In each experiment, a Wildlife Computers TDR-MK9 archival tag was used (attached to the front center section of the forward square mesh ramp and facing upward) to measure the amount of light available (Fig. 1). The calibration function used to convert the MK9 relative light units to irradiance units was:

$$y = 1 \times 10 - 9e^{0.1476x} \qquad (1)$$

where x is the relative light unit from the MK9 and y is the corresponding irradiance unit in μmol photons m^{-2} s^{-1} (Lomeli et al., 2018a).

2.3. Experiment 1: illuminating specific escape windows

To test whether artificial illumination could attract Chinook salmon out specific escape windows of the BRD, we attached clusters of LEDs inside the net along the outer edge of the top panel of either the port or starboard side escape windows (Fig. 2, image B). For example, if the port side was selected for illumination then the LEDs would only be attached along the forward and aft escape windows of the port side. The sequence in which the port and starboard side escape windows were illuminated was randomly selected. The LEDs were attached ca. 61 cm apart over the distance of the escape windows (Fig. 2, image B). Because the forward and aft sets of escape windows differ in length, this attachment distance resulted in 8 LED clusters along a forward escape window and 6 LED clusters along an aft escape window.

We used a video camera system at each escape window to observe fish behavior and escapement. Because the LEDs alone could not provide enough illumination for the cameras to produce an image of useable quality for identifying fish, we integrated a DeepSea Power and Light nano Sealite® white LED (color temperature = 6500–8000 K; lumens = 700; beam pattern 70° flood) with each camera system to obtain video of suitable quality. Each camera system was mounted on an ultra-high-molecular-weight board (60.9 × 30.4 × 2.5 cm, L × W × H) and placed in the same location on all tows inside the trawl against the center of the trawl top panel just aft of the escape openings. To avoid illuminating one side of the trawl more than the other with the nano

Table 2
Chinook salmon catch data for Experiment 1 tows where specific escape windows were illuminated. S = starboard; P = port; values in parentheses represent 95% confidence intervals surrounding the mean value; *p*-values in bold represent significant values.

Tow	LED side	No. observed	No. to exit the BRD	% to exit the BRD	No. of escapes that occurred out an LED window	% of escapes to occurred out an LED window	*p*-value
1	S	117	84	71.8	73	86.9	**< 0.0001**
2	P	6	0	0	0	0	n/a
3	P	0	–	–	–	–	–
4	S	11	6	54.5	5	83.3	0.1003
5	P	51	34	66.7	27	79.4	**< 0.0001**
6	S	25	19	76.0	16	84.2	**0.0002**
7	P	3	3	100.0	3	100.0	0.2482
8	S	12	5	41.7	5	100.0	0.0736
9	P	34	24	70.6	21	87.5	**< 0.0001**
10	S	27	17	63.0	14	82.4	**0.0015**
11	S	11	9	81.8	6	66.7	0.4795
12	P	38	24	63.2	17	70.8	**0.0433**
13	P	11	8	72.7	6	75.0	0.2207
14	S	53	45	84.9	38	84.4	**< 0.0001**
15	P	15	7	46.7	6	85.7	**0.0308**
16	S	24	14	58.3	6	42.9	0.7871
Total		438	299	68.3 (63.8–72.4)	243	81.3 (76.5–85.3)	**< 0.0001**

Sealite®, the light was positioned along the midline of the BRD. Thus, the only modification in the placement of artificial illumination between tows were the blue LEDs mounted along the BRD escape windows (Supplementary Video 2).

Tow durations were set to 3.5 h. to maximize video recording time. After each tow, codend catches were dumped on deck and sorted for Chinook salmon. Escapement rates were subsequently measured from combining the video and trawl codend catch data.

A one proportion Z test was used to examine whether the proportion of Chinook salmon to exit out an illuminated escape window was significantly greater than the proportion of Chinook salmon to exit out a non-illuminated escape window:

$$Z = \frac{\hat{p} - p_o}{\sqrt{\frac{p_o(1-p_o)}{n}}} \tag{2}$$

where $\hat{p}$ is the observed proportion, p_O is the null hypothesized proportion (0.5), and n is the sample size.

2.4. Experiment 2: comparing tows with and without artificial illumination

To determine the effect that illumination had on the overall escapement of Chinook salmon, we conducted tows with and without artificial illumination on the BRD. The only source of artificial illumination used in this experiment were the blue LED fishing lights. The sequence in which the trawl was fished with and without artificial illumination was randomly selected. When fishing with LEDs, all escape windows were illuminated (Fig. 2, image C). Seven LED clusters were used on each forward escape window, whereas 5 LED clusters were used on each aft escape window.

We used a recapture net with its main body constructed of Euroline premium diamond netting of 102 mm knot-to-knot nominal mesh size (3.5 mm single twine) to enumerate fish escapement out the BRD. The recapture net codend and trawl codend were also made of Euroline premium diamond netting of 102 mm knot-to-knot nominal mesh size, but with 6.0 mm single twine. A combination of trapezoidal-shaped kites (0.95 cm thick conveyor belt material; dimensions = 61 × 31 × 31 cm) and 28 cm diameter floats were used to spread and lift the recapture net open. Before data was collected, video camera systems with LED lights were used to confirm that the recapture net was performing as expected and not masking the BRD escape windows (Fig. 3; Supplementary Video 3). Once data collection began, the blue LEDs were the only source of artificial illumination present.

Tow durations were set to 1.5 h. to maximize the number of tows conducted. After each tow, the entire recapture net catch was dumped on deck and sorted for bycatch of Chinook salmon and rockfishes. All other fish from the recapture net were then discarded. Subsequently the trawl codend was progressively hauled onboard where the catch was gradually dumped on deck and sorted for Chinook salmon and rockfishes, and then discarded. Catches of Chinook salmon and rockfishes between the two codends were then sampled with fork length (cm) data collected on Chinook salmon and total weight (kg) data collected on rockfishes.

A Student's *t*-test was used to: 1) examine whether the proportion of Chinook salmon to exit the BRD when artificial illumination was present was significantly greater than the proportion of Chinook salmon to exit the BRD when artificial illumination was absent, and 2) analyze the Chinook salmon length data and rockfish weight data.

3. Results

3.1. Experiment 1: illuminating specific escape windows

Chinook salmon were encountered in 15 of the 16 tows conducted. In this experiment, interactions with Chinook salmon were exceptionally high, which was likely a result from increased Chinook salmon ocean abundances occurring in 2015 compared to previous years (Pacific Fishery Management Council (PFMC, 2018).

We observed 438 Chinook salmon, of which 299 individuals escaped (68.3%, 95% confidence interval [CI] = 63.8–72.4%). Of the 299 Chinook salmon to escape, 243 individuals exited out a window that was illuminated (81.3%, 95% CI = 76.5–85.3%) (Table 2). The proportion of Chinook salmon exiting out of an illuminated escape window was significantly greater ($p < 0.0001$) than the proportion to exit out a non-illuminated escape window. These data demonstrate the ability of blue LED lights, placed along specific escape windows, to influence Chinook salmon escapement.

Chinook salmon exhibited various behaviors while encountering the BRD. For example, some individuals would enter the BRD and immediately burst towards and out an illuminated window and continue to swim away from the trawl, whereas others would gradually move towards and out an illumination window then swim alongside the trawl (one individual was noted to swim alongside the trawl for ca. 10 min.) before swimming away. On a few occasions, individuals would be swimming towards and out a non-illuminated window before changing direction and swimming across the BRD tube to exit out an illuminated window. On one occurrence, a Chinook salmon was noted to feed on a shortbelly rockfish (*S. jordani*).

Additional fish species observed, but encountered in numbers too large to enumerate escapement, included Pacific hake, Pacific herring (*Clupea pallasii*), and widow (*S. entomelas*), yellowtail (*S. flavidus*), shortbelly, canary (*S. pinniger*), and redstripe (*S. proriger*) rockfishes. When in the BRD area, Pacific herring and shortbelly rockfish would usually swim upwards and school near the top panel of the net until haulback, at which time they would exit out the BRD in large numbers. Widow, yellowtail, and canary rockfishes moved throughout the BRD area before either exiting out the BRD or drifting back to the codend. Observations of Pacific hake (fish ca. 20–30 cm in length) were of fish either actively swimming, but unable to swim forward enough to exit out the BRD, or tumbling or passively drifting back towards the codend.

The mean light level during this experiment was $3.3\mathrm{e}^{-02}$ (SE ± $2.6\mathrm{e}^{-03}$) μmol photons $\mathrm{m}^{-2}\ \mathrm{s}^{-1}$ and ranged from $4.1\mathrm{e}^{-05}$ to $9.4\mathrm{e}^{-01}$ μmol photons $\mathrm{m}^{-2}\ \mathrm{s}^{-1}$.

Various video footage of Chinook salmon, Pacific hake, Pacific herring, yellowtail, shortbelly, and redstripe rockfishes, and jack mackerel (*Trachurus symmetricus*) observed during Experiment 1 can be viewed in Supplementary Video 2.

3.2. Experiment 2: comparing tows with and without artificial illumination

A total of 39 tows were completed. In contrast to Experiment 1, estimated Chinook salmon ocean abundances in 2017 were exceptionally low (Pacific Fishery Management Council (PFMC, 2018), which likely contributed to the small sample size for Chinook salmon during the second experiment.

For tows conducted with artificial illumination, 24 Chinook salmon encountered the BRD with escapement occurring in 18 of those individuals, a mean escapement rate of 75.0% (95% CI = 56.3–93.6%) (Table 3). During tows made without artificial illumination, 38 Chinook salmon encountered the BRD with escapement occurring in 20 of those individuals, a mean escapement rate of 52.6% (95% CI = 35.9–69.2%) (Table 3). Overall, the proportion of Chinook salmon to exit the BRD when artificial illumination was present was significantly greater ($p = 0.0362$) than the proportion to exit the BRD when artificial illumination was absent.

Table 3
Chinook salmon catch data for Experiment 2 for tows with and without artificial illumination. Values in parentheses represent 95% confidence intervals surrounding the mean value.

	With artificial illumination			Without artificial illumination		
Tow	No. in trawl	No. in recapture net	% escapement	No. in trawl	No. caught in recapture net	% escapement
1	4	4	50.0	–	–	–
4	–	–	–	0	2	100.0
9	–	–	–	2	7	77.8
11	–	–	–	4	5	55.6
14	–	–	–	2	2	50.0
15	0	1	100.0	–	–	–
16	0	1	100.0	–	–	–
17	1	0	0.0	–	–	–
19	–	–	–	2	0	0.0
21	0	1	100.0	–	–	–
22	–	–	–	1	0	0.0
23	0	4	100.0	–	–	–
27	0	1	100.0	–	–	–
28	–	–	–	0	2	100.0
32	0	1	100.0	–	–	–
35	0	4	100.0	–	–	–
36	–	–	–	2	0	0.0
37	0	1	100.0	–	–	–
38	–	–	–	5	2	28.6
39	1	0	0.0	–	–	–
Total	6	18	75.0 (56.3–93.6)	18	20	52.6 (35.9–69.2)

The mean length of Chinook salmon caught between the recapture net and codend when artificial illumination was present was 59.7 cm (SE ± 3.2) and 67.1 cm (± 4.4), respectively. This difference in mean length was not significant ($p = 0.2017$). When artificial illumination was absent, the mean length of Chinook salmon caught between the recapture net and the codend was 70.4 cm (± 3.4) and 55.7 cm (± 2.9), respectively. This difference in mean length was significant ($p = 0.0026$).

Five rockfish species were caught, however, only two of these species (widow and yellowtail rockfishes) occurred in trawls made with and without artificial illumination. Due to the limited sample size, no statistical analysis of escapement between tows made with and without artificial illumination could be performed for these two species. For all rockfish catches combined, the overall mean percent escapement (by weight) between tows with and without artificial illumination was 45.8% (95% CI = 43.3–48.2%) and 47.9% (95% CI = 41.8–54.3%), respectively (Table 4). The presence of artificial illumination did not have a significant effect on rockfishes' escapement out of the BRD ($p > 0.05$).

The mean light level for tows made with artificial illumination was $1.0\mathrm{e}^{-01}$ (SE ± $2.9\mathrm{e}^{-02}$) μmol photons $\mathrm{m}^{-2}\ \mathrm{s}^{-1}$ and ranged from $1.4\mathrm{e}^{-02}$ to $2.9\mathrm{e}^{-01}$ μmol photons $\mathrm{m}^{-2}\ \mathrm{s}^{-1}$. For tows made without artificial illumination, the mean ambient light level decreased to $4.6\mathrm{e}^{-03}$ (± $2.7\mathrm{e}^{-03}$) μmol photons $\mathrm{m}^{-2}\ \mathrm{s}^{-1}$ and ranged from $6.1\mathrm{e}^{-06}$ to $2.4\mathrm{e}^{-02}$ μmol photons $\mathrm{m}^{-2}\ \mathrm{s}^{-1}$.

Various video footage of the recapture net surrounding the BRD, and Chinook salmon and Pacific herring interacting with the gear can be viewed in Supplementary Video 3.

4. Discussion

In our experiments, we influenced the behavior and escapement of Chinook salmon out a BRD using artificial illumination. In Experiment 1, we demonstrated the ability of artificial illumination to influence their escapement out specific windows of the BRD. Specifically, the proportion of Chinook salmon to exit out of an illuminated escape window was significantly greater than the proportion to exit out a non-illuminated escape window. One explanation for this observed behavior is having illumination along one side of the BRD hinders their ability to perceive the environment outside the BRD on the other side. Thus, deterring them away from non-illuminated escape windows and towards illuminated escape windows where they can better perceive the environment outside the trawl. Findings from this experiment supports previous research by Lomeli and Wakefield (2012) suggesting that illumination can influence where Chinook salmon exit out of a BRD. In Experiment 2, our results showed the proportion of Chinook salmon to exit the BRD when artificial illumination was present was significantly greater than the proportion to exit the BRD when artificial illumination was absent. Although this result was moderate in effect, a significant difference was still noted while having a small sample size of Chinook salmon.

Prior to our research, studies using artificial illumination inside trawls have been unsuccessful at reducing bycatch (Hannah et al., 2015; Larsen et al., 2017, 2018; Grimaldo et al., 2018; Melli et al., 2018). The studies that have demonstrated the ability to reduce fish catches using artificial illumination have occurred in the front part of the trawl (Hannah et al., 2015; Lomeli et al., 2018a,b). While our study found that use of artificial illumination inside the trawl can reduce Chinook salmon bycatch, the endurance and strong swimming ability of Chinook salmon coupled with the BRD used in our experiments likely contributed to our successful results. As prior video observations (Lomeli and Wakefield, 2012) and catch data have noted that Pacific hake lack the ability to escape out of the BRD in meaningful numbers, the device is able to utilize escape windows with exceedingly large openings that span several meters in length. Further, the square mesh ramps used in the design create a large area above them where fish

Table 4
Total catch by weight (kg) for rockfishes between the recapture net and trawl codend for tows with and without artificial illumination along the BRD escape windows during Experiment 2. Values in parentheses represent 95% confidence intervals surrounding the mean value.

	With artificial illumination			Without artificial illumination		
Species	Trawl	Recapture net	% escapement	Trawl	Recapture net	% escapement
Darkblotched rockfish	17.7	14.5	45.0	–	–	–
Widow rockfish	33.2	91.7	73.4	9.3	7.0	42.9
Yellowtail rockfish	223.7	110.8	33.1	11.8	28.3	70.6
Chilipepper	–	–	–	113.4	88.6	43.9
Canary rockfish	602.5	522.8	46.5	–	–	–
Total	877.1	739.8	45.8 (43.3–48.2)	134.5	123.9	47.9 (41.8–54.3)

swimming forward can interact with the escape areas while avoiding contact with fish passing aft under the ramps. As Chinook salmon are attracted towards the illuminated area, these aspects of the BRD provide an easy opportunity for Chinook salmon to escape. An example where fish responded to artificial illumination stimuli, but were unable to escape as a result of the size of the escape opening occurred in the Grimaldo et al. (2018) study. In their research, they were able to direct haddock towards panels of square mesh netting using artificial illumination. However, haddock responded to the stimuli in an erratic behavior and upon contacting the netting they were positioned in an orientation that prevented escapement through the meshes.

In Experiment 2, 18 of the 24 Chinook salmon encountered when artificial illumination was present exited out of the BRD. From these data, the analysis showed larger-sized Chinook salmon occurred in the codend than the recapture net. However, this result was not significant and the small number of Chinook salmon retained in the codend (6 fish) was not a large enough sample size to make any conclusions on fish length and its effect on escapement in response to illumination. In contrast, a larger number of Chinook salmon were encountered when artificial illumination was absent (18 fish in the trawl codend vs. 20 fish in the recapture net). From catches when artificial illumination was absent, the length analysis showed Chinook salmon caught in the recapture net were on average significantly larger than Chinook salmon caught in the codend. This result suggests that fish length could potentially be a contributing factor to Chinook salmon escapement. Had the sample size of Chinook salmon encountered in Experiment 1 been encountered in Experiment 2, a length-dependent catch comparison analysis (Larsen et al., 2018; Lomeli et al., 2018a,b) could have been performed to determine if a difference in catch efficiency between non-illuminated to illuminated trawls is related to specific length classes. Further research investigating how length may affect fish escapement is needed.

In recent years, several overfished and rebuilding rockfish stocks have been rebuilt (e.g., darkblotched [*S. crameri*], widow, and canary rockfishes, Pacific Ocean Perch [*S. alutus*], and bocaccio [*S. paucispinis*]) along the U.S. West Coast (He et al., 2011; Thorson and Wetzel, 2016; He and Field, 2017; Wallace and Gertseva, 2017; Wetzel et al., 2017). These stock recoveries have resulted in an emerging midwater trawl rockfish fishery. However, there are management concerns on the potential impact that the fishery could have on Chinook salmon bycatch as many of the rockfish stocks targeted occur at depths were Chinook salmon bycatch rates are relatively high (National Marine Fisheries Service, West Coast Region (NMFS WCR, 2017b). Because the BRD we evaluated performed well at reducing Chinook salmon catches, its use as a salmon excluder in the midwater trawl rockfish fishery would likely create economic trade-offs between catch yields and bycatch reduction as considerable catch reductions (> 40% by weight) of rockfishes occurred both with and without artificial illumination on the BRD. As other designs of salmon excluders have been developed by the industry for use in the Pacific hake fishery, the designs are the same in concept as the BRD we tested (e.g., use of large open escape windows). Thus, developing new approaches (such as gear designs, use of other light colors, wavelengths, and/or patterns) and understanding their effects on rockfishes and Chinook salmon would provide critical information if Chinook salmon bycatch became an issue impacting the midwater trawl rockfish fishery.

While the mechanism(s) triggering Chinook salmon to exhibit the behaviors we observed in our experiments is unclear, the presence of artificial illumination appears to enhance their visual perception and their ability to perceive the contrast between the trawl gear and the surrounding environment that otherwise they would not be able to perceive as well under dark conditions. How Chinook salmon perceive and interact with this BRD under conditions when artificial illumination is absent is unclear. Further research using imaging sonar equipment such as ARIS (Adaptive Resolution Imaging Sonar) or DIDSON (Dual-Frequency Identification Sonar) to observe how Chinook salmon interact with this BRD under dark conditions could provide insights that could help improve our knowledge of what makes artificial illumination affective at reducing their bycatch.

The escapement of Pacific hake was not quantified in Experiment 2 due to logistical difficulties of sampling catches of Pacific hake aboard a catcher vessel. However, past gear trials (Lomeli and Wakefield, 2012; Table 1; PSMFC unpubl. data 2014) conducted under conditions with and without artificial illumination on this BRD design all indicate that Pacific hake lack the ability to escape out this BRD design in meaningful numbers. Nonetheless, we acknowledge that the BRD configuration used in Experiment 2 is different from the configurations tested in past sea trials and that the BRD configuration used in Experiment 2 may produce different results. Thus, research quantifying the effect of artificial illumination on Pacific hake escapement out the BRD tested in Experiment 2 is needed to determine if this gear configuration performs similarly to the other configurations tested.

In summary, our research demonstrated that artificial illumination can influence where Chinook salmon exit out of the BRD we tested, and that illumination can be used to enhance their escapement overall. These results contribute new information on how artificial illumination can minimize adverse interactions between the Pacific hake fishery and Chinook salmon. Improving gear selectivity and reducing the level of Chinook salmon bycatch would also contribute to the conservation and management of ESA-listed Chinook salmon. Lastly, while our research has regional impacts, our findings may have potential applications in the Bering Sea walleye pollock (*Gadus chalcogrammus*) midwater trawl fishery, and in the Icelandic pelagic mackerel (*Scomber scombrus*) trawl fishery where salmon bycatch also occurs (Stram and Ianelli, 2015; Olafsson et al., 2016).

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fishres.2019.04.013.

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