Evaluating Off-Bottom Sweeps of a U.S. West Coast Groundfish Bottom Trawl: Effects on Catch Efficiency and Seafloor Interactions

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Abstract

In the U.S. West Coast groundfish bottom trawl fishery, lengthy sweeps (>85 m) that maintain seafloor contact are traditionally used. While these sweeps are effective at herding groundfishes, their bottom tending characteristics increase the potential to cause seafloor disturbances, and injury and unobserved mortality to benthic organisms. In this study, we examined if changing from conventional to modified sweeps (with sections elevated 6.5 cm off bottom) would affect catch efficiency of target groundfishes and seafloor interactions. We used a DIDSON imaging sonar to observe how each sweep configuration interacted with the seafloor. An altimeter was periodically placed on the modified sweep to measure height off bottom. Results detected no significant catch efficiency effect of changing from conventional to modified sweeps. The DIDSON and altimeter data showed the modified sweeps exhibit elevated sections where infaunal and lower-profile epifaunal organisms can pass under without disturbance. Results demonstrate that seafloor interactions can be substantially reduced using elevated sweeps in this fishery without impacting catch efficiency. Further, findings from this research could be potentially applicable to other fisheries nationally and internationally.

Introduction

The U.S. West Coast limited entry (LE) groundfish bottom trawl fishery is managed under Individual Fishing Quotas (IFQ) (PFMC and NMFS, 2011, 2015). The IFQ program provides the option to catch quota using trawl or fixed gear for selected species, but most participants fish with bottom trawls as this method is the most efficient technique for harvesting assemblages of groundfishes (e.g., Dover sole [*Microstomus pacificus*], petrale sole [*Eopsetta jordani*], sablefish [*Anoplopoma fimbria*], lingcod [*Ophiodon elongatus*])

Over the continental shelf and shelf break of the U.S. west coast, fishers engaged in the LE bottom trawl fishery target a variety of groundfishes over low-relief trawlable habitats consisting of a range of indurations (e.g., mud/sand, mixed mud-rock). Trawls outfitted with lengthy sweeps (>85 m in length) designed to maintain seafloor contact and herd groundfishes towards the trawl mouth, are used. While the conventional sweep is highly effective at herding groundfishes, their long lengths and bottom tending characteristics increase the potential to cause habitat disturbances, and injury and unobserved mortality to non-target benthic-dwelling organisms. Over soft-bottom habitats of this fishery, Dungeness crab (*Metacarcinus magister*), urchins (Echinoidea), polychaete worms (Polychaeta), sponges (Porifera), burrowing brittle stars (Amphiuridae), sea whips (*Stylatula* spp., *Halipterus* spp.), and sea pens (*Ptilosarcus*) are some of the more prominent macroinvertebrates present (Hixon and Tissot, 2007; Hannah et al., 2010; Hemery and Henkel, 2015; Hemery et al., 2018). In the groundfish bottom trawl fishery, reducing disturbances and physical impacts to the seafloor by trawling has been a management priority, resulting in footrope diameter restrictions, and trawl area closures to protect essential fish habitat (Hannah, 2003; NOAA, 2016, 2018; PFMC, 2018).

Conventional sweeps are known to play a significant role in herding demersal fishes, particularly flatfishes, towards the trawl mouth (Ryer and Barnett, 2006; Ryer, 2008; Ryer et al., 2010; Winger et al., 2010). However, because of their long length (> 85 m), they constitute the most significant portion of the ground gear that contacts the seafloor along the towline for any given trawl event. Thus, modifications to sweeps could have the greatest affect at reducing seafloor-gear interactions. In an eastern Bering Sea flatfish fishery, Rose et al. (2010a) and Ryer et al. (2010) evaluated if raised sweeps could effectively herd flatfishes (e.g., yellowfin sole [*Limanda aspera*], northern rock sole [*Lepidopsetta polyxystra*], flathead sole [*Hippoglossoides* *elassodon*], arrowtooth flounder [*Atheresthes stomias*]). Comparing conventional sweeps to sweeps with raised sections of 5, 7.5, and 10 cm off bottom, they showed flatfish catches during the day were not impacted until the sweeps were raised to 10 cm. At night, catches between the conventional and 10 cm elevated sweep did not differ (Ryer et al., 2010). In the Bay of Biscay, Guyonnet et al. (2008) demonstrated the ability to reduce benthic community disturbances without impacting target catch compositions using innovative sweeps constructed of dyneema rope and drop chains. In the Barents Sea Artic cod (*Gadus morhua*) fishery, a more substantial sweep modification was tested where Sistiaga et al. (2015) evaluated a semi-pelagic trawl with sweeps lifted entirely off bottom. They found herding of cod was negatively impacted as the lifted sweep design caught 33% fewer cod than the conventional sweep. In the U.S. west coast multi-species bottom trawl fishery, the efficacy of modified sweeps has not been tested.

The objectives of this study were: 1) compare the catch efficiency of demersal groundfishes between conventional and modified sweeps with elevated sections across their length, 2) examine how the sweeps interact with the seafloor, and 3) evaluate the potential efficacy of modified sweeps in the U.S. West Coast groundfish bottom trawl fishery.

Materials and Methods

Sea Trials and Sampling

Sea trials occurred aboard the *F/V Last Straw*, a 23.2 m long, 540-hp trawler. Tows were conducted off Oregon between 29 July and 13 August 2018 (Fig. 1). A single trawl was used in this study with the sweeps being the only change in gear configuration. The conventional sweeps (*control*) and modified sweeps (*treatment*) were fished in a predetermined random alternating order following Sistiaga et al. (2015). After each tow, fishes were sorted in baskets to species, weighed using a motion compensated platform scale, and then measured. Subsampling was avoided when possible; however, time constraints and relatively large catches often required subsampling for length measurements. When subsampling occurred, every third to fourth sorted basket was set aside for length measurement with a maximum of 10 baskets set aside for length measurements.

The conventional sweeps consisted of three sections each ca. 30.5 m in length of 1.9 cm steel cable covered with continuous 7.5 cm rubber disks to create an overall length of 91.4 m (Fig. 2 top image). The sweep sections were connected by hammer locks. The modified sweeps consisted of, for each of the two sweeps, three sections each ca. 30.5 m in length, of 4.8 cm combination wire (steel cable covered with polyethylene fiber) with ten 17.8 cm diameter disc clusters spaced at 8.2 m intervals along their overall length of 91.4 m. In concept, this design elevates over 95% of the sweep off bottom with a nominal height above the seafloor between the disc clusters of 6.5 cm. Where the sweep sections connected, chain was run through the disc clusters and connected by hammer locks (Fig. 2 middle image). To secure the disc clusters where they were positioned directly on the combination wire, steel cable was placed through the disc clusters and interlaced through the combination wire fore and aft of the disc clusters (Fig. 2 bottom image). A two-seam Eastern 400 low-rise selective flatfish trawl was used (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. Thyborøn type-11 standard doors were used to spread the trawl. Simrad PI spread sensors were used to measure door spread. The codend was a four-seam tube of 114 mm (6.0 mm double twine) T90 mesh that was 88 open meshes in circumference.

On seven tows, a mechanical altimeter was placed on the port modified sweep, centered between two disc clusters to measure height off bottom. The altimeter was fabricated from a mechanical arm integrated with a Onset Hobo Pendant® acceleration data logger that provided a continuous digital record of tilt angle. The sensor was positioned ca. 38 m forward of the trawl lower bridle in a customized bracket outfitted with a rod that extended from the sweep to the seafloor (Fig. 3). The tilt angle for the x-axis was converted to height using the following formula:

$$\text{Sweep height} = y \times \text{SIN}(x) \qquad (1)$$

where y is the length of the bracket (21.6 cm) and x is the tilt angle in the vertical plane perpendicular to the sweep.

To observe how each sweep configuration interacted with the seafloor, we towed a sled outfitted with a Sound Metrics ultrasonic Dual-frequency IDentification SONar (DIDSON), operating at 1.8 MHz, across trawl tracks at bottom depths between 192 and 205 m. The sled was towed with a 4:1 scope at a target speed of 1.8 km h^{-1} (1 knot). Sets of floats were clamped to the tow cable approximately 20 and 50 meters up from the sled to prevent the cable from disturbing the seafloor in the sled's path. The DIDSON was mounted to the sled with its acoustic lens 61 cm above the seafloor, tilted down ca. 4-degrees, and oriented horizontally providing a 29-degree field of view of the seafloor surface over a range from 2.5 to 12.5 m. The trawl tracks to be observed by the DIDSON imaging sonar were made within the Rockfish Conservation Area (an area closed to bottom trawling) to assure the tracks observed were from our trawls. Our original goal was to observe the trawl tracks one day after being made, however, mechanical issues and vessel availability did not allow us to observe the trawl tracks until 31 days afterwards. The DIDSON sled was towed from the *R/V Pacific Surveyor*, a 17.1 m long, 450 hp vessel.

Estimating relative catch efficiency between elevated and conventional sweeps

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., 2018a, 2018b).

Using the catch data, we wanted to determine whether there was a significant difference in the catch efficiency when using conventional (*control, c*) vs. the modified sweeps (*treatment, t*). We also wanted to determine if a difference in catch between the two sweeps designs was related to fish size. Specifically, to assess the effect of changing from conventional to modified sweeps on length-dependent catch efficiency, we used the method described in Herrmann et al. (2017). This method models the length-dependent catch comparison rate (CC_l) summed over tows:

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

where nc_{li} and nt_{lj} are the numbers of fish measured in each length class l for the conventional and the modified sweep in tow i and j, respectively. qc_i and qt_j are the related subsampling factors (fraction of the caught fish being length measured), and mc and mt are the number of tows carried out with the conventional and the modified sweep, respectively. Following Sistiaga et al. (2015), all tows were standardized in the analysis to have the same towing duration as the longest tow, 60 min. The functional form catch comparison rate $CC(l,\boldsymbol{v})$ (the experimental being expressed by equation 2), was obtained using maximum likelihood estimation by minimizing the following equation:

$$-\sum_l\left\{\sum_{i=1}^{mc}\left\{\frac{nc_{li}}{qc_i}\times ln\left(1.0-CC(l,\boldsymbol{v})\right)\right\}+\sum_{j=1}^{mt}\left\{\frac{nt_{lj}}{qt_j}\times ln\left(CC(l,\boldsymbol{v})\right)\right\}\right\} \qquad (3)$$

where $\boldsymbol{v}$ 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 conventional and the modified sweep and the number of tows are equal ($mc = mt$), the expected value for the summed catch comparison rate would be 0.5. In our study, the catch comparison rate is 0.51 as the number of tows between the conventional and modified sweep was unequal (26 vs 27). Therefore, this baseline can be applied to judge whether 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:

$$CC(l,\boldsymbol{v}) = \frac{exp\left(f(l,v_0,\ldots,v_k)\right)}{1+exp\left(f(l,v_0,\ldots,v_k)\right)} \quad (4)$$

where f is a polynomial of order k with coefficients v_0 to v_k. The values of the parameters $\boldsymbol{v}$ describing $CC(l,\mathbf{v})$ are estimated by minimizing equation (3), which are equivalent to maximizing the likelihood of the observed data. We considered f 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 multi-model inference to obtain a combined model (Burnham and Anderson, 2002; Herrmann et al., 2017).

The confidence interval (CI) for the catch comparison curves were estimated using a double bootstrapping method (Herrmann et al., 2017). This bootstrapping method accounts for the uncertainty in the estimation resulting from tow variation in catch efficiency and availability of fish as well as uncertainty about the size structure of the catch for the individual tows. By multi-model 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) CIs.

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

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

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

Based on (6) the percentage change in average catch efficiency by shifting from fishing with the conventional and the modified sweep was estimated by:

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

By incorporating $\Delta CR_{average}$ into each of the bootstrap iterations described above, we could assess the 95% CI for $\Delta CR_{average}$. We used $\Delta CR_{average}$ to provide a length-averaged value for the effect of changing from conventional to modified sweep on the catch efficiency.

Results

Towing occurred during daylight hours at an average bottom fishing depth of 171 m. Towing speed over ground ranged from 4.0 to 4.8 km h^{-1} (2.2-2.6 knots). Target tow duration was 60 min., however, some tows of 30 min. (4 tows) and 45 min. (7 tows) occurred due to time constraints and anticipated large catches. These tows were standardized in the analysis to the duration of 60 min. following Sistiaga et al. (2015).

Overall, 53 tows were completed: 26 tows with the conventional sweeps, and 27 tows with the modified sweeps. The mean door spread for the conventional and modified sweep configuration was 120.6 m (SE ±2.2) and 117.4 m (±2.5), respectively. Species caught in sufficient numbers for use in the catch efficiency analyses were petrale sole, rex sole (*Glyptocephalus zachirus*), Dover sole, sablefish, shortspine thornyhead (*Sebastolobus alascanus*), lingcod, and greenstriped rockfish (*Sebastes elongatus*) (Table 1).

In general, the modified sweep configuration on average caught more shortspine thornyhead, sablefish, lingcod, greenstriped rockfish, and petrale sole, but fewer Dover sole and rex sole than the conventional sweep configuration. However, these changes in average catch efficiency between the two sweep configurations were not significantly different (Fig. 4). The catch comparison analysis detected no significant length-dependent catch efficiency effect of changing from conventional to modified sweeps as shown by the 95% CIs of the mean $CC(l,\boldsymbol{v})$ for these species extending across the rate of 0.51 (Figs. 5 and 6). These results demonstrate that the catch efficiency for target groundfishes between the conventional and modified sweeps do not differ significantly from each other.

The DIDSON imaging sonar allowed us to detect and identify the disc cluster tracks on the seafloor and measure their distance between clusters and the width of the clusters tracks (Fig. 7 and Supplementary Video S1). Moving fore to aft along the sweeps length, the mean distance between the disc cluster tracks gradually increased from 3.36 m (SE ±0.08) to 4.93 m (±0.17) due to variation in the sweeps angle of attack. The overall mean distance between the disc cluster tracks was 3.91m (SE ±0.10). The mean width of the disc cluster tracks was ca. 22.5 cm (SE ±0.32; n = 105). This value estimates the area contacted by the disc clusters is ca. 4.9% of the total swept path. Between the disc clusters, the seafloor texture did not appear affected by the modified sweeps (Fig. 7 and Supplementary Video S1). For the seven tows that the sweep altimeter was placed on the sweep, the mean height off bottom measured was 6.3 cm (SE ±0.3) and ranged from 5.5 (±0.5) to 6.8 cm (±0.5). DIDSON imagery of the path swept by the conventional sweeps in general showed mild smoothing of the seafloor texture. However, this observation is qualitative.

Discussion

Bottom trawling has received considerable attention from fisheries management regarding its potential impact on habitat complexity, infaunal and epibenthic communities, and benthic productivity (Sciberras et al., 2017). In efforts to minimize trawl gear disturbances to the seafloor, trawl gear modifications such as doors that fish off bottom (He et al., 2002; He and Winger, 2010), elevated sweeps (Rose et al., 2010a; Ryer et al., 2010; Sistiaga et al., 2015), floating bridles (He et al., 2015), and trawls with lighter groundgear (He, 2007; He and Winger, 2010; Hannah et al., 2013) have been tested. In our study, we demonstrated the ability to raise ca. 95% of the sweeps of a west coast groundfish bottom trawl off bottom without significantly impacting the herding behavior and catches of target groundfishes (e.g., shortspine thornyhead, sablefish, Dover sole, petrale sole). Further, the DIDSON imagery and altimeter data show that sections of the sweeps are fishing several centimeters off bottom and capable of passing over infaunal organisms (i.e., polychatea) without sweep disturbance and lower-profile epifaunal (i.e., crabs, urchins) organisms without sweep contact. For higher-profile epifaunal organisms (>6.5 cm high) such as sea whips, sea pens, and sponges, the modified sweeps we tested would not eliminate interactions with these organisms as they would not be able to pass under the sweeps without contact. However, some data indicates that bottom trawl gear modified with elevated bobbins or discs can reduce negative disturbances to sea whips and other macroinvertebrates compared to conventional bottom tending gear (Rose et al., 2010b; Hannah et al., 2013).

In recent NOAA Fisheries mortality reports for the West coast groundfish bottom trawl fishery, Dungeness crab (a species supporting one of the west coast’s most valuable fisheries) annual discard mortalities have been ca. 190 mt (Bellman et al., 2013), and 150 mt (Somers et al., 2014). These estimates are from landed catches and likely under represent the level that Dungeness crab interact with conventional bottom trawl gear components. However, the degree unobserved interactions are occurring between bottom trawl gear and Dungeness crab is uncertain. In the current study, the modified sweeps we tested would likely have a positive impact on reducing the level of any injury and unobserved mortality to Dungeness crab and other benthic organisms. Using an ocean shrimp trawl, Hannah et al. (2013) found raising the groundgear with 20.3 cm bobbins significantly reduced interactions and disturbances with Dungeness crab and other epifaunal organisms. Off Alaska, trawl sweeps raised by 20.3 cm bobbins reduced morality of Tanner crab (*Chionoecetes bairdi*) from 4.1% to 1.0%, and snow crab (*C. opilio*) from 4.9 to 0.0% (Hammond et al., 2013). Further research exploring the interactions between trawl gear and Dungeness crab would provide beneficial information to fishers and managers when assessing gear modifications and their potential fishery impacts.

In our study, the modified sweep design we tested consisted of disc clusters spaced at 8.2 m intervals along the sweeps lengths. We selected this interval as it is similar to the interval employed in the Rose et al. (2010a) study, and in efforts to maintain the sweeps nominal height off bottom of 6.5 cm; as increasing spacing intervals can lower sweeps height off bottom over soft substrates as the sweep can oscillate between the disc clusters (Rose et al., 2010b). In our study, we placed some disc clusters directly over the combination wire and interlacing steel cable through the disc clusters and combination wire fore and aft of the disc clusters to maintain their position on the sweep. This method was effective at holding the disc clusters in position during our study; however, may not be a viable method for long-term use as repairing or replacing the cable or disc clusters if damaged could be time consuming. In the Bering Sea directed sole fishery, fishers currently use sweeps consisting of combination wire manufactured in 27.4 m long sections that are then connected by hammer locks and chain that run through a 25.4 cm steel bobbin. This design has improved the ease of construction and handling of the sweeps, but can cause increased fluctuation in the sweeps height off bottom (both upwards and downward) over soft substrates compared to smaller discs sizes spaced at shorter intervals (Rose et al., 2010b).

Developing techniques that can reduce trawl gear disturbances to the seafloor would have positive impacts on habitat complexity, infaunal and epibenthic communities, and fish habitat in areas where such impacts are significant. In our study, we compared the catch efficiency between conventional and modified sweeps and found there was no significant length-dependent catch efficiency effect of changing from conventional to modified sweeps. The DIDSON imaging sonar and altimeter data also showed the modified sweeps exhibit elongated sections where infaunal and lower-profile epifaunal organisms can pass under without sweep disturbance or contact. These findings are comparable to previous research in the Bering Sea directed sole fishery (Rose et al., 2010a). Use of these sweeps would also likely increase fuel to catch efficiencies (e.g., less fuel consumed per kg of fish caught) as drag forces should be reduced with sweep sections elevated off bottom. Prior to our study, the efficacy of elevated sweeps in the U.S. West Coast groundfish bottom trawl fishery had not been evaluated. Results from our study demonstrate there are clear benefits to using elevated trawl sweeps. Incorporating additional gear modifications such as semi-pelagic trawl doors that fish off bottom and/or light touch groundgear could be effective at further reducing trawl gear interactions with the seafloor and associated non-target organisms. Lastly, this study provides fishers and management quantitative information on a simple and practical technique that can minimize trawl gear disturbances to the seafloor.

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Table 1. Raw length data used for the catch efficiency analyses. Values in parentheses are the length measurement subsample ratio from the total catch.

	No. measured	
Species	Conventional sweeps	Modified sweeps
Shortspine thornyhead, *Sebastolobus alascanus*	2,005 (0.50)	2, 020 (0.46)
Greenstriped rockfish, *Sebastes elongatus*	423 (1.0)	395 (0.95)
Sablefish, *Anoplopoma fimbria*	1,809 (0.28)	2,267 (0.39)
Lingcod, *Ophiodon elongatus*	531 (0.62)	655 (0.59)
Rex sole, *Glyptocephalus zachirus*	3,253 (.050)	3,156 (0.51)
Dover sole, *Microstomus pacificus*	4,569 (0.40)	4,285 (0.40)
Petrale sole, *Eopsetta jordani*	1,137 (0.21)	1,806 (0.17)

Figure

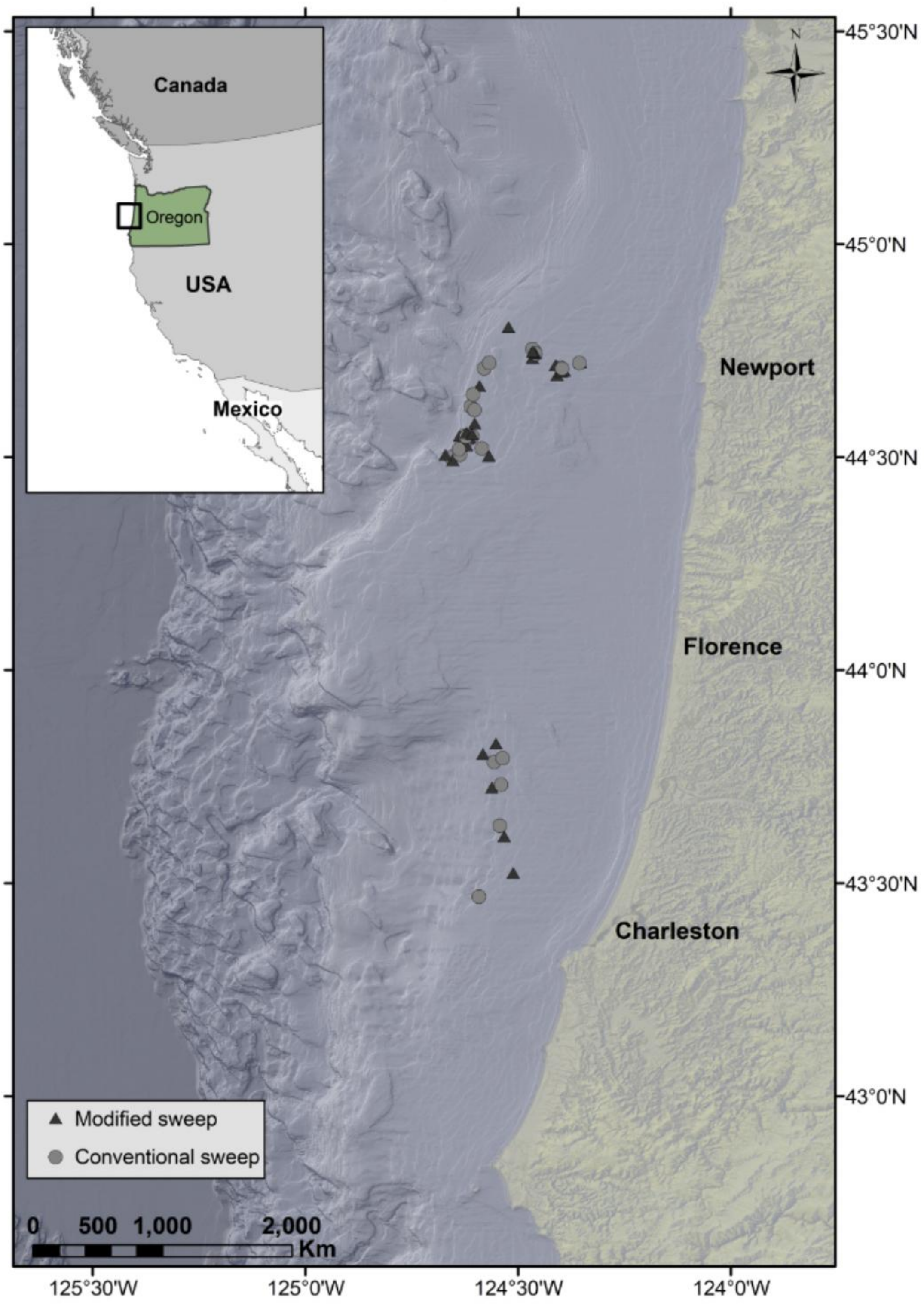

Figure 1. Map of the area off the Oregon coast where sea trials were conducted.

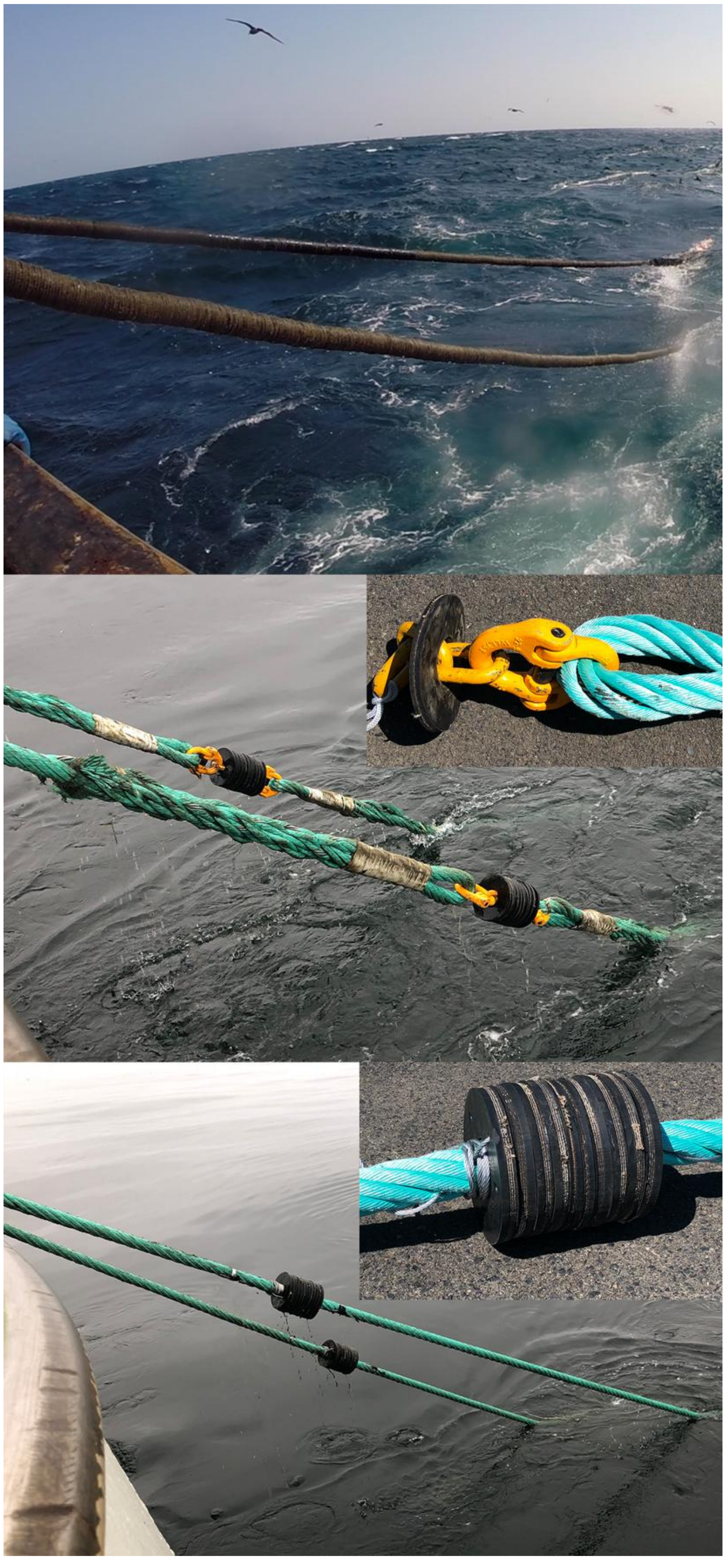

Figure 2. Images of the conventional sweeps (top image) and the mechanism used to attach the disc clusters to the modified sweeps (middle and bottom images).

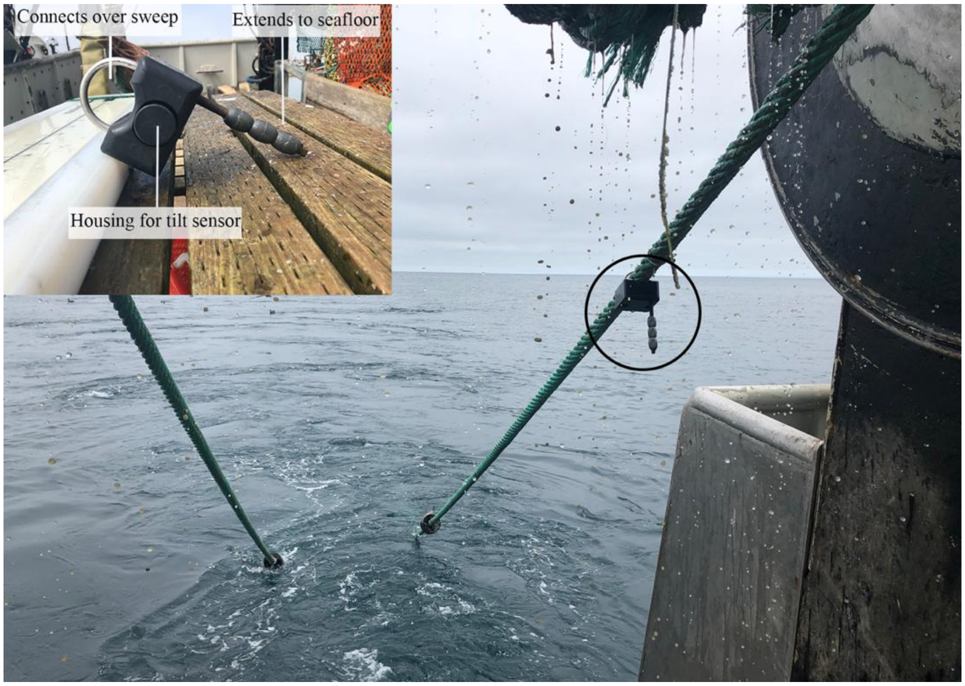

Figure 3. Mechanical trawl sweep altimeter which incorporated an acceleration data logger that provided a continuous digital record of tilt angle and a measure sweep height off bottom.

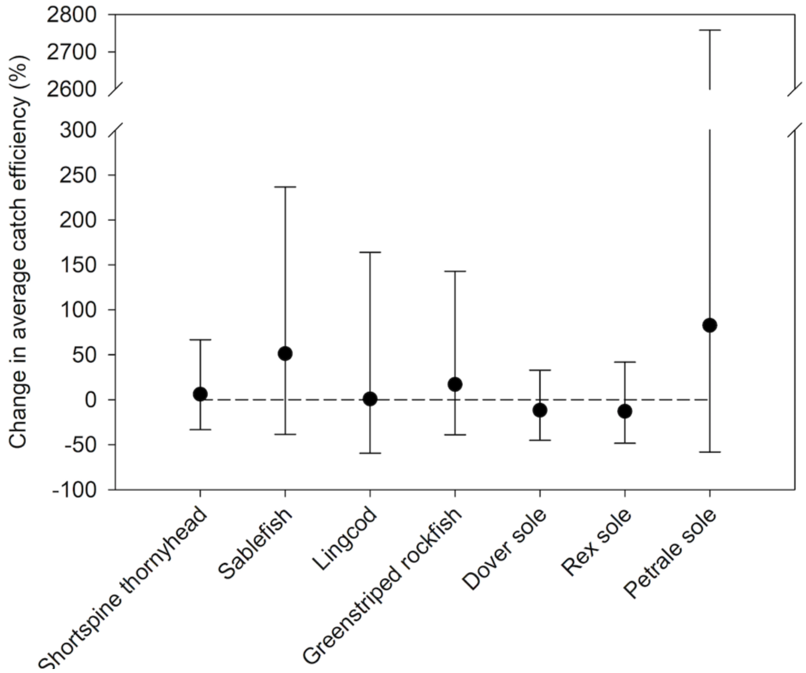

Figure 4. Change in average catch efficiency (%) between conventional and modified sweeps. Values above zero indicate more fish were caught by the modified sweeps, and vice versa for values below zero. Vertical lines are 95% CIs.

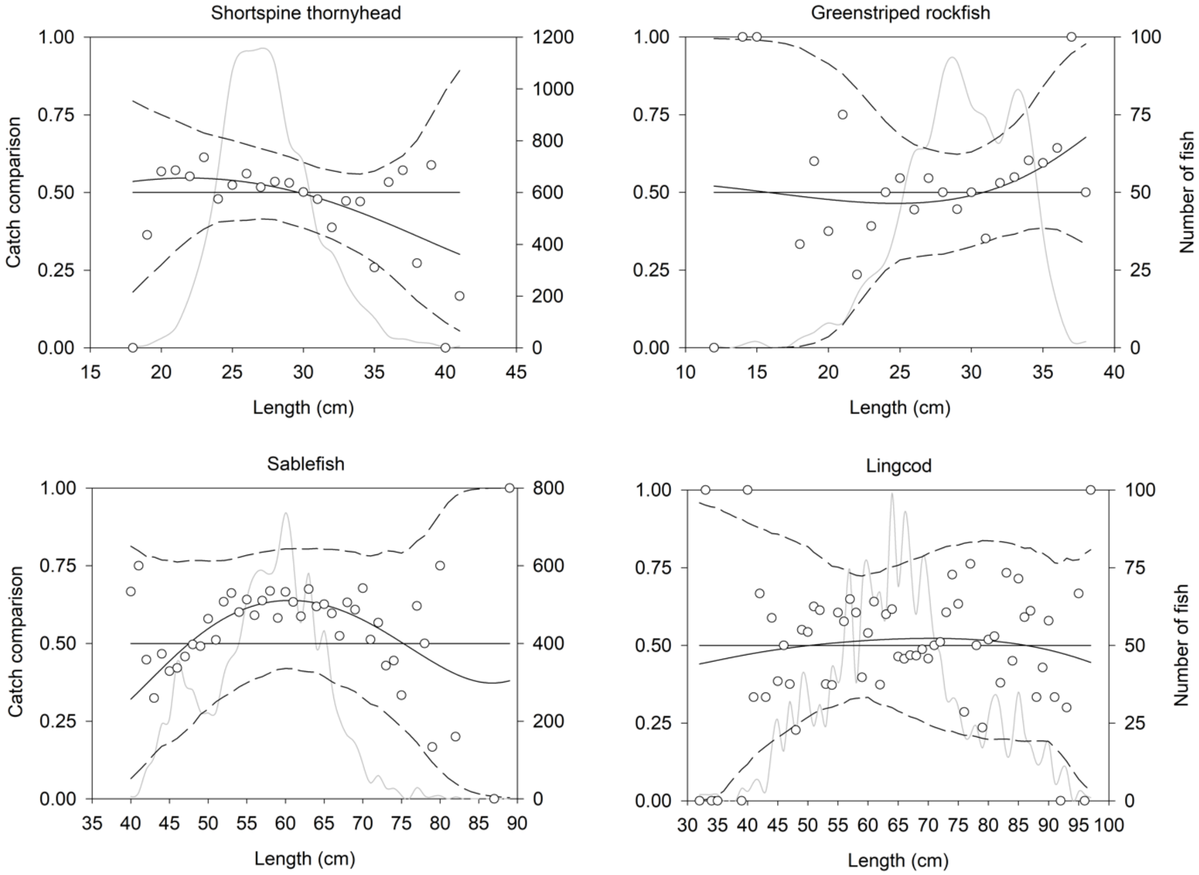

Figure 5. Mean catch comparison curves for shortspine thornyhead, greenstriped rockfish, sablefish, and lingcod between conventional and modified sweeps. Circles are the experimental data; fitted lines are the modeled value; dashed lines are 95% CIs; grey lines are the number of fish caught for both gears combined with extrapolation from subsampling; straight lines depict the baseline catch comparison rate of 0.51 indicating equal catch rates between conventional and modified sweeps. A value above 0.51 would indicate more fish were caught by the modified sweeps, and vice versa for values below 0.51.

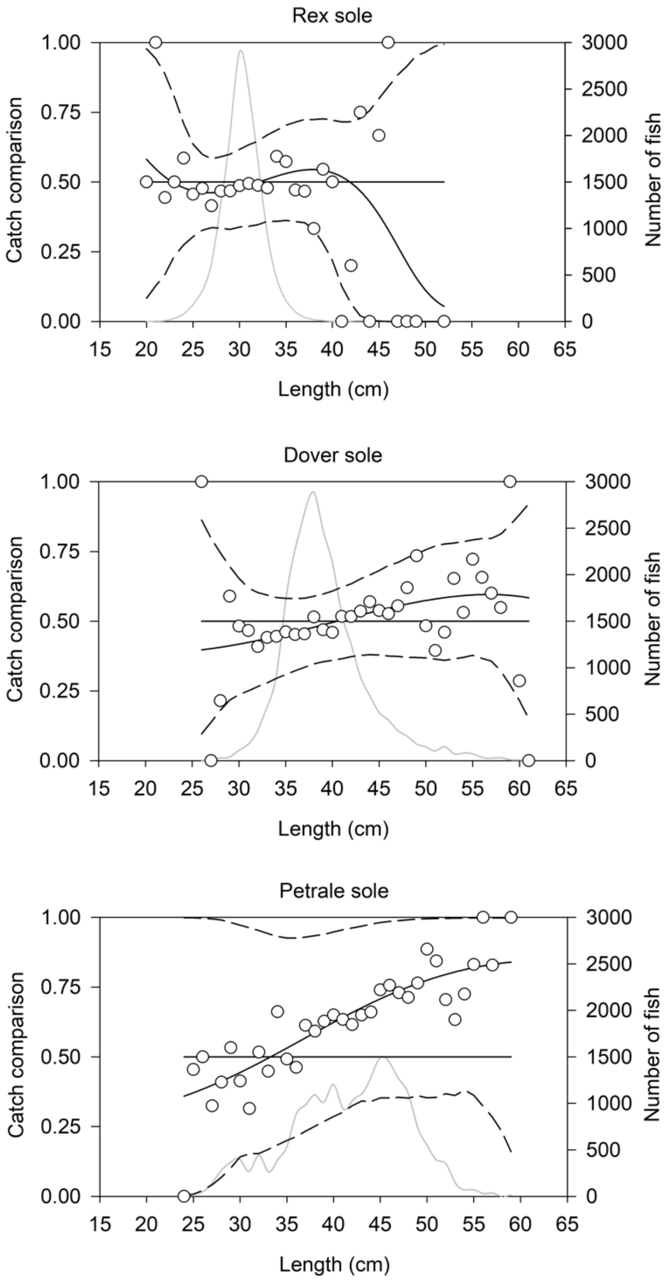

Figure 6. Mean catch comparison curves for rex sole, Dover sole, and petrale sole between conventional and modified sweeps. Circles are the experimental data; fitted lines are the modeled value; dashed lines are 95% CIs; grey lines are the number of fish caught for both gears combined with extrapolation from subsampling; straight lines depict the baseline catch comparison rate of 0.51 indicating equal catch rates between conventional and modified sweeps. A value above 0.51 would indicate more fish were caught by the modified sweeps, and vice versa for values below 0.51.

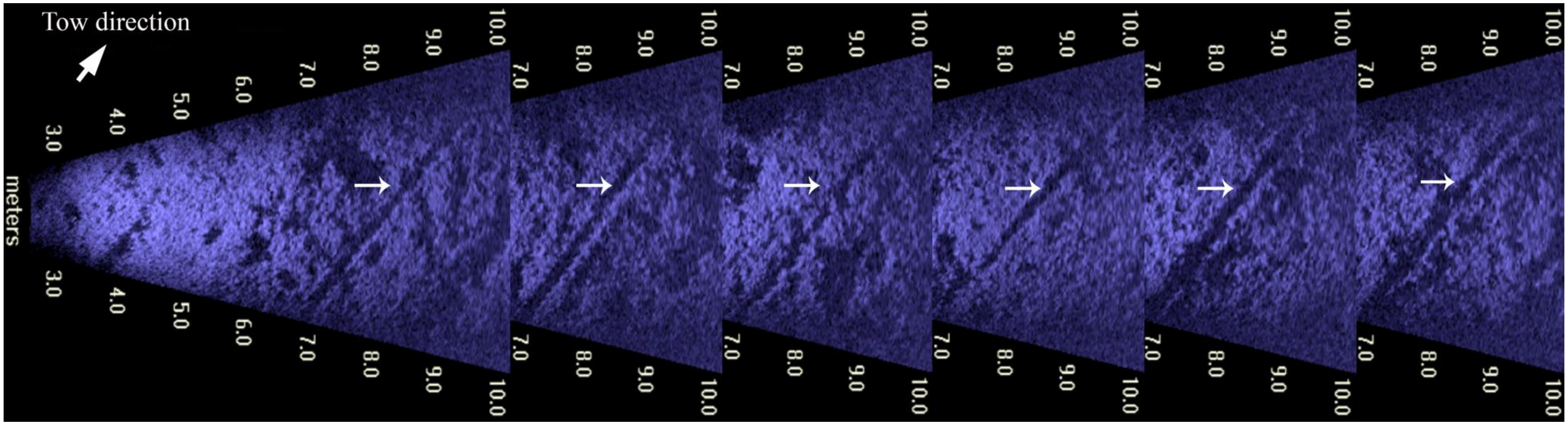

Figure 7. Mosaic of DIDSON imaging sonar frame grabs for a section of the path of the starboard side modified sweep. Arrows depict disc cluster tracks on the seafloor.