Semi-Pelagic Trawling in The U.S. West Coast Groundfish Bottom Trawl Fishery: Effects on Catch Efficiency and Seafloor Interactions

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Abstract

Reducing the impacts of bottom trawling on seafloor habitats is a management priority in the U.S. West Coast groundfish bottom trawl fishery as well as other trawl fisheries internationally. Modifications to conventional bottom trawls, such as semi-pelagic trawl technology, are commonly used in demersal fisheries to reduce trawl-seafloor interactions by elevating the doors and portions of the sweeps off the seafloor. This study evaluated changes in catch efficiency and trawl geometry between a conventional bottom trawl outfitted with bottom-tending doors and the same trawl modified with midwater doors to fish semi-pelagically. We observed the seafloor interactions using Dual-frequency IDentification SONar (DIDSON) and quantified the reduction in trawl-seafloor interactions by periodically placing an altimeter on the semi-pelagic trawl door to measure height off bottom. Across the tows where the altimeter was used, results showed that the midwater doors fished off bottom >96% of all tow durations at a minimum height of 0.6 m. The midwater doors also spread 43 m wider on average than the conventional doors, which was significant ($p<0.001$). Catch comparison results showed no significant difference in catch efficiency between the two gear types for any target groundfish species, however, the mean catch per unit effort for sablefish (*Anoplopoma fimbria*) did substantially increase when switching from the conventional to semi-pelagic trawl. Mean door spread did not significantly affect the catch efficiency of any species. DIDSON and altimeter data showed the midwater doors and raised sweeps provide clearance for low profile and infaunal benthic organisms to pass beneath without contact. This study demonstrates semi-pelagic trawl gear can effectively harvest demersal groundfishes in this fishery while substantially reducing trawl interactions with the seafloor. While our study has direct management implications for the U.S. West Coast groundfish bottom trawl

fishery, our findings are also likely to apply to other demersal trawl fisheries internationally where reducing the impacts of bottom trawling on seafloor habitats is a management priority.

1. Introduction

Bottom trawling is widely practiced for harvesting demersal species. Globally, trawling intensities are highest on continental margins with potential negative impacts on habitat complexity, sedimentation, benthic communities, and marine carbon storage (Eigaard et al., 2017; Bradshaw et al., 2021; Pitcher et al., 2022). On the U.S. West Coast, bottom trawl gear is used to target groundfishes (e.g., Dover sole [*Microstomus pacificus*], petrale sole [*Eopsetta jordani*], sablefish [*Anoplopoma fimbria*], lingcod [*Ophiodon elongatus*], and shortspine thornyhead [*Sebastolobus alascanus*]) over low-relief seafloor consisting of a range of substrate types (e.g., mud, sand, gravel, cobble, boulder, and rock) and is an efficient means of harvesting these species. However, the potential impacts of bottom trawl gear on habitat complexity, benthic communities, biogeochemistry and essential fish habitat (EFH) remain major management concerns (PFMC, 2018; NOAA, 2019).

Significant effort has been put towards understanding the impacts of bottom trawling on seafloor habitats, community structure, sediment resuspension, and biogeochemical processes around the world where bottom trawl fisheries occur (Kaiser et al., 2002; Rijnsdorp et al., 2018; Sciberras et al., 2018; Bradshaw et al., 2021). In the U.S. West Coast groundfish bottom trawl fishery, conventional bottom trawls utilize low-aspect ratio doors (aspect ratio is determined by dividing the door height by its width, where values below 1 refer to “low-aspect” and values above 1 refer to “high-aspect”) and lengthy sweeps (e.g., >85 m) designed to maintain seafloor contact as they move along the seafloor and herd groundfishes towards the trawl mouth. The high degree of bottom contact exhibited by a conventional trawl increases the potential to cause physical disturbances to the seafloor or other impacts, including unobserved injuries or mortalities to non-target benthic organisms such as Dungeness crab (*Metacarcinus magister*), brittle stars (Ophiuroidea), polychaete worms (Polychaeta), structure-forming invertebrates like sponges (Porifera), sea whips, and sea pens (Cnidarians), which are the most predominant macro-invertebrates found in soft-sediment fishing grounds off the U.S. West Coast (Hixon and Tissot, 2007; Hannah et al., 2014; Hemery and Henkel, 2015). The Pacific Fishery Management Council (PFMC), that recommends fishery management measures in federal waters off the U.S. West Coast to the federal government, has utilized trawl area closures and footrope diameter restrictions within the fishery management plan to protect EFH and species of concern from being impacted by trawling (Hannah, 2003; PFMC, 2015; PFMC and NMFS, 2022). While these regulations have been put in place to reduce trawl-seafloor-habitat interactions, it still remains a high priority of the PFMC in their “Research and Data Needs” for the fishery to “*minimize fishing impacts on habitat by adopting gear modifications to trawls to reduce the area of direct seafloor contact*” (PFMC, 2018).

In demersal groundfish trawl fisheries, bottom-tending trawl doors constitute a small portion (3-10%) of the groundgear that contacts the seafloor along the towline for any given trawl event (Valdemarsen et al., 2007). However, they are considered a significant source of bottom impact because of their weight, ability to penetrate the seafloor, and their potential to significantly impact invertebrate abundances, habitat complexity, and recovery rates after a disturbance (Sciberras et al., 2018). Conventional trawl sweeps and footropes, on the other hand, constitute the most significant portion of the trawl gear that contacts the seafloor because of their long lengths and can cause potential disturbances and impacts to benthic communities, biogeochemistry, and

EFH. To address management concerns of trawl-seafloor impacts, trawl designs have been developed that reduce seafloor interactions by making modifications to the footrope (He and Winger 2010; Nguyen et al., 2015), sweeps (Rose et al., 2010; Lomeli et al., 2019), and/or trawl doors (Sistiaga et al., 2015; Eayrs et al., 2020; Winger et al., 2024). Semi-pelagic trawl designs refer to modifications to a demersal trawl that lift sections of the footrope, sweeps, and/or doors off bottom. Semi-pelagic trawls have also been employed to reduce fuel consumption in fisheries where operating costs have become prohibitively high, as reduced seafloor contact decreases the drag forces on the trawl (Grimaldo et al., 2015; Sistiaga et al., 2016).

While semi-pelagic trawling has been used in demersal fisheries internationally and in Alaska, this same uptake has not been seen in the West Coast bottom trawl fishery. In Alaska, pelagic trawling and the use of elevated sweeps were quickly adopted by the groundfish fleets due to bycatch considerations from other significant fisheries such as crab and Pacific halibut (*Hippoglossus stenolepis*) (Rose et al., 2010; He and Winger, 2010) and impending regulatory changes (Balsiger, 2010; Eayrs and Pol, 2019). Fishers may be unmotivated to voluntarily modify conventional gear configurations, even ones with potential cost savings, if the impacts on catch efficiency are unknown. In the groundfish fishery, Lomeli et al. (2019) have already shown that using modified sweeps elevated 6 cm above the seafloor did not significantly change catch efficiencies of target groundfishes and reduced the overall sweep-seafloor interaction by 95% over the length of the sweep. In the West Coast groundfish bottom trawl fishery to date, the efficacy of a trawl outfitted with midwater doors and elevated sweeps has not been reported in peer-reviewed sources, leaving fishers and fisheries managers unclear of their benefits and impacts.

In efforts to address fisheries managers priority of reducing trawl-seafloor interactions, and development in technologies that can contribute to more sustainable fishing practices, our study objectives were: 1) compare the catch efficiency of demersal groundfishes between a conventional trawl outfitted with bottom-tending trawl doors and a semi-pelagic trawl outfitted with midwater doors, 2) quantify the degree that the semi-pelagic trawl reduces trawl-seafloor interactions compared to the conventional trawl, and 3) provide West Coast groundfish bottom trawl fishers and fisheries managers data for assessing trawl modifications that can mitigate trawl-seafloor interactions and disturbances to important macro-invertebrates and fish habitat.

2. Materials and Methods

2.1. Sea trials and sampling

Our experiment was conducted aboard the F/V *Last Straw* (23.2 m LOA, 540 HP) off Oregon during September 2021 (Fig. 1, Table 1). Fishing occurred during daylight hours using the vessel's groundfish trawl. The only experimental change to the fishing gear during our study was the door type and rigging (detailed below). The trawl had a fishing mouth circumference of 180 meshes (241 mm mesh size, between knot measurement [BK]) that tapered down over 77.5 meshes to a codend circumference opening that was 88 meshes. The footrope at the opening of the net 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. A T90 mesh codend (127 mm nominal mesh size [BK], 6.0 mm double twine) that was 88 meshes in circumference and 75 meshes in length was used. After each tow, fishes were sorted into baskets by species or group (e.g., shelf and slope rockfishes [*Sebastes* spp.]) and weighed using a motion-compensated platform scale. We had a target tow duration of 60 minutes, however, tow duration varied from 30 minutes (1 tow) to 75 minutes (1 tow), so all catch data were standardized per hour, and a catch per unit effort (CPUE) of kg hr^{-1}.

The conventional bottom trawl (CBT) employed Thyborøn type-11 low-aspect ratio demersal doors (size = 4.8 m^2; weight = 995 kg [weight in air]) (Fig. 2) rigged with a 3.1 m back strap and 10.4 m chain (16 mm long link) connected to the sweeps. The semi-pelagic trawl (SPT) employed NET Systems series 2,000 high-aspect ratio midwater trawl doors (size = 4.5 m^2; weight = 568 kg [weight in air]). This door was chosen for its high aspect ratio which provides a higher lift to drag ratio, allowing the doors to fish off bottom when towed by the size of vessel used in this study per the manufacturer's specifications. The SPT rigging consisted of 2.5 m Spectra rope back strap, 18.3 m of bare wire, and 285 kg (weight in air) of in-line chain (30.5 cm link length, 16 links totaling 3.6 m in length) aft of the door on each side to provide proper door setback and to keep the sweeps and net fishing on bottom (Fig. 3). Simrad PI door spread sensors were used to measure door spread between the two trawl configurations. Sweeps 121.2 m in length consisting of 4.8 cm combination wire with steel bobbins 25.4 cm in diameter placed every 30.5 m, designed to elevate sections of the sweeps off-bottom, were used on both trawls. In concept, the elevated sweeps are designed to lift 97% of the sweep off bottom, with an anticipated height of 3-4 cm above the seafloor between bobbins for each configuration. Further, the midwater doors combined with the elevated sweeps is designed to elevate 85% or more of the total length of gear between the doors and the bridles off bottom.

Due to limited space on the vessel, the conventional and midwater trawl doors could not be stored on the vessel at the same time requiring us to return to port to change between bottom and midwater doors. The sampling order for the CBT and SPT designs is shown in Table 1. During our gear trials, the CBT and SPT designs were each fished over similar fishing grounds and depths (Fig. 1).

A mechanical altimeter was attached to the bottom of the port SPT door to measure the height off bottom continuously throughout the tow. The altimeter consisted of an Onset Hobo Pendant® acceleration data logger in a stainless-steel housing weighted with two links of chain (35.6 kg [weight in air]) which combined extended a total of 77 cm below the bottom SPT door (Fig. 2). From a series of calibrations, the conversion function used to convert the bottom contact sensor's relative units to door height was:

$$\text{Door height} = 1804.3x^{-0.949} \tag{1}$$

where x is the voltage output from the data logger. Eq. 1 was used to measure when the door height (distance between the bottom edge of the door and the seafloor) was between 0–77 cm, averaged over the on-bottom duration of the tow. Beyond 77 cm, the sensor unit would lose contact with the seafloor and door height could not be measured, but the door was noted as being off bottom. Altimeter data was also binned as the proportion of the tow duration that the SPT doors spent off bottom (any reading >0 cm), on bottom (readings = 0 cm), and near bottom (readings between 0 – 77 cm when door height could be measured).

Following methods employed by Rose et al. (2010) and Lomeli et al. (2019), a bottom-tending sled outfitted with a Sound Metrics ultrasonic Dual-frequency IDentification SONar (DIDSON, operating at 1.8 MHz) and an HD video camera system (equipped with scaling lasers) was towed across a pair of SPT and CBT paths (Fig. 1). Measurements were taken near start and end of tow locations to measure how each trawl configuration interacted with the seafloor. DIDSON survey tows occurred on 21 November aboard the R/V *Oceanus* (54 m LOA, 3,000 HP). Using our gear's known location and dimensions (bobbin size and spacing, footrope rockhopper configuration, etc.) we verified that the observed tracks in the DIDSON sonar imagery were from our trawling activities.

2.2. Catch comparison analysis

We performed a catch comparison sampling analysis to determine how changing from the CBT to SPT configurations affects the mean CPUE of target groundfishes (e.g., lingcod, sablefish, shortspine thornyhead, Dover sole, petrale sole). Mean CPUE (kg hr^{-1}) value was estimated species by species separately for CBT and SPT configurations based on the standardized catch data for the tows from each configuration. Specifically, the mean $CPUE_i$ value for species i for a specific gear configuration CBT or SPT was estimated by:

$$CPUE_i = \frac{60}{n} \sum_{j=1}^{n} \left\{ \frac{w_{ij}}{t_j} \right\} \tag{2}$$

where the summation is over the n tows carried out with the specific gear configuration. t_j is the towing time in minutes for tow j and w_{ij} is the weight in kg of the catch of species i in the j. Following Lomeli et al. (2020), a bootstrapping method was used to estimate confidence limits (CLs) for the mean CPUE values for each species. Specifically, 1,000 bootstrap repetitions were conducted for CBT (n=23) and SPT (n=21) gear configurations. In each bootstrap repetition the n tows for the specific gear configuration were resampled n times with replacement and mean CPUE was subsequently estimated by Eq. 2 to obtain a bootstrap population of results for the mean CPUE. Finally, the Efron percentile 95% CLs (Efron, 1982) for mean CPUE were obtained from this bootstrap population of values. To quantify the percent change in mean CPUE ($\Delta CPUE_{mean}$) for each species between the CBT and SPT gear types, the following equation was used:

$$\Delta \mathrm{CPUE}_{\mathrm{mean}} = 100 \times \frac{(\mathrm{SPT}_{\mathrm{mean}} - \mathrm{CBT}_{\mathrm{mean}})}{\mathrm{CBT}_{\mathrm{mean}}} \tag{3}$$

where SPT_{mean} is the mean CPUE for the semi-pelagic trawl and CBT_{mean} is the mean CPUE for the conventional trawl. Based on the two independent bootstrap populations of results for SPT_{mean} and CBT_{mean} we obtained a bootstrap population of results for $\Delta CPUE_{mean}$ following the rules for bootstrap calculus outlined in Herrmann et al. (2018). This allows for estimating the mean percentage change in catch efficiency ($\Delta CPUE_{mean}$), but also to obtain the Efron 95% CLs for the estimated mean change. Following Eq. 3, if the SPT has an increase in mean CPUE for a species, then the $\Delta \mathrm{CPUE}_{\mathrm{mean}}$ value will be above zero, whereas if the mean CPUE for the SPT decreases then $\Delta \mathrm{CPUE}_{\mathrm{mean}}$ will be below zero. The analyses described above were performed using the statistical package SELNET (Herrmann et al., 2012), software version date 13 March 2023.

2.3. Analysis of DIDSON imagery footage measurements and door spread

We used the measuring tool within the DIDSON sonar software (V5.26) to analyze the imaging sonar footage and measure the width of tracks (if present) created by the doors, sweeps, and footrope of the two trawls. This provided quantification of the trawl-seafloor interaction of each configuration tested. This measuring tool was also used to estimate the height of the sweeps above the seafloor. Given the bobbin has a fixed diameter of 25.4 cm, we can measure the width of the track left by the bobbin to determine the distance between the combination wire and the seafloor given the following formula:

$$h = \sqrt{r^2 - \left(\frac{w}{2}\right)^2} - 2.4 \qquad (4)$$

where h is the height between the seafloor and bottom of the combination wire, r is the radius of the bobbin (12.7 cm), w is the width of the bobbin track measured from the DIDSON sonar footage, and 2.4 is the radius of the combination wire (Fig. 4).

Fish directly in the path of the trawl's footrope and wings will have a probability of being captured during the trawl event; however, outside of this path, fish need to be herded towards the trawl to become captured. Doors provide the horizontal force to spread the net, meaning the spread of the doors and sweeps is greater than the net path, creating a herding zone between the trawl net path and the sweeps. The length and angle relative to the direction of tow of the sweeps alter the width of the herding zone, and total trawled area, which can affect the catch efficiencies of target species. We calculated the estimated angle of attack of the sweeps (incidence angle) in relation to the direction of tow using the following equation:

$$\theta = \sin^{-1}\left(\frac{d_s - f_s}{2S_l}\right) \tag{5}$$

where θ is the sweep angle, d_s is the door spread distance, f_s is the average footrope spread of each configuration from the DIDSON survey, and S_l is the total length of the sweeps from the footrope to the trawl door for each configuration shown in Fig. 5. This equation is modified from Eighani et al. (2023), who used wing spread instead of f_s, as wing spread sensors were installed on their trawl. Since our trawl footrope extends to the trawl wing tips, the average footrope spread is an accurate proxy for this calculation in lieu of sensor data. We also used door spread along with the f_s, and S_l to calculate the trawled area of each configuration. Considering that this is a demersal fishery, sections of the sweeps near or in contact with the seafloor may have a more herding effect than those lifted off by midwater doors of the SPT. In this case, we also used sweep spread (S_s) instead of d_s, to estimate the trawled area of the SPT that would have comparable sweep herding effects to the CBT. S_s was calculated as the distance between the first section of elevated sweeps 24.4 m behind the doors due to the rigging (Fig. 3), which would be in contact with the bottom during fishing.

To determine if the mean door spread differed statistically between trawl type, a two-sided Welch's two-sample t-test analysis was used.

3. Results

3.1. Fishing effort and catch comparison

In total, 44 valid tows were completed and used in the catch comparison analysis, with 23 and 21 tows occurring for the conventional and semi-pelagic trawls, respectively. Mean tow duration, tow speed, bottom depth, and door spread values for each trial are shown in Table 2.

For both trawl configurations, the most abundant species caught by weight were sablefish, arrowtooth flounder (*Atheresthes stomias*), and Dover sole (Fig. 6). Shortspine thornyhead, longnose skate (*Caliraja rhina*), shelf and slope rockfishes, petrale sole, rex sole (*Glyptocephalus zachirus*), and lingcod were also frequently caught in both trawl configurations. The SPT on average caught more sablefish, Dover sole, lingcod, and petrale sole, but fewer arrowtooth flounder, longnose skate, rex sole, shelf rockfishes, and shortspine thornyhead than the CBT (Fig. 6). The change in catch efficiency was not significantly different for any species (Fig. 7). However, sablefish showed a substantial increase in mean CPUE from 487.9 kg hr^{-1} (CL: 235-964) to 1,167.5 kg hr^{-1} (CL: 630-1,848) when switching from the CBT to SPT, respectively. The average difference in catch efficiencies for all other species was <44% between the two gear types.

3.2. Trawl-seafloor interactions

The bottom contact sensor was deployed on 11 of the 21 SPT tows, as adverse weather conditions made connecting the device to the door unsafe while setting the gear for the other tows. Across the tows where the bottom contact sensor was used, the altimeter data showed the SPT doors were completely off bottom on average 99.6% (SE ± 0.3) of the tow duration and only contacted the seafloor on average 0.6% (± 0.3) of the time (Table 3). The duration of door-seafloor contact ranged from 0–3.9% between each tow sampled. The vertical position of the midwater door above the seafloor could only be accurately estimated with readings between 17.7–65.0 cm (the "height off bottom" range in Table 3), rather than the full range of 0-77 cm. This was due to the resolution of the altimeter sensor data as well as the water velocity passing below the door and affecting the tilt angle of the sensor when the doors were lifted fully off the seafloor. Over the tows where the bottom contact sensor was used, the altimeter data showed the SPT doors spent 16.3% of the time in the near bottom range, with an average altitude of 57.7 cm (± 0.1). This mean value ranged from 47.3 cm (± 5.6) to 62.9 cm (±0.1) between each tow (Table 3). These results confirm that, for the tows that included the altimeter, the SPT doors were primarily fishing off bottom as designed.

We could clearly identify and measure one pair of conventional and semi-pelagic trawl paths using the DIDSON imaging sonar. The pair used in the measurement analysis are denoted with the asterisk in Fig. 1. Due to the delay between fishing and the DIDSON survey, as well as survey complications towing around the Ocean Observatories Initiative Endurance Cable Array, the other pair of trawl tracks could not be reliably identified and measured for this study. The analyzed pair of CBT and SPT tows were made 3.4 km apart in similar depths of 241 m and 247 m, respectively, within 28 hours of each other. Two transects were made across these tracks as seen in Fig. 1, which captured a snapshot (<1% of total length) of each trawl path. The semi-pelagic trawl track showed that near the start of the tow, both port and starboard doors were contacting the seafloor, as well as the starboard in-line chain (Fig. 8). However, near the end of the tow the DIDSON imaging sonar showed only the port door and in-line chain were off bottom. When the SPT doors and in-line chain did make contact (which was <4% of the tow duration on tows where the bottom contact sensor was used), the average width of the door mark of 0.35 m (SE ± 0.02) and 0.76 m (± 0.1), respectively. Door marks were present in both CBT transects with an average door width of 0.48 m (± 0.02).

For both trawl configurations moving fore to aft along the length of the sweep (towards the trawl), the average distance between bobbin tracks increased due to variations in the sweeps' angle of attack. This was more pronounced in the SPT where the distance between the bobbin tracks increased from 7.7 m (± 0.9) to 10.8 m (± 1.4) compared to the CBT where the distance between bobbin tracks increased from 8.0 m (± 0.8) to 8.7 m (± 0.5). The footrope track was wider when using the SPT (23.9 m) than the CBT (22.4 m). The tracks correspond to a slight "U" shape of the lower bridles towards the footrope in both configurations, which is more pronounced with the significantly wider trawl door spread of the SPT ($p<0.001$, df = 25.3, Table 2). The mean width of the SPT bobbin track appears slightly wider (0.22 m ± 0.004) than the CBT bobbin track (0.21 m ± 0.003), corresponding to the sweeps fishing at a mean height off bottom between the bobbins of 4.4 cm (± 0.4) for the CBT compared to 3.1 cm (± 0.3) for the SPT configuration. Due to the precision of the measurement software and small sample size, we are unable to determine if this trend persisted for each tow. The seafloor between bobbin tracks appeared undisturbed when compared to the areas outside of the trawl path, when comparing areas around the door and bobbin marks in Fig. 8. This corresponds to the sweep sections between bobbins likely having enough clearance to avoid disturbing the seafloor, however, this is only a qualitative observation on a subset of two trawl paths.

The door spread of each configuration (Table 2) resulted in the SPT having a greater angle of attack of the sweeps compared to the CBT (Fig. 5). The angle of attack increased from 14.8º (SE ± 0.3) to 21.2º (± 0.5) for the conventional and semi-pelagic trawls, respectively. Although the SPT is designed to have 152 m of sweep in close contact with the seafloor compared to 166 m for the CBT (with rigging included), the spread of the SPT doors resulted in a 100 m^2 (9%) increase in trawled area. It should be noted that the calculation of angle of attack represents the average angle over the entire sweep, from the door to the footrope, and does not account for the parabolic shape of the sweeps between the doors and the trawl that we observed in the DIDSON survey. This analysis estimates the trawl geometry, and given the significant difference in door spread, allows for a comparison of the potential herding differences between the two configurations.

4. Discussion

4.1. Gear performance

We evaluated how changing from a conventional bottom trawl rigged with bottom-tending doors to a semi-pelagic trawl rigged with midwater doors affected the catch efficiency of target groundfishes within the U.S. West Coast groundfish bottom trawl fishery. The SPT showed no significant change in mean CPUE for any species sampled. This is similar to other studies that found little to no change in groundfish catch efficiencies when using a semi-pelagic trawl in a conventionally demersal trawl fishery (Eayrs et al., 2012). The high-aspect ratio midwater doors were elevated above the seafloor for >96% of each tow where an altimeter was deployed, influencing the trawl geometry. Notably, the SPT had an average door spread 43 m wider than the

CBT, a significant increase of 33%. This resulted in a 9% increase in trawled area by the portion of sweeps in close contact with the seafloor for the SPT over the CBT. Jones et al. (2021), found that increased wing spread only impacted the total catch weight of flatfishes due to higher trawled area, rather than an influence of spread on catch efficiency. Our results agree with this study, as door spread did not affect the catch efficiency of any targeted species. Thus, the increase in the SPT's trawled area likely contributed to increased catches of sablefish, Dover sole, lingcod, and petrale sole.

We observed that the increased spread of the SPT configuration also increased the average angle of attack and trawled area than that of the CBT configuration. This increased trawled area results in higher fishing efficiency by covering more fishing grounds in a single pass. Increased sweep angles increase the swimming distance required to be herded into the trawl path, which may not be feasible for fish with lower endurance (e.g., smaller individuals) who get overrun by the sweeps rather than herded into the trawl (Winger et al., 1999). Although we did not measure fish lengths in this study, the SPT configuration could create length-dependent herding effects where catches select for larger-sized individuals. Understanding the length-based effects of SPT gear within the West Coast Groundfish fishery would be important for fisheries management practitioners and the fishing industry.

The trawl configurations we tested were designed to have 121.2 m sweeps with elevated sections off bottom, and the trawl doors rigged to be either on bottom (e.g., CBT) or elevated to hydrodynamically fly above the seafloor (e.g., SPT). We did not have door sounders to measure continuous door height for either trawl configuration, but made the assumption (from the bottom contact sensor data) that the SPT doors primarily fished above the bottom. Trawl door elevation likely fluctuated due to extrinsic factors such as sea state, altering the seafloor contact, but the variation in door height above 0.7 m is unknown. This fluctuation would put portions of the in-line chain or bare wire in contact with the seafloor, or potentially lift sections of the elevated sweeps and footrope. We acknowledge that the door sensors were not deployed on 10 tows during rough weather conditions, which could have amplified fluctuations of door position in relation to the seafloor. Issues of door and sweep uplift can occur with the conventional trawl due to changes in sea state or seafloor topography, but are likely less variable than the SPT. Overall, trawl footprint and resulting trawled area are important in this study, and the increased contact of the in-line chain or bare wire could bias these results. However, since door spread data was collected for all tows in both trials and door altimeter data was collected on more than half the SPT tows, we are confident in our results presented here. Having finer scale door sounders, as well as altimeters on parts of the in-line chain for future studies would better quantify both the trawled area and trawl footprint.

Increased control of the trawl door height continues to be a technical challenge for any vessel switching to a semi-pelagic trawl configuration in a demersal fishery (Valdemarsen et al., 2007; Sistiaga et al., 2016; Eayrs et al., 2020). Although we know the SPT doors spent >99% of the time fishing without contacting the seafloor when the altimeter was deployed, the actual variation in door height was largely unknown in both configurations in our study. While we have shown it is possible to successfully fish a semi-pelagic trawl without wing and door height sensors, we acknowledge that including them in both configurations would have greatly improved our ability to assess the gear performance and ensure the midwater doors were fishing at a consistent height above the seafloor. Sensors allow for better control over the position of the doors in the water column, allowing optimal trawl geometry for fishing and eliminating the doors contacting the seafloor. Alternatively, a new design of self-adjusting, semi-pelagic otter boards has recently been tested by Eighani et al. (2023), showing more consistent door height control over the total tow duration. Consideration of the spreading force of a particular door is also necessary, as being too weak (Grimaldo et al., 2015) or too strong (Sistiaga et al., 2016) can adversely affect trawl geometry.

4.2. Trawl-seafloor interactions

Our results show that the doors of the semi-pelagic trawl spent on average >99% of the tow duration above the seafloor (when the altimeter was deployed). For 83% of the total fishing duration, the doors were elevated a minimum of 0.7 m above the seafloor (the maximum height of the sensor recording ability), and >96% of the time 0.6 m above the seafloor. This would provide sufficient clearance for lower-profile epifaunal (e.g., Dungeness crab, sea anemones, brittle stars, and urchins) and infaunal (e.g., polychaetes, mollusks) organisms to pass under the doors without contact. Elevated doors would also reduce contact with structure forming invertebrates that are commonly associated with fish habitat along the West Coast, and can be vulnerable to impacts by mobile fishing gears due to their slow growth rates (Whitmire and Wakefield, 2019).

The elevated sweeps on the SPT appeared to provide 3 cm of clearance estimated from the DIDSON imagery of one tow path, however, this was lower than the 4 cm of elevation estimated from the CBT trawl path. Lomeli et al. (2019) found that using bobbins 17.8 cm in diameter placed every 8.2 m was able to raise the sweeps 6.3 cm above the bottom. The elevated sweeps used in our study followed the Alaska industry standard of placing 25.4 cm diameter steel bobbins at the end of each sweep section (30.5 m in length in our setup) just before the hammerlock. We found that using larger bobbins spaced further apart likely reduces the clearance of the sweep above the seafloor, but doesn’t diminish it completely. The sweep height estimated from the DIDSON analysis shows the elevated sections of the sweeps are capable of passing over infaunal organisms without sweep disturbance and lower-profile epifaunal organisms without physical sweep contact. Further exploration of the elevated sweeps and midwater door riggings, specifically more accurate elevation data, would expand on the potential benefits of this reduced interaction with the seafloor and benthic species.

Bottom-tending mobile gears with large amounts of drag (such as heavy trawl doors with more contact area) can cause greater seafloor disturbance and resuspension of sediment that rises higher above the seafloor than lighter trawl components, which can affect biogeochemical processes and fluxes (Van de Velde et al., 2018; Bradshaw et al., 2021; Breimann et al., 2022). The reduced overall footprint of the SPT in our study likely causes less resuspension of sediment than a conventional trawl. Similarly, the lighter weight midwater doors with a smaller footprint may also disturb the seafloor less than the demersal door at times when it did touch down. Research into the turbidity associated with SPT modifications, as well as the impact of trawling on sediments in West Coast fishing grounds would clarify the seafloor impacts of semi-pelagic trawling in the fishery.

4.3. Implementation into the West Coast fishery and applicability to fisheries management

Technical innovations in trawl gear that minimize trawl-seafloor-habitat interactions while being effective at catching target species would be of interest to policymakers, highly beneficial to fishers, and promote ecosystem health and sustainable fisheries. Results from our research provide fishers and policymakers new data for assessing gear modifications that can mitigate trawl-seafloor interactions and disturbances to structure forming invertebrates, mobile benthic organisms, infauna, and groundfish EFH. Our research directly addresses statutory mandates in the Magnuson-Stevens Fishery Conservation and Management Act (legislation providing for the management of marine fisheries in U.S. federal waters) to develop technologies designed to assist fishing industry participants in reducing fishing gear interactions with invertebrate communities and EFH (16 U.S.C. 1884 MSA § 408), and management priorities of the PFMC (PFMC, 2018), NOAA Fisheries Deep-Sea Coral Research and Technology Program, and NOAA Fisheries West Coast Region. While our study has direct positive management implications to the U.S. West Coast groundfish bottom trawl fishery, our ability to fish a demersal trawl using midwater trawls doors is transferable to other demersal trawl fisheries regionally and internationally where conventional bottom tending doors are used.

For fishers needing to purchase both midwater doors and sensing equipment, this may cost upwards of US$80,000 depending on the size of the vessel. Proper door selection and monitoring equipment are important for ensuring the benefits of reduced seafloor interactions and consistent fishing for a semi-pelagic trawl, but this can be cost prohibitive for fishers switching to this configuration. Some fishers currently participating in the U.S. West Coast groundfish bottom trawl fishery already own some or all additional sensing equipment, especially if they participate in other West Coast midwater trawl fisheries (e.g., Pacific hake [*Merluccius productus*], and widow rockfish [*S. entomelas*] and yellowtail rockfish [*S. flavidus*] fisheries), making this transition to semi-pelagic trawling easier. Increased fuel savings and catch efficiencies may incentivize switching for the portion of fishers that exclusively use conventional bottom gear not requiring this equipment. While we did not measure fuel efficiency or consumption in our study, the reduced drag of high-aspect ratio midwater doors over conventional low-aspect ratio bottom doors has been found to reduce energy consumption by 12-18% (Eayrs et al., 2012; Grimaldo et al., 2015; Eighani et al., 2023). If these benefits are also present with our design, this will yield a larger fishing capacity with decreased energy consumption due to the increased mean trawled area of the SPT. For fishers targeting sablefish, and to a lesser extent Dover sole, lingcod and petrale sole, there is a potential to fill a desired trip quota with fewer hauling hours due to increased catch efficiencies for these species. The ability to land your catch in three days instead of four, for example, would have significant benefits to fuel savings, as well as other trip costs, which are harder to quantify. The improved catch efficiencies and reduced trawl-seafloor interactions we demonstrated in this study warrants further research into fuel efficiency and consumption and output of emissions (e.g., CO_2 and NO_x) between conventional and semi-pelagic trawls in this fishery.

Dungeness crab, a species that supports one of the West Coast's most valuable fisheries, inhabits areas along the coast that overlap with the bottom trawl fishery. NOAA mortality reports for the West Coast groundfish bottom trawl fishery show that recent annual discard mortalities for Dungeness crabs have been ca. 45 mt (Somers et al., 2023), but as high as 200 mt in the last decade (Somers et al., 2019). These landing estimates provide data on what was retained by the trawl codend but may be missing interactions with other portions of the gear. Thus, the extent of unobserved injury or mortality of crab encountering the trawl on the seafloor is largely unknown. In the ocean shrimp trawl fishery, Hannah et al. (2013) raised the trawl footrope with 20.3 cm diameter bobbins and significantly reduced trawl interactions with Dungeness crab and other epifaunal organisms. Off Alaska, Hammond et al. (2013) predicted that tanner crab (*Chionoecetes bairdi*) and snow crab (*C. opilio*) mortality from bottom trawls would both decrease by >3% when using the raised sweeps tested by Rose et al. (2010) that rise 7.5 cm above the seafloor. In this study, the 0.6 m and 3 cm elevation of the doors and sweeps off the seafloor, respectively, would likely contribute to reduced interactions with Dungeness crab and other benthic organisms. In the event fishery managers seek to implement additional gear modifications in the West Coast groundfish bottom trawl fishery to reduce trawl-seafloor interactions, our study findings coupled with prior research (Rose et al., 2010; Hammond et al., 2013; Hannah et al., 2013; Lomeli et al., 2019) provide fishery managers valuable data for making well-informed and sound management decisions.

5. Conclusions

Reducing trawl-seafloor interactions and disturbances to epifaunal and infaunal invertebrate communities and EFH is a high priority to U.S. West Coast marine fisheries managers. Our research addressed this management priority by evaluating the use of a demersal trawl outfitted with midwater doors, in place of conventional bottom-tending doors commonly used for harvesting demersal groundfishes. We demonstrated that using a trawl outfitted with midwater trawl doors and elevated sweeps can significantly reduce trawl-seafloor interactions, while also allowing lower-profile benthic organisms to pass below the doors and sweeps without contact. Further, we found that changing from a conventional bottom trawl to a semi-pelagic trawl does not affect catch efficiencies of target groundfishes. These results provide valuable information to fishery managers and contribute to techniques that support sustainable fishing practices within the U.S. West Coast groundfish bottom trawl fishery. Although our study outcomes were positive, in terms of reducing trawl-seafloor interactions without impacting groundfish catches, changing from bottom tending doors to midwater doors will be a barrier to fishers that lack trawl mensuration sensor equipment needed for monitoring door spread and height. While the majority of vessels in the fishery are outfitted with trawl mensuration sensor equipment that would support the use of midwater trawl doors, for fishers lacking this equipment gear modifications such as changing from conventional bottom tending sweeps to elevated trawl sweeps can be made to reduce trawl-seafloor interactions. (Rose et al., 2010; Lomeli et al., 2019). Lastly, while our research has direct impacts and management implications to the U.S. West Coast groundfish bottom trawl fishery, our study results are likely to apply to other demersal trawl fisheries internationally where reducing trawl-seafloor interactions are a management priority.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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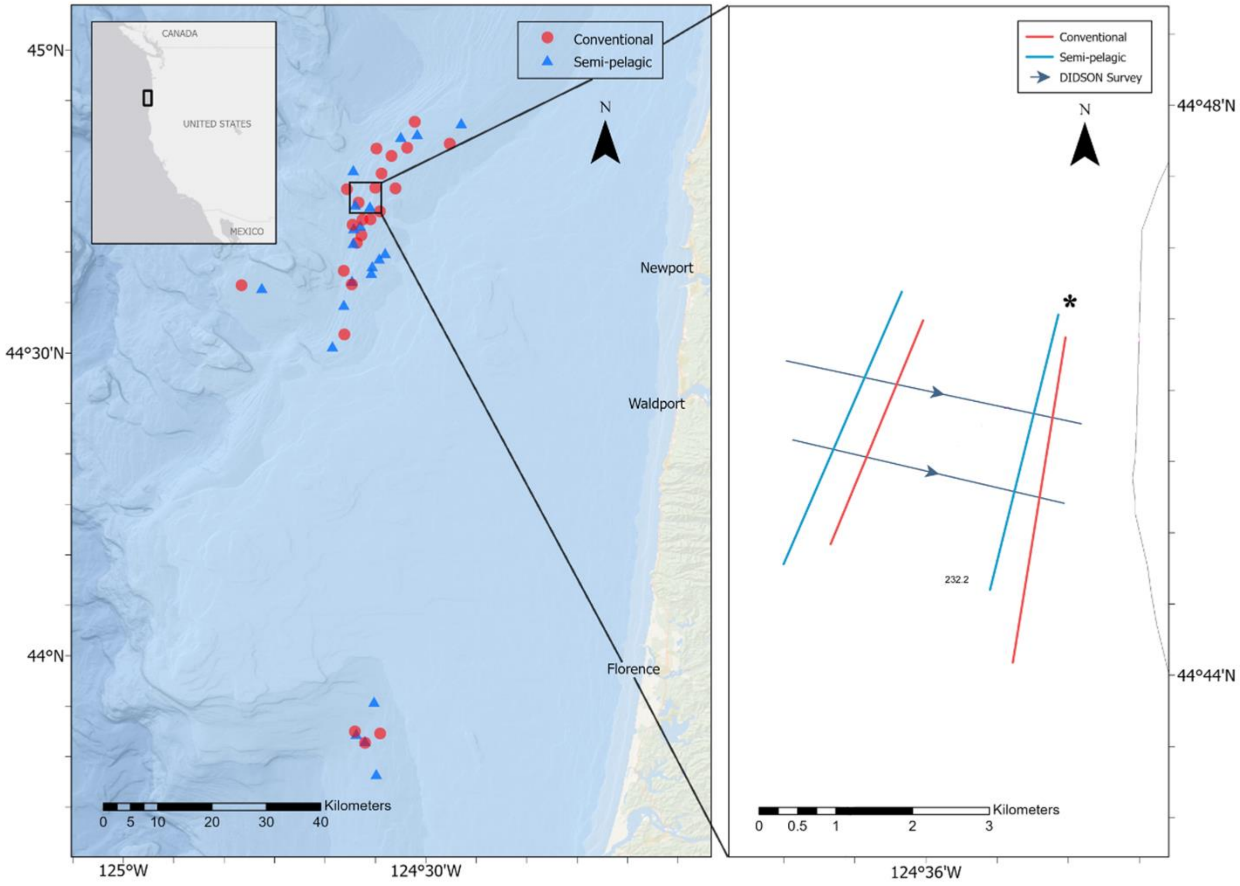

Figure 1. Tow locations of the two trawl configurations tested in this study (left) and DIDSON survey of pairs of trawl tracks (right). Arrows in the right panel indicate direction of tow. An asterisk denotes the paired tows used in the analysis.

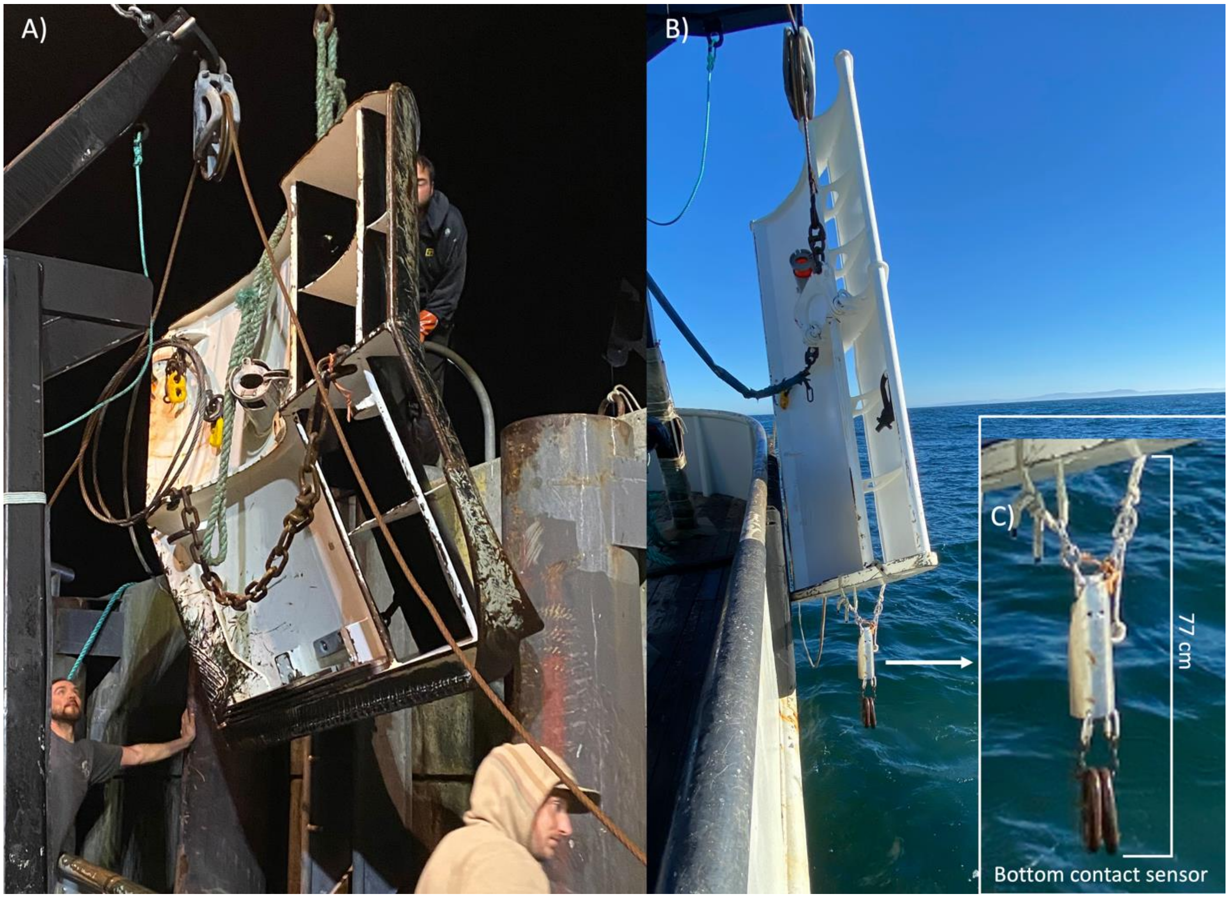

Figure 2. A) Image of the Thyborøn type-11 bottom trawl door (size = 4.8 m^2; weight = 995 kg [weight in air]) used on the conventional trawl; B) image of the NET Systems midwater series 2,000 trawl door (size = 4.5 m^2; weight = 568 kg [weight in air]) used on the semi-pelagic trawl; C) Image of a bottom contact sensor (altimeter) rigged to the port midwater trawl door of the semi-pelagic trawl.

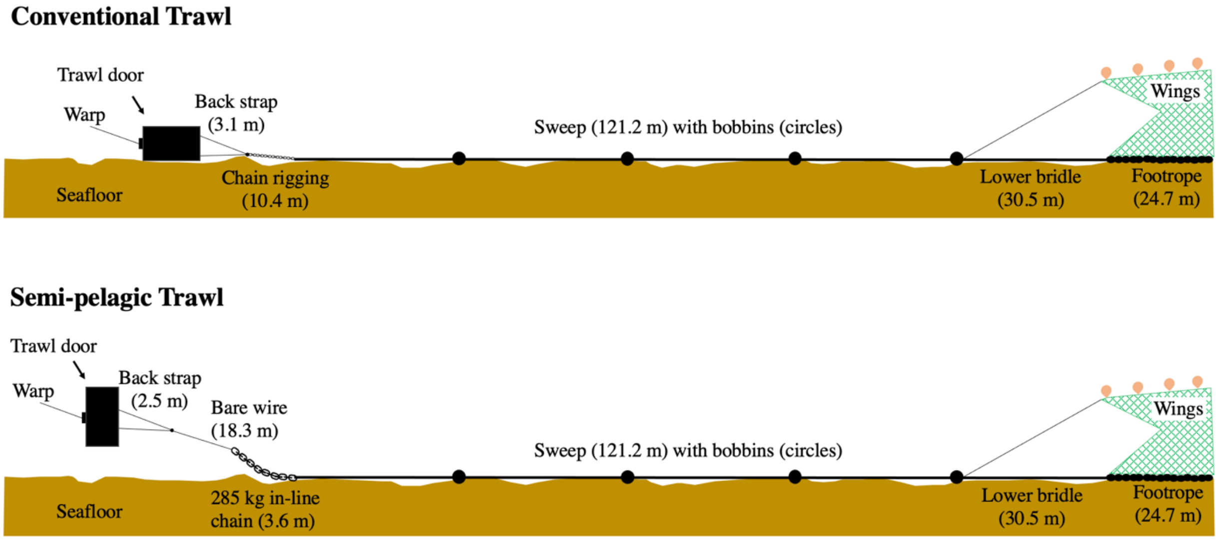

Figure 3. Conventional and semi-pelagic trawl gear configurations used during the sea trials. Numerical values in () are lengths of each section. Drawing is not to scale.

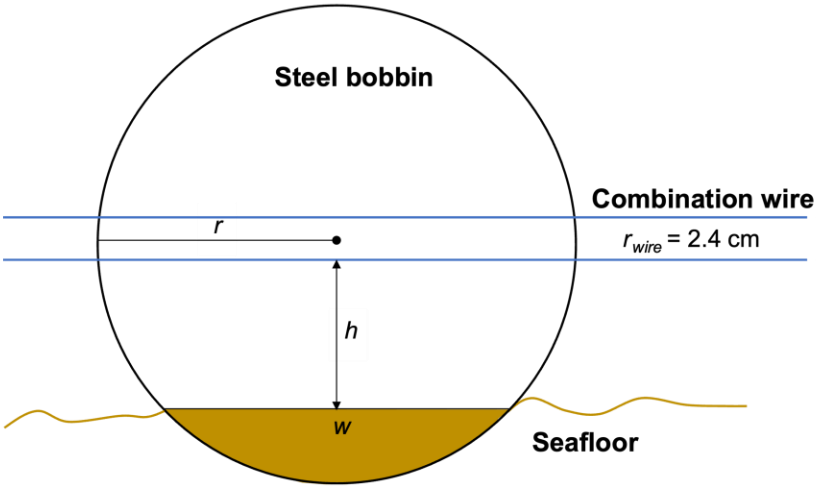

Figure 4. Illustration displaying the measurements used in Eq. 4, where *h* is the height between the seafloor and bottom of the combination wire, *r* is the radius of the bobbin (12.7 cm), *w* is the width of the bobbin track measured from the DIDSON sonar footage, and r_{wire} is the radius of the combination wire (2.4 cm). Drawing is not to scale.

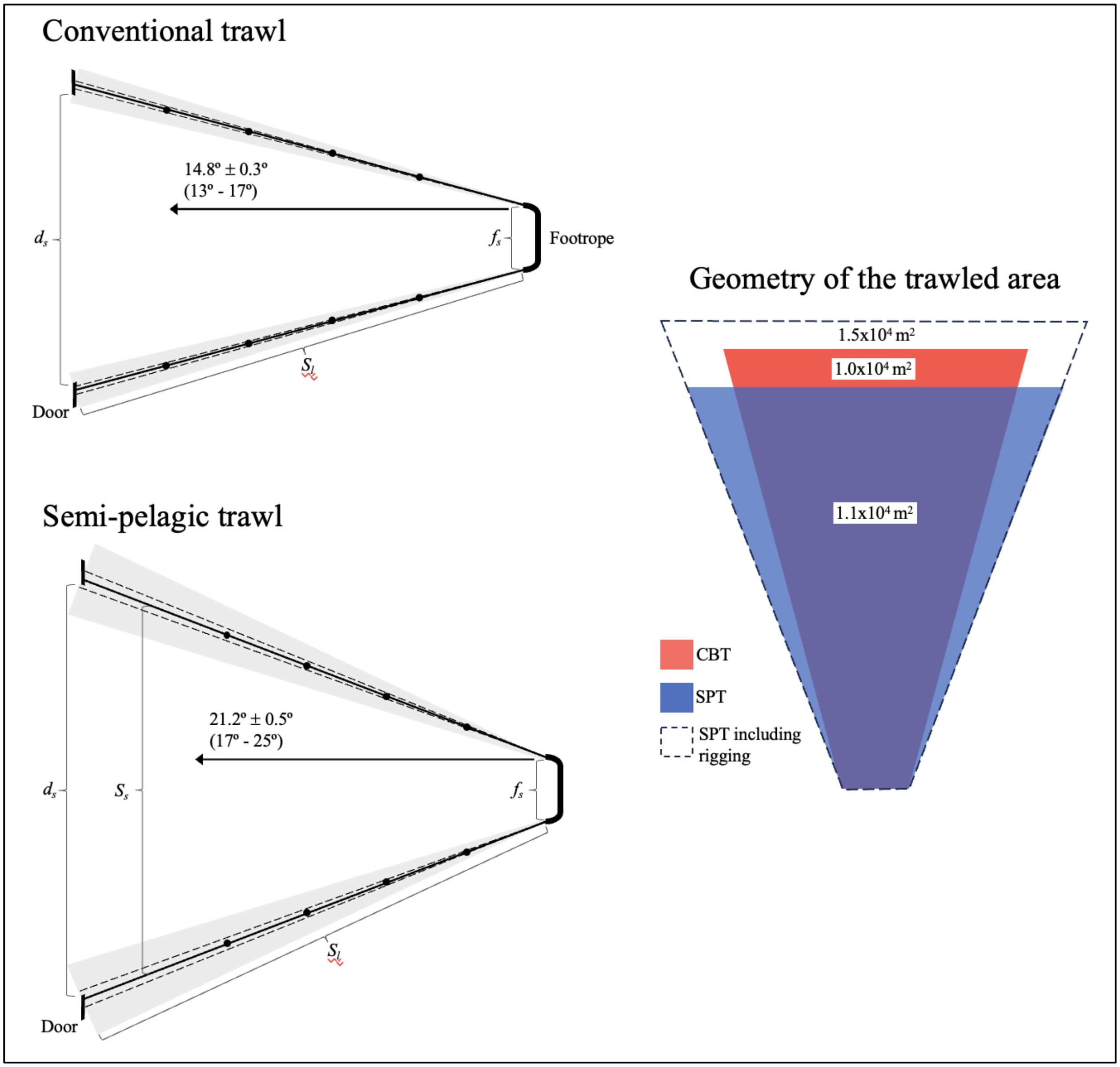

Figure 5. Average angle of attack of the sweeps (left) and geometry of the trawled area (right) of each trawl configuration tested. On the left, dashed lines represent standard errors, and the grey ribbon represents the maximum range of calculated sweep angles. d_s is the door spread distance, f_s is the footrope spread, S_l is the total sweep length including any rigging, and Ss is the estimated sweep spread between the first section of sweeps behind the in-line chain on the semi-pelagic trawl. The superimposed red and blue trapezoids on the right represent the available area between the doors and the footrope for the conventional trawl and semi-pelagic trawl.

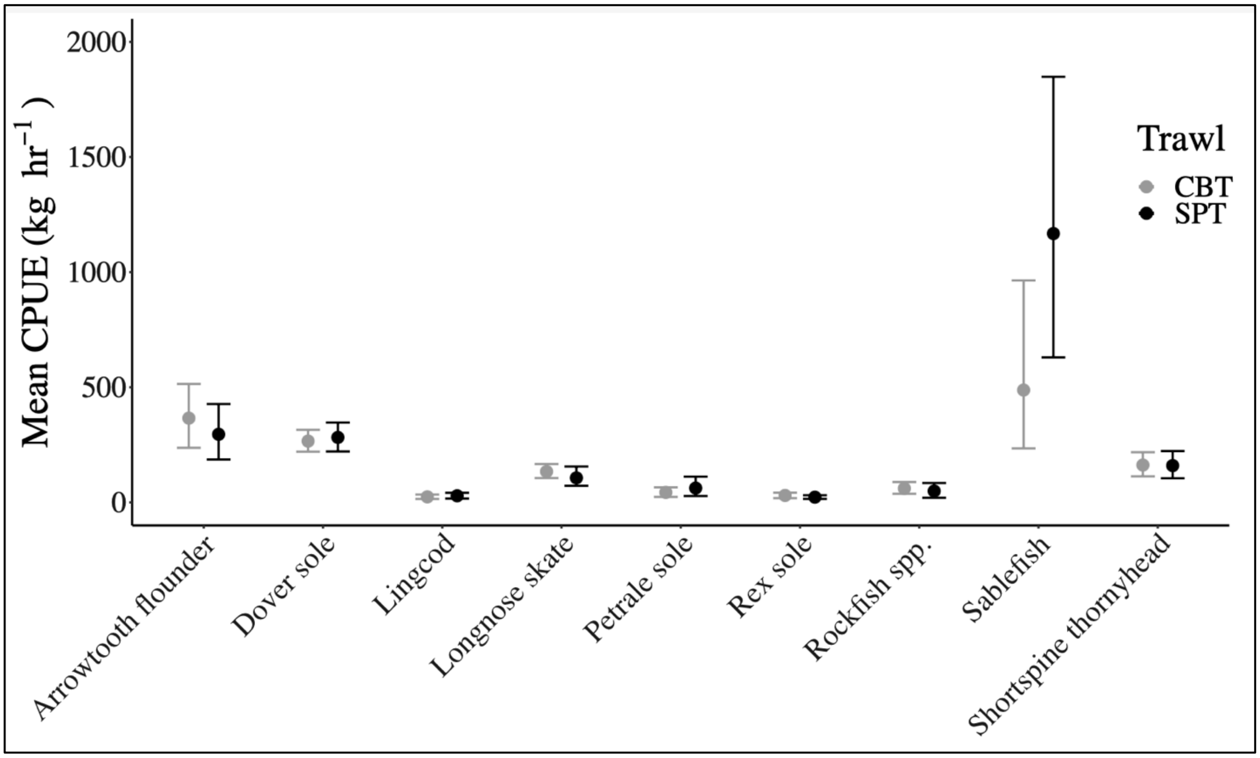

Figure 6. Mean CPUE of target and commonly landed groundfish species for each trawl configuration tested. Symbols represent the mean and vertical lines are the 95% CLs.

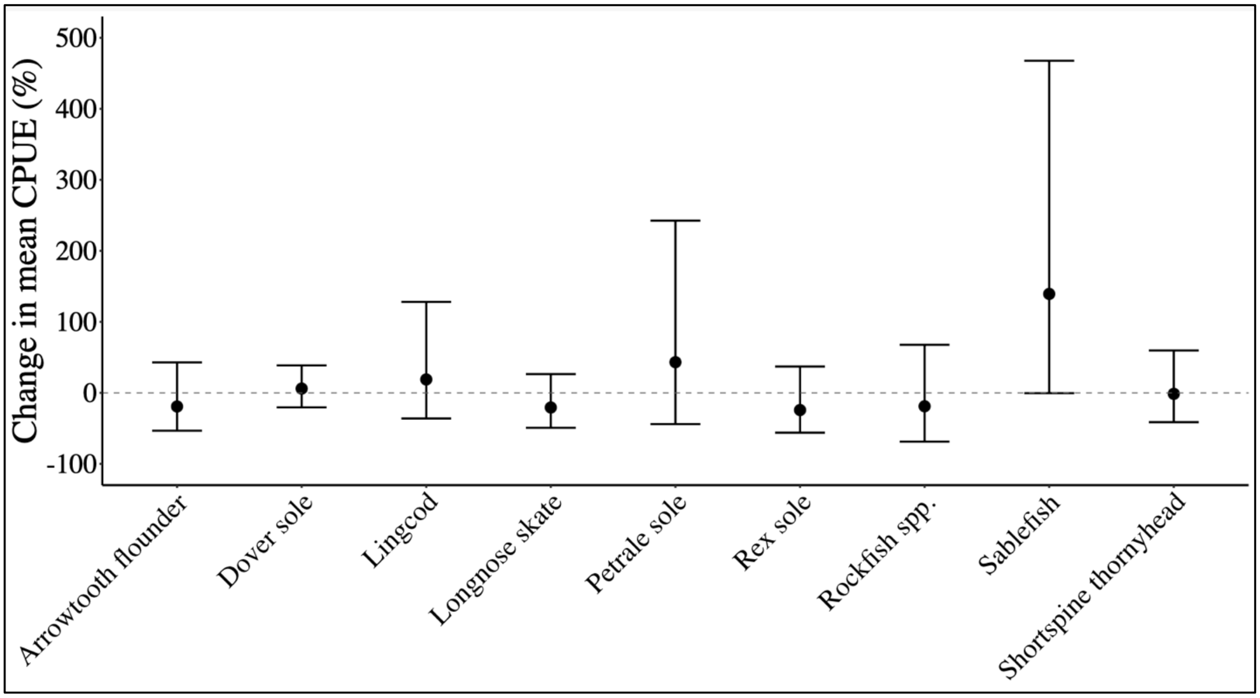

Figure 7. Difference in mean CPUE (%) between CBT and SPT configurations. Values above zero denote higher CPUE using the SPT and vice versa for values below zero. Symbols represent the mean and vertical lines are the 95% CLs.

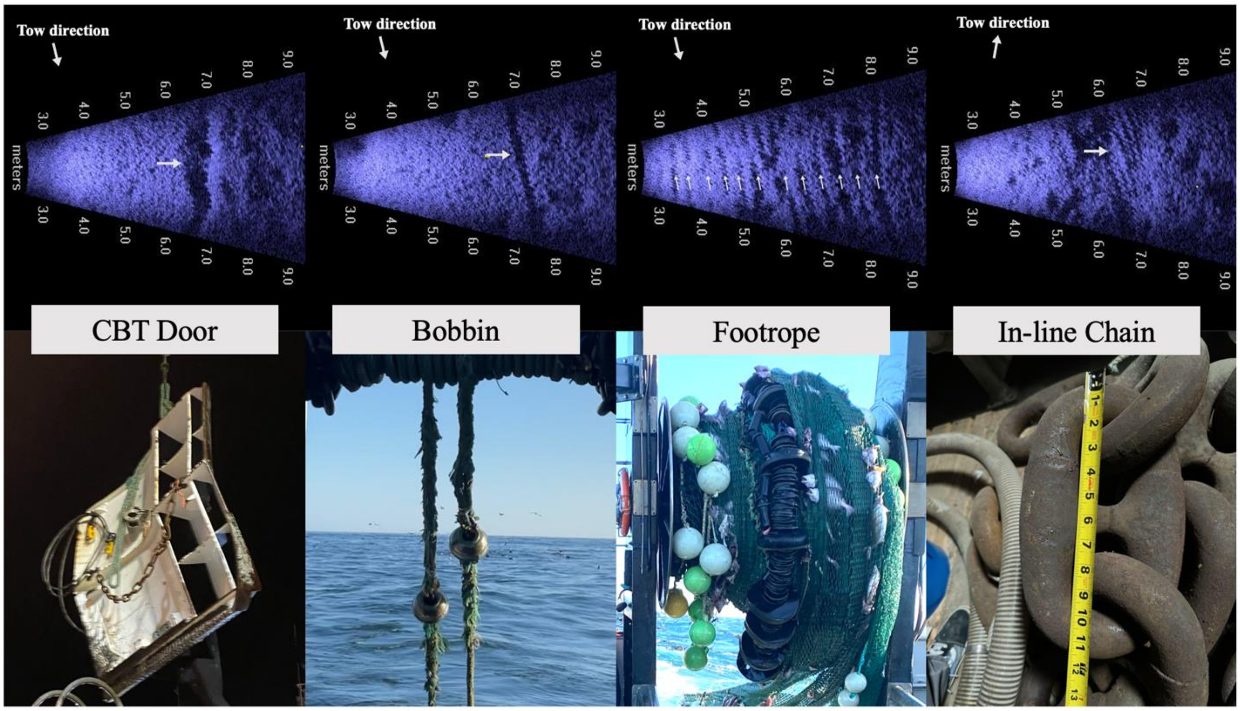

Figure 8. DIDSON sonar images (top row) of marks left by each groundgear component of the trawls (bottom row).

Table 1. Detail in which the conventional bottom trawl (CBT) and semi-pelagic trawl (SPT) designs were fished.

Date (dd/mm/year)	Trawl fished	Trawl doors used	# of tows
08/09/2021	CBT	Thyborøn type-11	2
09/09/2021	CBT	Thyborøn type-11	4
10/09/2021	SPT	NET Systems midwater 2,000 series	5
11/09/2021	SPT	NET Systems midwater 2,000 series	2
15/09/2021	SPT	NET Systems midwater 2,000 series	4
16/09/2021	SPT	NET Systems midwater 2,000 series	3
17/09/2021	CBT	Thyborøn type-11	4
18/09/2021	CBT	Thyborøn type-11	4
21/09/2021	CBT	Thyborøn type-11	5
22/09/2021	CBT	Thyborøn type-11	4
23/09/2021	SPT	NET Systems midwater 2,000 series	4
24/09/2021	SPT	NET Systems midwater 2,000 series	3

Table 2. Mean tow duration, tow spread, bottom depth, and door spread values for conventional bottom trawl and semi-pelagic trawl trials. An asterisk indicates statistically significant differences between trawl design. SE = standard error.

	Conventional bottom trawl		Semi-pelagic trawl	
Parameter	Mean (SE)	Range	Mean (SE)	Range
Tow duration (min.)	62.0 (0.8)	55-70	61.8 (1.8)	30-75
Tow speed (km h^{-1})	4.2 (0.02)	4.0-4.5	4.2 (0.03)	4.0-4.5
Bottom depth (m)	237.0 (9.4)	173-350	232.8 (10.3)	172-337
Door spread (m)	*107.8 (1.6)	97-121	*150.6 (3.2)	128-173

Table 3. Altimeter data showing the proportion of time the SPT doors spent on, off, and near the seafloor, and the height off bottom when within 77 cm of the seafloor, during the tow duration. SE = standard error.

Tow	Time on bottom (%)	Time off bottom (%)	Time near bottom (%)	Height off bottom (cm) (SE)
10	0.1	99.9	2.3	51.0 (1.3)
11	0.0	100.0	19.5	62.3 (0.1)
12	0.2	99.8	17.7	61.1 (0.3)
13	0.6	99.4	10.3	56.4 (0.6)
14	0.5	99.5	24.9	58.9 (0.3)
15	0.3	99.7	22.7	57.1 (0.4)
16	3.9	96.1	46.0	52.8 (0.3)
18	0.7	99.3	14.6	53.5 (0.5)
19	0.0	100.0	0.1	47.3 (5.6)
42	0.0	100.0	17.5	62.5 (0.1)
44	0.0	100.0	3.9	62.9 (0.1)
Mean (SE)	0.6 (0.3)	99.6 (0.3)	16.3 (3.6)	57.7 (0.1)