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ARTICLE

Evaluating Pacific salmon swimming behavior in the aft end of a pelagic trawl to inform bycatch reduction device design and use

David R. Bryan | **Noëlle Yochum** | **Katherine C. Wilson**

National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Alaska Fisheries Science Center, Resource Assessment and Conservation Engineering Division, Seattle, Washington, USA

Correspondence
David R. Bryan
Email: david.bryan@noaa.gov

Present address
Noëlle Yochum, Trident Seafoods, Seattle, Washington, USA

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Abstract

Objective: Although the bycatch of Pacific salmon *Oncorhynchus* spp. is relatively low in the Walleye Pollock *Gadus chalcogrammus* and Pacific Hake *Merluccius productus* pelagic trawl fisheries, different efforts are employed to reduce it, including the use of bycatch reduction devices (BRDs) that retain the targeted species and provide Pacific salmon a pathway to escape. The objective of this study was to evaluate Pacific salmon behavior inside a pelagic trawl and to determine what conditions favor the probability of a salmon moving forward in the trawl and increase their probability of escapement.

Methods: We placed a video camera at the entrance of the cod end and recorded the behaviors of Pacific salmon as they passed by. The timing of the forward movement Pacific salmon in relation to fishing operations and the correlations between forward movement of Pacific salmon and vessel speed over ground, water flow rate, ambient light levels, and abundance of Walleye Pollock were examined.

Result: Of the 2969 Pacific salmon observed, 71% were moving aft toward the cod end, 24% were observed moving forward, and 5% were moving aft then forward or forward then aft. The percentage (77%) and rate (0.86 fish per minute) of forward-moving Pacific salmon was greatest once the trawl doors were back on the vessel and water flow within the trawl was reduced. Speed over ground and Walleye Pollock abundance were negatively correlated with forward movement of Pacific salmon. Only 6.5% of Pacific salmon that were in the cod end when fishing ended were able to move forward before the cod end was on the vessel.

Conclusion: Pacific salmon can move forward in the trawl throughout fishing operations and haulback, but the percentage increases as the speed over ground and water flow inside the trawl is reduced. The low percentage of Pacific salmon that move forward after fishing has ended suggests that Pacific salmon escapement at the end of a tow is relatively low and suggests that BRD design should focus on stimulating escapement at the first BRD encounter.

KEYWORDS

bycatch reduction device, commercial trawling, conservation engineering, Pacific salmon, salmon behavior, underwater cameras

INTRODUCTION

Trawl fisheries often have to contend with bycatch, including species that can result in early fishery closures and catch quotas that are underutilized (Baudron and Fernandes 2015; Mortensen et al. 2018; Karp et al. 2023). Shifts in spatial and temporal patterns of fishing can limit unwanted catches in some fisheries; however, additional means are often necessary to aid in selectivity (Little et al. 2015). For example, bycatch reduction devices (BRDs) are used in a wide range of fisheries with varying levels of effectiveness (Kennelly and Broadhurst 2021). In cases where the target and nontarget species differ in size or shape, modifications in mesh sizes, panels, and grates can be successful in sorting out the catch (Santos et al. 2016; Palder et al. 2023). However, when both the target and nontarget species are morphologically similar, selective harvest can be more challenging (Beutel et al. 2008). Instead, BRD designs rely on biological or behavioral differences to separate the fish (He et al. 2008; Lomeli et al. 2018; Santos et al. 2022).

Due to limited information regarding fish behavior in and around trawls, a trial-and-error approach has typically been used to make modifications in fishing gear to reduce bycatch (Pol and Eayrs 2021). Although this approach is an important part of research, the indirect inference of fish behaviors and time-consuming nature of the work can hinder further developments for BRDs (Pol and Eayrs 2021). Another approach is to conduct research to understand fish behavior and to use that knowledge to make gear modifications that could reduce bycatch. Although it is technically challenging to observe fish and quantify their behavior as they interact with the gear, video observations can help with this and several such studies have been conducted (Jones et al. 2008; Queirolo et al. 2010; Robert et al. 2020; Santos et al. 2020). Examples of fish behavior that have been studied as a way to reduce bycatch include species-specific tendencies to rise in a trawl or avoid lights along with attributes such as swimming speeds and endurance (Beutel et al. 2008; Hannah and Jones 2012; Lomeli and Wakefield 2019).

For over two decades, there has been a focus on developing BRDs for Pacific salmon *Oncorhynchus* spp. (primarily Chum Salmon *O. keta* and Chinook Salmon *O. tshawytscha*) that are incidentally caught in the fishery for Walleye Pollock *Gadus chalcogrammus* in Alaska (Stram and Ianelli 2009) and in the U.S. West Coast groundfish fishery targeting Pacific Hake *Merluccius productus*, but there has been limited research evaluating their behavior inside the fishing gear. Escapement rates from BRDs have varied during trials (Lomeli and Wakefield 2019; Yochum et al. 2021), and the reasons for these differences in escapement rates are uncertain. After a salmon has entered the trawl mouth, they are presumed to be forced back toward the cod end along with the rest of the catch. It is during this aft-ward travel that a salmon first encounters the BRD, but many of these BRDs rely on a salmon's ability to move forward in the trawl (against the direction of the water flow) to access the escapement pathway provided by the device (e.g., Gauvin et al. 2015). The optimal conditions enabling salmon to move forward are unknown, but previous observations of salmon in trawls suggest that a large amount of forward movement of salmon occurs during haulback when vessel speeds are reduced (Gauvin et al. 2011; Yochum et al. 2021).

Impact statement

A better understanding of Pacific salmon behavior inside of a pelagic trawl can be used to improve the design and use of devices that allow salmon to escape while retaining species that are targeted. Here we placed a camera near the end of a trawl to examine how Pacific salmon behave under varying fishing and environmental conditions.

The Alaska Walleye Pollock fishery is the second largest single-species fishery in the world by volume and has a tremendous economic value for the state of Alaska (Witherell et al. 2002; Ianelli et al. 2020), and the U.S. West Coast Pacific Hake fishery is the largest groundfish fishery by volume along that coast (Richerson et al. 2020). In the Pacific Hake and Walleye Pollock fisheries, a variety of regulations are in place to minimize Pacific salmon bycatch. Chinook Salmon in the Bering Sea are managed as a protected species by the North Pacific Fishery Management Council, and their bycatch in the Walleye Pollock fishery has been monitored and managed for over a decade with bycatch limits that can close the Walleye Pollock fishery if reached (Stram and Ianelli 2015; Sugihara et al. 2018). Similarly, in the Pacific Hake fishery, bycatch caps for Chinook Salmon have been in place since 2005 and various incentives and techniques are used to minimize their bycatch (Holland and Martin 2019). Given the importance of the Walleye Pollock and Pacific Hake fisheries and the status of Pacific salmon stocks, significant effort is taken to reduce salmon bycatch.

The objective of this study was to evaluate Pacific salmon behavior inside a pelagic trawl and to determine what conditions favor the probability of a salmon moving forward in the trawl. To do this, we placed an underwater video camera at the entry to the cod end of a pelagic trawl while fishing for Walleye Pollock in regions of the eastern Bering Sea where salmon were likely to be encountered. We evaluated the effects of ambient light level, vessel speed over ground, water flow, and Walleye Pollock abundance on the movement of salmon near the cod end of a trawl. We also evaluated the timing of salmon moving forward in the trawl in relation to phases of fishing operations. A better understanding of forward movement behavior of salmon and the stimulus affecting it may inform BRD design and fishing techniques that can be used to reduce bycatch.

METHODS

In 2021, the FV *Pacific Explorer*, a 46-m trawl vessel, was chartered to fish under a scientific research permit for Walleye Pollock in the eastern Bering Sea, delivering fish to a plant in Akutan, Alaska, on fishing grounds where Pacific salmon were likely to be present (from −165.78° to −165.25° and 55.25° to 54.32°). The pelagic trawl had a 186-m-long footrope and 188-m-long headrope. The length of the net from the mouth to the start of the funnel section was 190 m. The net was followed by a 10-m section that included the BRD, two 10-m intermediate sections, and the approximately 160-metric-ton cod end made from 10.2-cm (4-in) diamond mesh. A Rope, Tube, and Funnel (RT&F) BRD (as described in Yochum et al. 2021) was present for all tows in the last tapered section of the pelagic trawl used on the vessel. This BRD differs from that most commonly used in the fishery in that it provides salmon the ability to escape without having to swim forward to access the escapement area and provides more area to escape. Over the course of four trips from July 15 to July 27, we collected video data in seven tows. While the research tows were similar to commercial tows in the locations fished and gear used, tow duration was limited due to battery run time of our camera system and to maximize the number of tows that could be completed during the day. Tows were conducted during daylight from 0930 hours to 1900 hours (sunrise = 0600 hours and sunset = 2230 hours).

Abiotic data

Vessel positions were recorded at 30–90-s intervals throughout each tow with GPS and used to calculate speed over ground (m/s). The time at which the trawl went out, fishing commenced, haulback began, the doors were on the deck, and the net was onboard were all recorded.

A light, depth, and temperature data logger (MK9; Wildlife Computers) was placed aft of the BRD escapement area and recorded data every 30 s. The light levels recorded by the MK9 loggers are provided as scaled relative units of irradiance (W/cm^2) that range from 25 to 225, corresponding to intensities ranging from 10×10^{-12} W/cm^2 to 5×10^{-2} W/cm^2. A second data logger (TDR10-DD; Wildlife Computers) was placed near the camera system forward of the cod end that recorded water flow at 1-s intervals and depth and temperature at 30-s intervals. We used linear interpolation to calculate MK9 light levels and TDR10-DD depth and temperature estimates at 1-s intervals to match with Pacific salmon observations.

Flow data were recorded at 1-s intervals, and outlier data points (>4 m/s and <0.02 m/s) were removed from the data set. At a 1-s interval, there was significant variability in flow measurements, and these data were smoothed using a 60-s running mean. Two different TDR10-DD devices were used for this project, and previous research has indicated possible differences in flow readings among devices (Yochum et al. 2021). Due to these earlier findings of inconsistency in measurements, we standardized the running mean flow by subtracting the tow mean from the observation and dividing by the standard deviation (SD) of the mean tow flow to create a relative value in order to compare flow rates across tows with different devices.

Pacific salmon data

Video was recorded using a trawl camera system depth-rated to 1000 m (The Sexton Corporation). The camera recorded wide-angle 1080p HD video at 30 frames/s. Illumination was provided by two red LED lights (peak wavelength = 650–670 nm) placed on either side of the camera within the housing and four red Lindgren-Pitman electralume lights (peak wavelength = 632 nm; Nguyen et al. 2017) placed on the bottom panel of the trawl from port to starboard sides 2 m aft of the camera. The camera system was attached 1 m forward of the start of the cod end at the center of the top panel facing aft at an approximately 20 degree angle down from horizontal (Figure 1). The diameter of the cod end at this position was approximately 2.75 m, and the camera system and position provided a view of approximately a 4-m section (lengthwise) of the trawl. Video data were recorded from when the trawl first went into the water until it was back on deck. Total weight of the Walleye Pollock catch for each tow was estimated by the captain ("hail weights"), and the total catch was weighed at a fish processing plant at the end of each

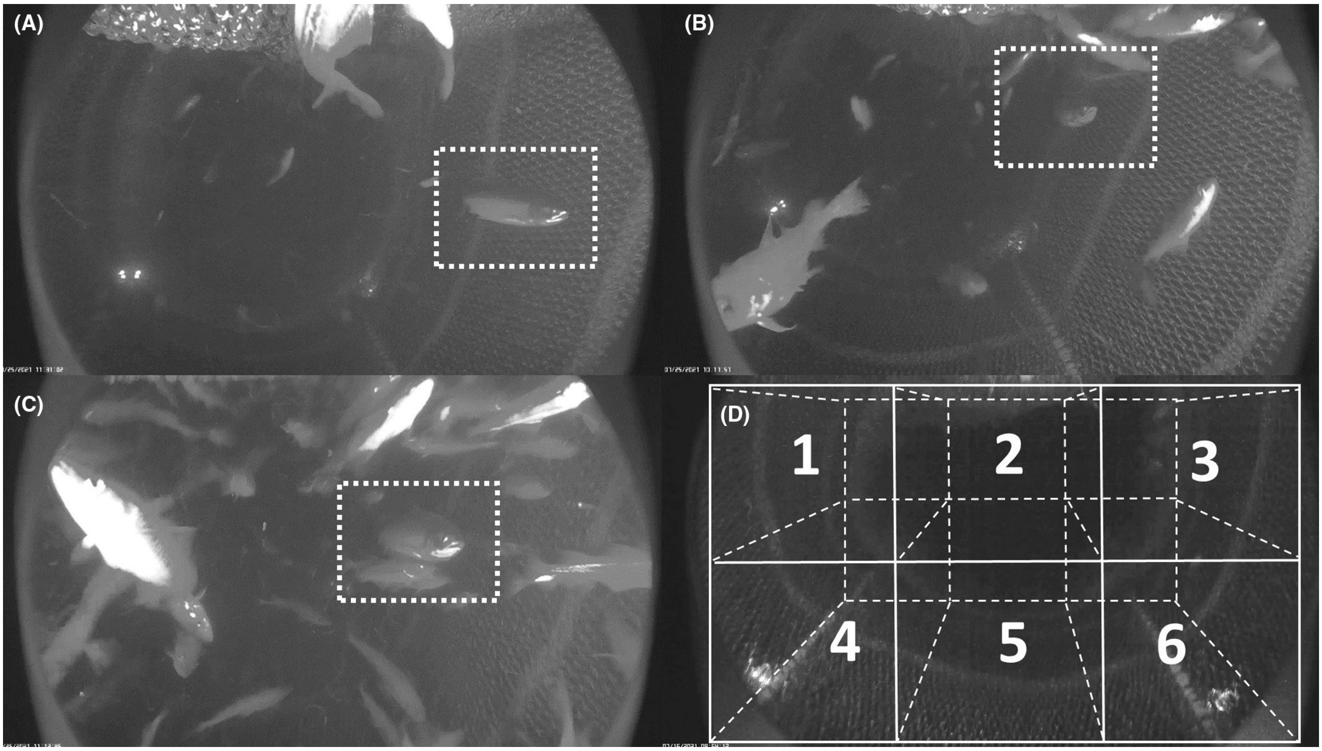

FIGURE 1 Views of Pacific salmon swimming forward (inside the dashed box) from the camera facing aft toward the cod end during (A) low, (B) medium, and (C) high abundances of Walleye Pollock. Panel (D) shows the three-dimensional grids used for Pacific salmon locations. Auxiliary red lights are seen on the bottom port and starboard sides of the bottom panel of the trawl and are seen as white lights in this figure.

trip. Additionally, 100% of the catch was observed prior to going into the fish hold on the vessel. A Walleye Pollock catch rate (metric tons per minute was calculated by dividing the hail weights by the fishing duration for each tow). All of the Pacific salmon that did not escape (landed salmon) were counted and measured after each tow.

Video was reviewed in gray scale by a single reviewer using VLC Media Player (VideoLAN). The time at which a Pacific salmon was first and last seen was recorded, along with its heading, which was defined as the direction it was moving relative to the net ("forward" was toward the mouth of the net; "aft" was toward or into the cod end). Each time a salmon entered the field of view it was considered a new observation as we were not able to determine if an individual fish left and reentered the field of view. Salmon that were moving aft when first seen and then went back forward out of view during their observation were recorded as aft–forward, and those that were moving forward from the cod end when first observed and then returned aft were recorded as forward–aft. The orientation of each salmon (head facing forward, aft, side-on, or vertical [head facing upwards]) was recorded when first and last observed. The duration (seconds) that a salmon was observed was recorded. When a salmon was in the frame, Walleye Pollock abundance was recorded as either none, low (1–5 individuals), medium (6–20), or high (21+) (Figure 1A–C). The video frame was visually divided into six three-dimensional grids within the trawl (Figure 1D). Areas 1–3 were along the top of the trawl from starboard to port, and areas 4–6 were along the bottom of the trawl from starboard to port. The location in the video frame where salmon were first and last observed was recorded. If a fish was observed across more than one grid, the fish was assigned to the grid that contained the majority of its body. When the trawl doors were on the deck of the boat, the trawl geometry was often changing (billowing or collapsed). This made the determination of a salmon's location in the trawl difficult, so location was not recorded during this tow period.

Data analysis

We used R (R Core Team 2021) to calculate all summary statistics, produce data visualizations, and conduct our statistical analyses.

A mixed-effects logistic regression model was used to determine if the probability of a Pacific salmon moving forward or aft was influenced by light level, speed over ground, water flow measured near the camera, and the number of Walleye Pollock present during the observation, with the tow number added as a random effect (Bates et al. 2015). The range of relative scaled values of light intensity were better suited and used for this modeling compared with the corresponding irradiance values.

Salmon orientation was not included as a variable in this analysis as forward-moving salmon were all oriented facing forward. Collinearity and multicollinearity among abiotic variables were a concern and were tested with two different methods. A Pearson's correlation test was used to measure the associations among light level, speed over ground, and water flow data ($\alpha = 0.05$). A variance inflation factor for each predictor variable in our model was also calculated (Fox and Weisberg 2019). Finally, we used a likelihood ratio test to compute the global *p*-value for the ordinal estimates of Walleye Pollock abundance and the multcomp package (Hothorn et al. 2008) to calculate Tukey's multiple comparisons tests of means among the four levels of Walleye Pollock abundance ($\alpha = 0.05$).

To investigate differences in forward- and aft-moving Pacific salmon during the course of a tow, each tow was divided into three tow periods: (1) fishing period—the time during which the net was open and being towed for catching fish, (2) haulback period—part of gear retrieval from when the trawl wires began to be wound in until the trawl doors were returned to the vessel, and (3) doors-up period—the remaining duration of gear retrieval from when the trawl doors were onboard the vessel until the camera came out of the water. No salmon were observed prior to the fishing period so data collected during gear setting were not included in this study. Differences in light level, speed over ground, and water flow among tow periods were tested individually with ANOVA tests using tow number as an additional explanatory variable ($\alpha = 0.05$). We also used a second mixed-effects logistic regression model with tow added as a random effect to test if the probability of a salmon moving forward or aft was influenced by the tow period ($\alpha = 0.05$). Salmon orientation was not included as a variable in these analyses.

The percentage of forward-moving Pacific salmon in each tow period (fishing, haulback, doors-up) was calculated as the total number observed moving forward divided by the total number of all salmon observed during that period. We also calculated the rate of forward-moving salmon by dividing the total number of forward-moving salmon during a period by the period duration.

We looked at the timing of Pacific salmon accumulation in the cod end of the trawl by designating each aft-moving salmon as +1, each forward-moving salmon as −1, and aft–forward and forward–aft salmon as 0 and then plotting the consecutive sums of these values for each tow. For some tows, during the doors-up period, more salmon were observed moving forward than aft. These salmon were considered "potential escapees at doors-up." To get a better understanding of the importance of the doors-up period for escapement, we compared the number of potential escapees among tows by dividing the net number of forward-moving salmon (forward minus aft) during the doors-up period by the total number of salmon that were landed in each tow. Finally, to estimate a detection probability, we divided the net number of salmon (aft minus forward) that were detected going into the cod end by the total number of salmon that were landed in each tow.

RESULTS

Abiotic data

During the seven tows conducted during the 2021 charter, the mean duration of the fishing period was 188 min (range = 126–236 min; Table 1). The mean duration of the haulback period was 8 min (range = 6–11 min), and the mean duration of the doors-up period was 27 min (range = 21–36 min). There were significant differences in light level, speed over ground, and water flow among the different tow periods ($p < 0.01$). The mean speed over ground during the fishing period was 1.9 m/s and was

TABLE 1 Abiotic, landings, and select video data summarized by tow.

Metric	Tow 1	Tow 2	Tow 3	Tow 4	Tow 5	Tow 6	Tow 7
Duration of fishing period (min)	155	227	216	205	126	236	151
Duration of haulback period (min)	10	8	6	11	6	8	8
Duration of doors-up period (min)	21	23	26	28	25	36	26
Mean speed over ground (m/s) during fishing period	1.8	1.8	2.2	1.9	1.9	1.9	1.8
Mean speed over ground (m/s) during haulback period	1.1	1.2	1.4	1.1	1.0	0.9	1.2
Mean speed over ground (m/s) during doors-up period	0.7	1.0	1.4	1.3	1.0	1.0	0.9
Mean water depth (m) during fishing period	102.2	111.3	94.2	134.1	130.2	131.6	131.3
Walleye Pollock catch (metric tons, captain's estimate)	55	100	65	28	55	10	45
Number of Pacific salmon landed	81	76	54	906	549	176	170
Cumulative number of Pacific salmon observed at the cod end camera	45	45	26	862	190	127	79
Mean length of caught Pacific salmon (cm)	51.4	53.0	55.0	51.1	51.2	50.5	50.0

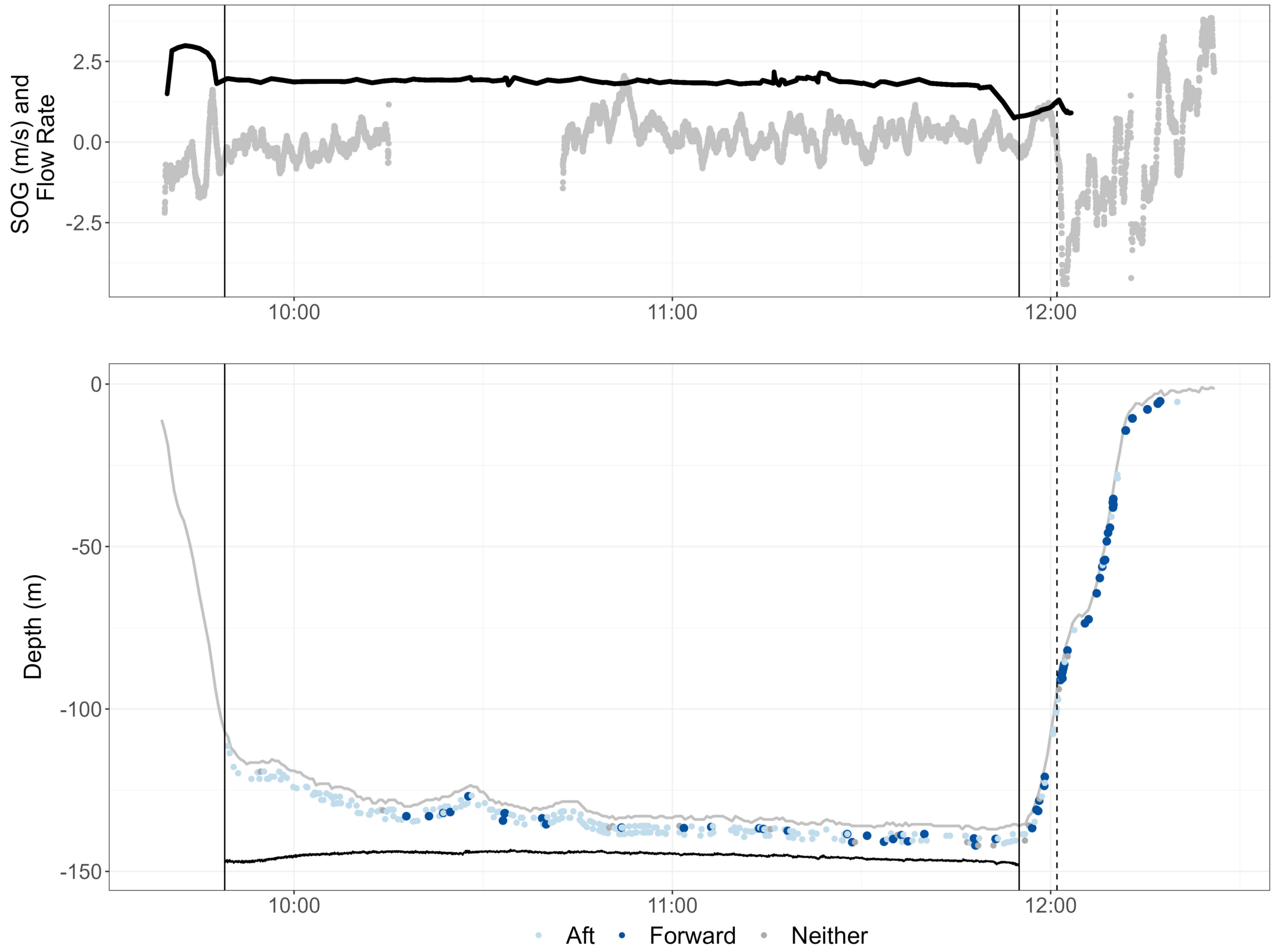

FIGURE 2 Time series plots of abiotic and Pacific salmon observations for a single tow. The top panel shows speed over ground (SOG; black line) and standardized water flow rate in the cod end (gray). The solid vertical lines indicate the start and end of the fishing period. The dashed vertical line indicates the time at which the doors were on the vessel deck. In the bottom panel, the times of first observation of Pacific salmon are shown by points that are color-coded by whether they were moving forward (dark blue), aft (light blue), or either aft–forward or forward–aft ("Neither"; dark gray). The gray line indicates the depth recorded at the camera, and the black line indicates bottom depth recorded from the trawl sonar.

consistent among tows (±0.1 SD). Mean ± SD speed over ground slowed during the haulback period as wire was wound in (1.1 ± 0.2 m/s) and remained the same during the doors-up period (1.1 ± 0.2 m/s).

The mean depth at the camera near the cod end during the fishing period was 119 m (range = 94–134 m). During the doors-up period, the mean depth was 27 m; however, when the doors first came on deck, the cod end was at a depth that was on average 73% of the mean depth during the fishing period (Figure 2). Water temperatures at the cod end were consistent during the research trip, with an average of 4.6°C and 4.7°C during the fishing period and haulback period, respectively, and 7.9°C during the doors-up period.

Water flow data from the cod end was usable for six of the seven tows. During the short duration of the haulback period, flow was variable across tows. For four tows water flow during haulback was greater than during the fishing period, and for two tows it was less. During the doors-up period, flow was variable within the tow, but the average was always less than during the fishing period. The mean reduction in flow from the fishing period to the doors-up period for all tows was 21.9%. However, there were some differences among tows; two tows had minimal reductions in water flow rate (6–8%) compared with the reductions measured during other tows (29–46%).

There were similar patterns of light level, speed over ground, and water flow for all tows 30 min before and after haulback (Figure 3). We found that there were small ($r \le 0.5$), but significant ($p \le 0.001$), correlations between the light level, speed over ground, and water flow when Pacific salmon were observed. Light level was negatively correlated with speed over ground and water flow, while speed over ground and water flow were positively correlated. Variance inflation factor values for each of these

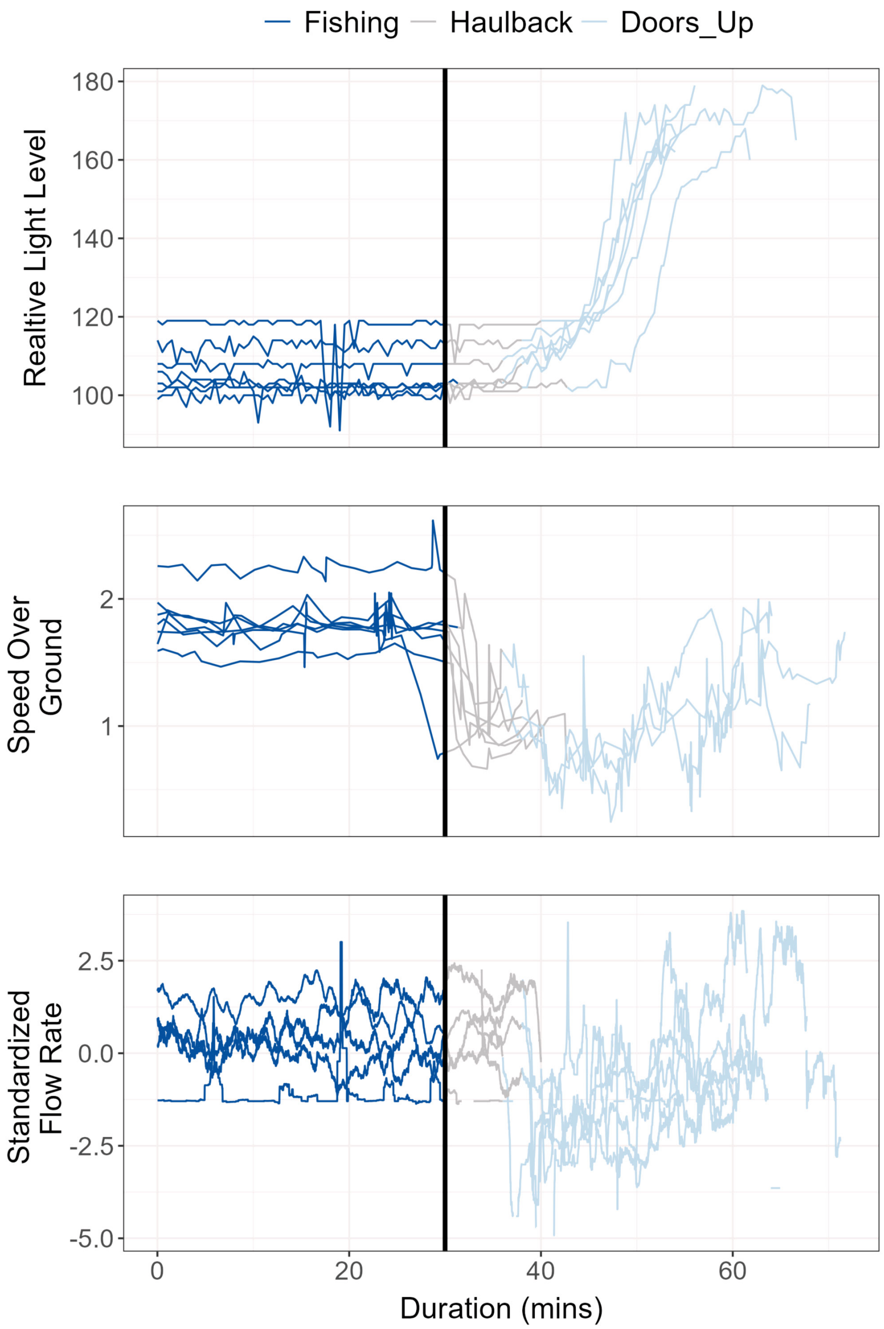

FIGURE 3 Relative light levels (W/cm^2), speed over ground (m/s), and standardized water flow rate for each tow from 30 min before the start of the haulback period (vertical black line) until the trawl was on the deck of the boat.

TABLE 2 The *p*-values and variance inflation factors (VIFs) from the mixed-effects logistic regression on the direction a Pacific salmon was moving. A global *p*-value is shown for the ordinal Walleye Pollock abundance variable.

Effects	*p*-value	VIF
Light	1.07×10^{-4}	1.16
Speed	2.10×10^{-7}	1.14
Flow	1.16×10^{-5}	1.04
Walleye Pollock	1.56×10^{-15}	1.07

predictor variables and the categorical estimate of the number of Walleye Pollock present in our salmon regression model were below 2, indicating minimal multicollinearity (Table 2) (Graham 2003).

Video data

During 1612 min of video taken across seven tows, there were a total of 2969 Pacific salmon observations. All of the salmon landed in the tows reviewed for this analysis were Chum Salmon, and their average ± SD length was 51.2 ± 3.5 cm. Total catches of Walleye Pollock per tow ranged from 10 to 100 metric tons, which, although low compared with industry standards, had similar catch rates as other vessels in the area (our tow durations were shorter). The number of salmon observations varied widely among tows (Table 1). During video review, we observed 68.3% (range = 34.6–95.1%) of the salmon landed ($n = 2012$) across all of the tows. There was a nonsignificant linear trend ($p = 0.06$) of decreasing salmon detection rates with increases in Walleye Pollock catch rates (Figure 4). The majority of salmon detected (71%) were observed moving aft toward the cod end, and approximately a quarter (24%) were observed moving forward. A small number of salmon (5%) were observed either moving aft then forward or forward then aft.

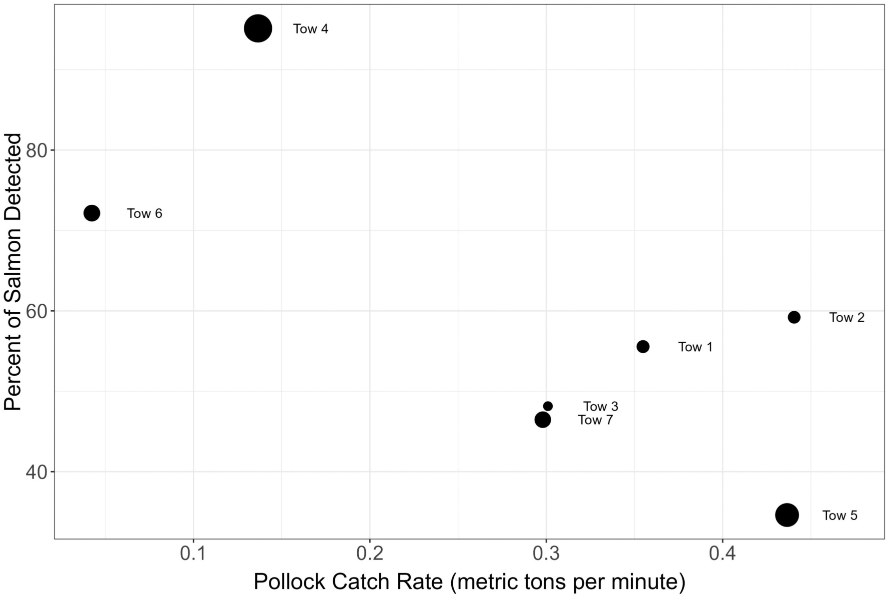

FIGURE 4 Percentage of Pacific salmon detected compared with the estimated Walleye Pollock catch rate in metric tons per minute. Point sizes are scaled to the number of Pacific salmon caught, which ranged from 54 to 906. Larger points indicated tows with a greater number of Pacific salmon caught.

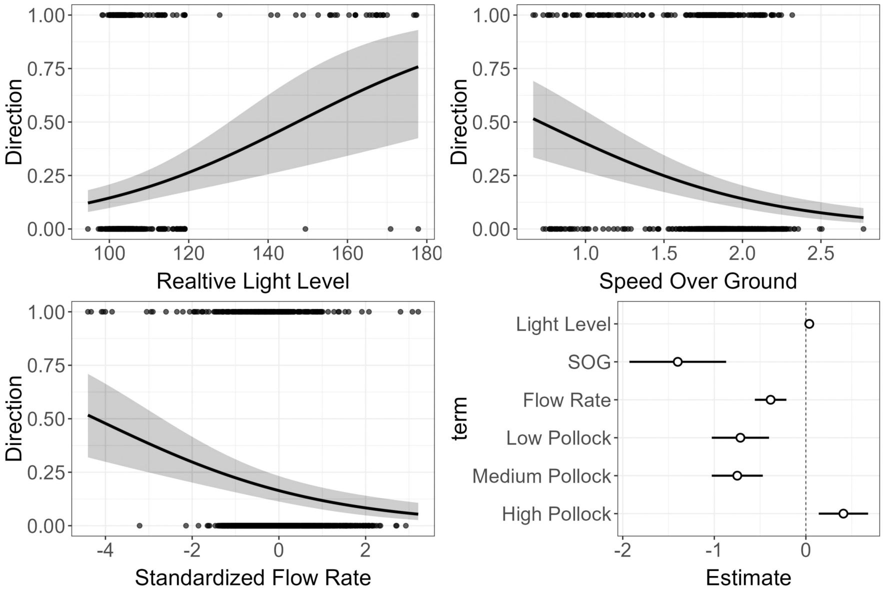

FIGURE 5 Binomial logistic regression of the direction a Pacific salmon was moving (forward [1] or aft [0]) for relative light level (W/cm^2), speed over ground (SOG; m/s), and standardized water flow rate. The black line shows the mean predicted value of Pacific salmon direction, and the gray shading represents a 95% confidence interval. The bottom right panel shows the coefficient estimates (open circles) for each term in the model, including Walleye Pollock abundance. The horizontal bars represent a 95% confidence interval.

Our logistic regression model suggested that light level, speed over ground, water flow, and Walleye Pollock abundance each had a significant effect on the probability of a Pacific salmon moving forward (Table 1; Figure 5). Salmon were more likely to be observed moving forward as light levels increased and as the speed over ground and water flow declined. The abundance of Walleye Pollock in the field of view also had a significant effect on the probability of a salmon moving forward. Tukey's test suggested that there was a higher probability of salmon moving forward when Walleye Pollock abundance was low (33.1%) than when abundance was medium (29.7%) or high (19.6%) or when no Walleye Pollock were present (15.2%).

The probability that a Pacific salmon was moving forward was significantly different between tow periods ($p \leq 0.001$). During the fishing period, 18% of salmon observed were moving forward (Figure 6), during haulback the percentage increased to 51%, and during the doors-up period most salmon were moving forward (77%). The average rate of forward-moving salmon among tows was 0.32 salmon/min during the fishing period and 0.86 salmon/min during the doors-up period.

The location of aft-moving Pacific salmon when first observed ($n = 1989$) was consistent among tows, with most salmon first observed on the bottom on the trawl (54.3%; grids 4–6 in Figure 1) and the top port side (23.1%; grid 3). Only 6.4% were observed at the top center (grid 2) where the camera was located. When last observed, the majority of aft-moving salmon were in the top of the net, with grid 2 as the most common location (42.1%). This trend of fewer salmon observed in grid 2 when first seen than when last seen was reversed when they were moving forward ($n = 453$). When moving forward during the fishing period, 37.1% were first observed in the top center (grid 2), and when last seen, the majority (79.4%) were observed in the bottom of the trawl (grids 4–6).

During the fishing period, 71% of the Pacific salmon that were moving aft were forward-oriented when first observed. For the remainder of aft-moving salmon during this period, 4.9% were aft-oriented, 20.7% had their side facing the camera, and 3.4% were vertically oriented with their head facing toward the top of the trawl. These ratios of orientations during the fishing period were consistent among tows. Salmon orientation after fishing stopped, particularly during doors-up, was more variable as salmon actively swam forward then aft (Figure 7).

During the fishing period, Pacific salmon that were moving aft were observed in the field of view for an average of 7.9 s compared with 14.5 s during the haulback period and 13.1 s during the doors-up period. Forward-oriented salmon were observed for an average of 9 s, while aft-oriented salmon were observed for 2.2 s. Although the majority of salmon (73.4%) moving aft during the fishing period moved through the field of view quickly (5 s or less), some salmon were able to hold station in this section of the trawl, with 1.2% of aft-moving salmon remaining within the view for >1 min. When moving forward, the average observation time was 12.3 s during the fishing period, 7 s during the haulback period, and 25.5 s during the doors-up period.

The accumulation of Pacific salmon in the cod end was not linear, and the number of salmon in the cod end typically peaked at the end of the fishing period (Figure 8). For most tows, more salmon were recorded moving

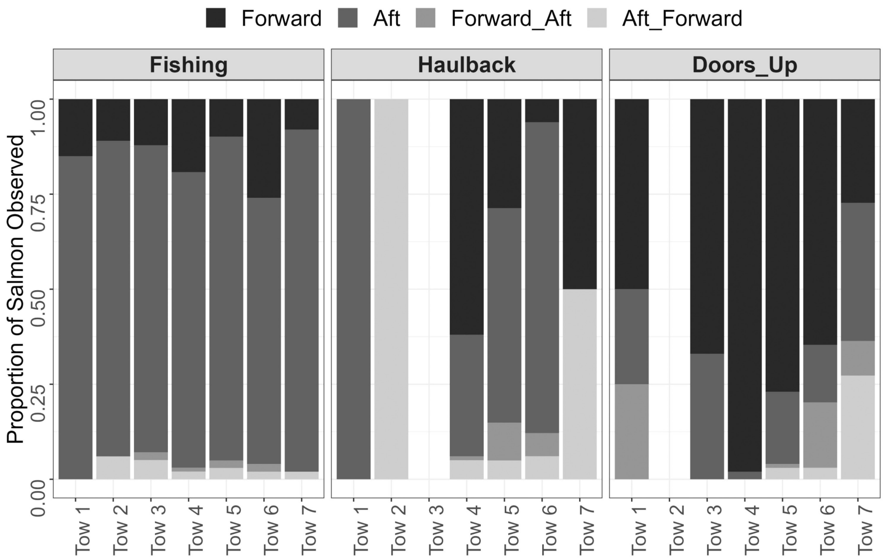

FIGURE 6 Proportion of Pacific salmon observed from video footage moving either forward, aft, forward–aft, or aft–forward by tow during three different fishing periods (fishing, haulback, and doors-up). No bar indicates that no Pacific salmon were observed during that fishing period in a tow.

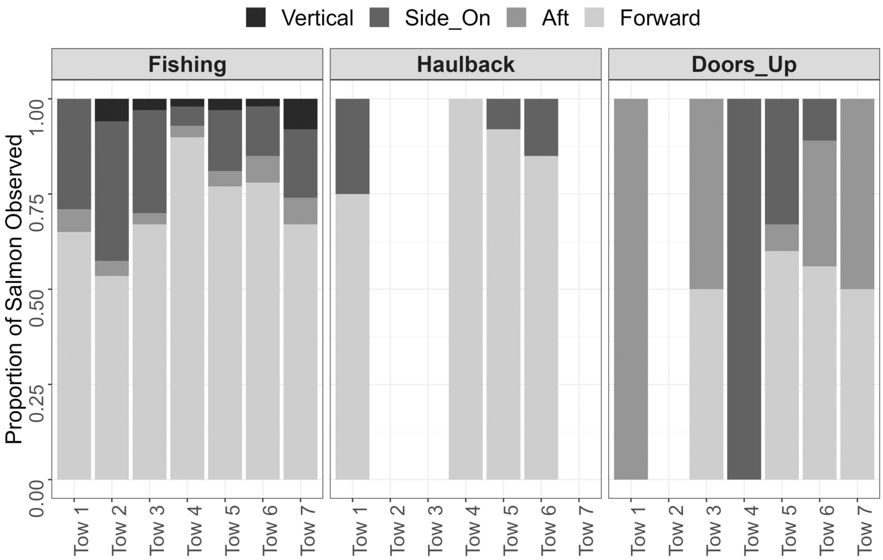

FIGURE 7 Orientation of aft-moving Pacific salmon when they were first observed by tow during three different fishing periods (fishing, haulback, and doors-up). No bar indicates that no Pacific salmon were observed during that fishing period in a tow.

forward versus aft during the doors-up period resulting in slight reduction in the number of salmon in the cod end at the end of the tow. The number of salmon observed moving forward during the doors-up period as a percent of the number of salmon landed in the tow averaged 6.5% (range = 0–17.8%) across tows.

DISCUSSION

The use of BRDs in the Alaska Walleye Pollock fishing fleet is an important component of a multifaceted approach to reducing Pacific salmon bycatch (Stram and Ianelli 2015). Differences noted in the escapement rates among several BRD designs (Lomeli and Wakefield 2019; Yochum et al. 2021) suggested that a better understanding of salmon behavior within a trawl was needed. In this study, we focused primarily on the behavior of salmon at the entrance to the cod end of a pelagic trawl to investigate the timing of when salmon move forward and the stimuli associated with that behavior. Although this research was conducted using one BRD design (the RT&F), the salmon behaviors noted are relevant to BRD design and use in general.

Previous review of underwater video within pelagic trawls suggested that forward-moving Pacific salmon during gear retrieval might have a large influence on the escapement rates associated with salmon BRDs (Yochum et al. 2021). Gear retrieval is typically considered the time from when fishing stops and the trawl is being hauled in until the time when the cod end is on the deck. During retrieval, the effective trawl speed (i.e., the speed at which the trawl is traveling over ground) can exceed towing speeds during fishing as wire is being wound onto the drums (Wallace and West 2006). Water flow results from this study suggested that retrieval could be further separated into two distinct periods—before the doors came on the vessel (“haulback” as described in our study) and after the doors came on the vessel (“doors-up”). Our data suggested that, even though speed over ground was reduced during haulback prior to the doors being brought on deck, water flow inside the trawl near the cod end remained similar to when fishing (Figure 3). Water flow was not reduced inside the trawl until all of the wire was wound in and the doors were on the deck of the vessel. At this point, the speed over ground remained reduced as compared with the fishing period, but there were sporadic fluctuations between low and high flow rates within the trawl as various components were removed (e.g., weight clumps and net sounder) and the remainder of the trawl was retrieved. Occasionally during the doors-up period the trawl near the cod end partially collapses. This may have impeded the forward movement of salmon. However, we did observe some salmon navigating through the tighter “channels” of mesh that appear to be created during this time. Unfortunately, our camera view was also limited during these events so it is not possible to draw concrete conclusions.

Key findings of this research were that Pacific salmon moved forward throughout the tow and that the proportion of forward-moving salmon increased dramatically after the doors were back on the vessel. Three factors that influenced the probability of a salmon to move forward (light levels, speed over ground, and water flow) were different during the doors-up period as compared with during fishing. We do not know if this forward movement was the result of salmon intentionally increasing their swimming

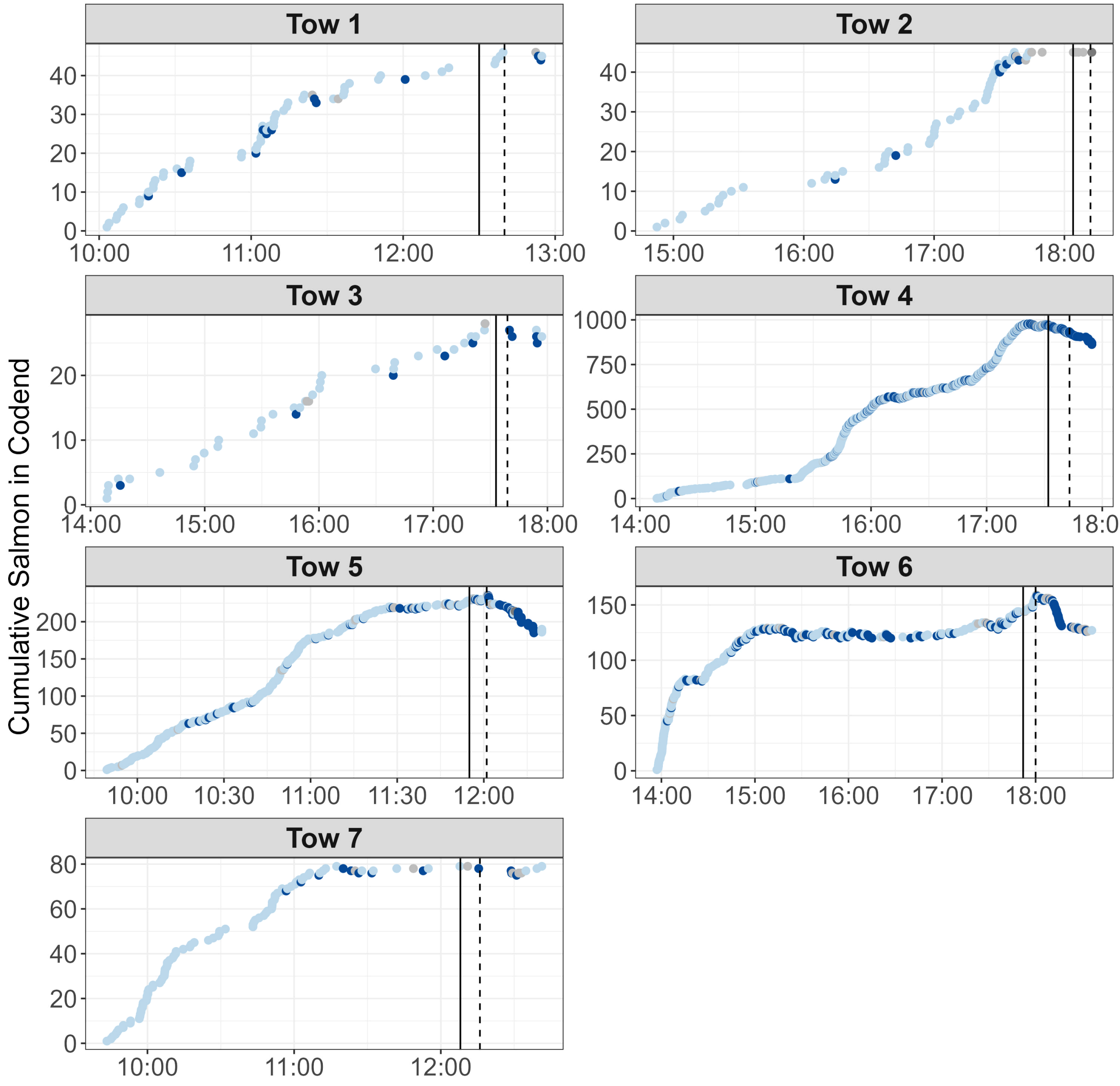

FIGURE 8 Cumulative counts of forward-moving (dark blue) and aft-moving (light blue) Pacific salmon in the cod end of the trawl. Gray points indicate Pacific salmon that were moving either aft–forward or forward–aft. The solid vertical line represents the time when the haulback period began, and the dashed vertical line was when the doors were up. The time of day during the tow is on the *x*-axis.

speed to move forward or if it was a result of their relative speed increasing as the speed of the trawl was reduced. Although the proportion and rate of forward-moving salmon was highest during the doors-up period, the number of salmon that moved forward (potential escapees) was low compared with the number in the cod end at that point (average = 6.5% and range = 0.0–17.8% over all tows). Previous escapement rates for the RT&F averaged 58% (Yochum et al. 2021), suggesting that the salmon that move forward at the end of a tow represent a small portion of overall escapement. If possible, creating durations of reduced water flow by periodically slowing the vessel during fishing could provide more salmon the opportunity to swim forward and access a BRD.

There were differences among tows in the proportion of Pacific salmon that swam forward during the doors-up period, but we were unable to associate those differences with any environmental conditions. One hypothesis is that the more time that a salmon spends in the trawl, the less likely it would be able to move forward due to physical exhaustion. By the time a salmon reaches the cod end of a pelagic trawl they would have passed through roughly 220 m of netting, which likely would reduce the amount of energy they have available. The first 188 m of net from the mouth to the taper section has a wide opening with large meshes, and salmon likely move through this relatively quickly. Once in the taper section, the opening and mesh sizes are reduced, which could elicit optomotor response as the trawl becomes visible. Maintaining the same position in the trawl (holding station) requires steady swimming at speeds that, depending on several factors, could be close to the trawl's speed over ground (Broadhurst et al. 1999). Migrating adult Chum Salmon (~66 cm) can maintain swimming speeds of 0.5–0.6 m/s but rarely exceed 1.0 m/s (Tanaka et al. 2001, 2005). At speeds above one body length per second, which on average for our salmon would be 0.51 m/s, salmon begin to power their swimming activity anaerobically, which then requires a recovery period (Hinch et al. 2006). In this study, the boat was traveling at 1.9 m/s during the fishing period, and it would have been energetically costly for a salmon to hold station within the trawl; in fact, only 1.2% of aft-moving salmon were able to remain within view for over a minute. Besides the energetic costs of swimming, the longer a salmon holds station, the higher the chances are that they may interact with another fish such as in a collision, which could cause them to move aft or be injured. Salmon that were caught early in a tow may have lacked sufficient energy reserves to move forward once flow decreased during the doors-up period. The duration of our research tows were within the range of commercial tows but were shorter than some of the longer tows that occur. We were not able to track individual salmon once they left the camera view, but in tows 4 and 6, we saw an increase in forward-swimming salmon following a rapid accumulation of salmon in the cod end near the end of the fishing period (Figure 8). This suggests that, while there may be an association between the timing of aft-moving salmon and subsequent forward-moving salmon at the end of a tow, other factors such as water flow rate and Walleye Pollock density may influence whether a salmon moves forward.

In addition to speed over ground, water flow, and light level, we also found that the abundance of Walleye Pollock in the trawl when Pacific salmon were observed was related to the probability that the salmon would move forward. There was a higher likelihood of a salmon moving forward when Walleye Pollock abundance was low in the camera's field of view than when Walleye Pollock abundance was medium or high. Fish density has been shown to affect swimming behavior in a trawl, including an increase in escape attempts by Haddock *Melanogrammus aeglefinus* during lower fish densities and an increase in the prevalence of the optomotor response with increasing densities (Jones et al. 2008). When exposed to strong currents in sea cages, salmon will form schools and swim to maintain their station within the cage (Johansson et al. 2014). In the trawl, where high densities of Walleye Pollock are moving aft, the salmon's propensity for schooling behavior may influence their decision to not move forward against the Walleye Pollock even if they energetically could. Likewise, at higher densities, Walleye Pollock may dominate a salmon's visual field and thus their optomotor response could be to maintain station with the aft-moving Walleye Pollock instead of the trawl. An exception to the inverse relationship between Walleye Pollock abundance and salmon moving forward was that the probability of a salmon moving forward was lowest when no Walleye Pollock were present. Ninety percent of our salmon observations with no Walleye Pollock present occurred during a single tow. In this tow, the percentage of forward-moving salmon with no Walleye Pollock present was lower (13.9%) than during other tows (mean = 26.9%), and we do not have an explanation for this difference.

Collinearity between light level, speed over ground, and reduced water flow made it difficult to interpret the independent effects of light level on forward-swimming Pacific salmon. Although our regression model suggested a significant positive relationship between light level and forward-moving salmon, higher light levels only occurred when the doors were on deck and the trawl was near the surface. This period coincided with lower speeds over ground and reduced water flow, both of which had a significant influence on salmon swimming forward. Previous research has indicated that salmon are more active during daylight hours and that swimming speeds can be increased with increases in light (Mork and Gulbrandsen 1994; Bui et al. 2013; Yochum et al. 2022). It is possible that the increase in light near the surface helped motivate or facilitate some salmon to swim forward, but we cannot determine if light alone increases forward-swimming behavior. Teasing these collinear factors apart could be achieved by either slowing down the vessel while the trawl is at depth and ambient light is low or by hauling back during the night. Lomeli and Wakefield (2019) found that salmon were more likely to utilize the escapement areas in a pelagic trawl when lights were present, perhaps due to enhanced visual perception of the trawl and escapement areas. Along with increasing perception of escapement areas, additional research could address whether light can be used to increase the number of forward-swimming salmon at depths where ambient light is minimal.

We observed a pattern of Pacific salmon rising in the trawl when moving aft and descending when moving forward, and this may have been a behavioral response to the camera and lights. Although relatively small (20-cm height), the camera system likely altered the flow of water along the top of the trawl, which the salmon can detect (Vowles et al. 2014; Silva et al. 2020). The red lights used for illumination could also illicit a negative phototactic response (i.e., avoidance). Yochum et al. (2022) found that juvenile salmon in captivity had a negative phototactic response to several different color lights, including red. From a behavioral modification perspective, this response to lights or water flow could be used in future BRD designs to help consistently shepherd salmon into certain areas of the trawl.

Water clarity, lighting, movement of the camera system, and/or occlusions may have affected our ability to detect Pacific salmon during video review. The red light we used to illuminate the trawl was more readily absorbed in water than other visible wavelengths, giving it a shorter penetration distance. This required a higher intensity setting, which during poor water quality events increased backscatter that reduced contrast and blurred the image (Bonin et al. 2011). The use of white lights placed at a further distance from the camera could be an improvement. The camera system was attached to the netting and often swayed up and down. This meant that the field of view was changing and sometimes part of the top or bottom of the trawl was not visible. Adding additional flotation to the trawl in the area of the camera might minimize movement. We found that tows with higher Walleye Pollock catch rates had lower salmon detection rates (Figure 4). When the trawl is filled with Walleye Pollock, the view was more likely to be obscured and some salmon may have been missed. Short periods (typically seconds) of time when the camera view was partially or fully occluded by Walleye Pollock may have also contributed to missing salmon during video review. An additional camera would reduce the area obscured during high densities and offer another view when the camera was occluded.

Trawl fisheries with morphologically similar target and bycatch species present a serious challenge for selective harvest with BRDs. Our results suggest that speed over ground and water flow both influenced a Pacific salmon's ability to move forward and that the highest percentage and rate of forward-moving salmon occurred when the doors are on deck. Once salmon reached the cod end of the trawl, only a small percentage were able to move forward and possibly escape. This suggests that future BRD designs for Pacific salmon should focus on providing an opportunity for escape when fish first encounter the BRD while moving aft as compared with requiring salmon to swim forward or relying on salmon to return to the BRD after moving past it.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data used for the analyses are available upon request.

ETHICS STATEMENT

This study meets the ethical guidelines outlined by the American Fisheries Society.

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