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Quantitative video analysis of flatfish herding behavior and impact on effective area swept of a survey trawl

David R. Bryan[a,*], Keith L. Bosley[b], Allan C. Hicks[a], Melissa A. Haltuch[a], W. Waldo Wakefield[b]

[a] Fishery Resource Analysis and Monitoring Division, Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 2725 Montlake Boulevard East, Seattle, WA 98112, United States
[b] Fishery Resource Analysis and Monitoring Division, Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 2032 S.E. Marine Science Drive, Newport, OR 97365, United States

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ABSTRACT

Uncertainty in fish behavior can introduce bias into density calculations from fishery-independent bottom trawl surveys that provide relative abundance estimates and population trends for stock assessments. *In situ* video was used to quantify flatfish behavioral responses to a bottom trawl sweep to improve the understanding of survey and assessment results. The behavior of 632 flatfishes was recorded during four tows. More than 90% of fish were observed in a perpendicular orientation away from the sweeps indicating a herding response. There was no significant effect of fish length on fish orientation or whether it reacted or remained stationary during the observation. Only 1.3% of fish were observed escaping the sweeps. A generalized linear model was used to estimate that at a distance of 73.8 cm (±3.4 SE) 50% of observed fish reacted to the sweep. The mean distance that stationary fish were first observed reacting to the sweep was 36.6 cm (±2.0 SE). Quantitative analysis indicates that flatfish herding occurs along trawl sweeps and the effective area swept is greater than the wing spread. Thus, the use of wing spread to calculate relative abundance estimates explains bias in stock assessment estimates of survey catchability that are greater than expected.

1. Introduction

An integral component of fisheries-independent trawl surveys is the ability to scale species-specific catch rates up to the larger population scale. The first step in this scaling process is a density estimate that incorporates species catch rate and area swept by the trawl. The area swept by the trawl is calculated using spread, which can be measured as the distance between the leading edge of the wings or the distance between trawl doors, and the distance traveled by the trawl (Dickson, 1993; Somerton et al., 1999; Fraser et al., 2007). The choice between the two spread measurements depends on an understanding of fish behavior in response to trawl sweeps and the availability of net wing or trawl door spread measurements. This choice affects the subsequent calculations of fish biomass.

The National Oceanic and Atmospheric Administration (NOAA) National Marine Fisheries Service, Northwest Fisheries Science Center (NWFSC) has been operating a trawl survey for groundfish stock assessments since 2003 (Keller et al., 2008). The trawl, rigging, and accessories are of a type commonly used in slope commercial fisheries, scaled to fit the class of vessels chartered for the NWFSC West Coast groundfish bottom trawl survey (WCGBTS) that range from 400 to 600 horsepower (Methot et al., 2000). The trawl configuration includes sweeps, defined here as the rubber disk encased steel core wire rope that extends from the trawl door to the footrope extension of the trawl, and includes both the mud gear and the lower bridle (as well as the “back strap” or “door leg extension”), with the goal to improve the herding of fish and to maintain desired net geometry (Fig. 1). Among the numerous species caught in the survey trawl, flatfishes, which have a strong affinity to the seafloor, are expected to have a herding behavior affected by the trawl sweep (Ryer, 2008). However, few studies have shown *in situ* evidence of herding for U.S. west coast flatfishes using a survey trawl with modified sweeps.

Behavioral work on flatfishes indicates that a predator avoidance response can be elicited by trawl gear (doors, sweeps and

* Corresponding author. Present address: University of Miami, Rosenstiel School of Marine and Atmospheric Science, 4600 Rickenbacker Causeway, Miami, FL 33149, United States. Tel.: +1 305 421 4736; fax: +1 305 421 4600.
E-mail address: dbryan@rsmas.miami.edu (D.R. Bryan).

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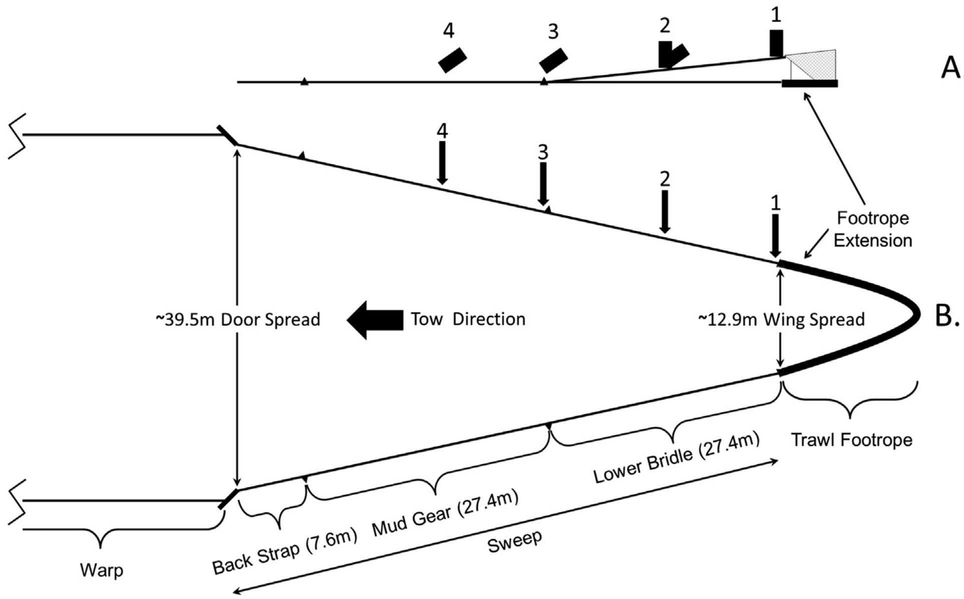

Fig. 1. Quasi-scale diagram of the Aberdeen-style trawl's footrope, bridles, mudgear, back strap, and doors under fishing conditions with indications of door and wing spread. The positions of the video camera system are marked with numerals 1–4.

footropes) and is the mechanism responsible for herding (Ryer et al., 2004; Ryer, 2008; Winger et al., 2010). The predator avoidance response, which differs among species, is characterized by a typically stationary flatfish rising off the bottom to flee a perceived threat (Ryer et al., 2004; Ryer, 2008). Early photography and video work along trawl sweeps suggest herding behavior (Main and Sangster, 1981; Wardle, 1983) and additional indirect studies comparing flatfish catches between modified gears suggest that herding occurs along the sweeps, but at different rates for different species (Somerton and Munro, 2001; Somerton et al., 2007).

The NWFSC trawl survey provides a relative index of abundance that is generated through the expansion of catch data using several calculations that are the same for all species. Species density is calculated for each tow by dividing the catch for each species by the area swept by the trawl. The area swept is calculated using the distance between the wings of the net (where the wing spread sensors are mounted at the leading edge of the wings) and the distance traveled by the trawl. An average density is calculated for each survey stratum and then multiplied by the area of that stratum to provide an estimate of the total stratum biomass. The sum of all stratum biomass estimates is considered the relative index of abundance.

The index of abundance for a given stock estimated from the trawl survey is related to the vulnerable biomass of the stock by a catchability coefficient (q), where q times the predicted vulnerable biomass from a stock assessment equals the survey index. Therefore, the actual value of the relative biomass estimate is not important to a stock assessment, but the relative change between each survey estimate is important. The estimate of q from a stock assessment is often expected to be less than 1, and when it is not, questions may arise as to why the expanded relative biomass estimate from the survey is greater than the biomass predicted by a stock assessment. Reasons for a greater survey estimate, i.e. $q > 1$, can include: (1) over-estimation of the density due to an incorrect area swept calculation, (2) expansion into un-sampled areas where the species does not occur (e.g. un-trawlable habitat), and/or (3) the predicted vulnerable biomass is incorrect.

This study addresses the possibility of an incorrect area-swept calculation generating a q larger than 1 by quantitatively investigating flatfish behavior in response to the sweeps used on the NWFSC Aberdeen-style bottom trawl. *In situ* video was used to examine the ability of the sweeps to evoke herding behavior in flatfishes on four experimental tows. *In situ* observations of movement, orientation, fish size, and distance from gear provide a better understanding of flatfish behavior and herding effects. This information may improve the understanding of the relationship between the area swept used to calculate the survey index of abundance and stock assessment estimates of q that are greater than expected.

2. Methods

2.1. Operations

The trawl-sweep herding experiment was conducted during 23–24 August 2009 in the northeast Pacific Ocean, off Newport, Oregon (44°37′ N 124°02′ W), at depths from 84 to 184 m using a 26-m chartered stern trawler, the FV "*Raven*" (Fig. 2). The vessel fished a standard Aberdeen-style trawl (online supplement 1–3) built and rigged to operate within strict specifications in compliance with protocols established for National Marine Fisheries Service bottom trawl surveys (Stauffer, 2004). Trawling procedures followed the NWFSC West Coast groundfish bottom trawl survey (WCGBTS) protocols (Keller et al., 2008), including towing only during daylight hours at a target vessel speed of 1.13 m/s. One deviation from normal WCGBTS protocols was a nominal tow duration of 12 min rather than 15 min which was done to maximize the number of tows within a limited amount of available ship time.

All fishing operations, including vessel operations and gear performance (spread between the leading edge of the wings, spread between doors, vertical distance from the center of the head rope to the bottom, distance from the head rope to the footrope, and clearance between the footrope and bottom), were monitored using a suite of trawl instrumentation systems. The tow officially began when the trawl was in proper fishing configuration and in contact with the bottom. The tow ended when the footrope lifted off the bottom after the start of haul back. Acoustic instruments were used to monitor ground gear contact during each haul in real time, but the actual bottom time was determined using data from a bottom contact sensor. Position data, collected at 2 s intervals for each haul, using a GPS-linked catch monitoring system (Simrad Integrated Trawl System and PI44 System), were used to monitor vessel speed over ground, track the vessel and trawl path, and estimate distance fished. Average trawl speed over ground and distance fished were

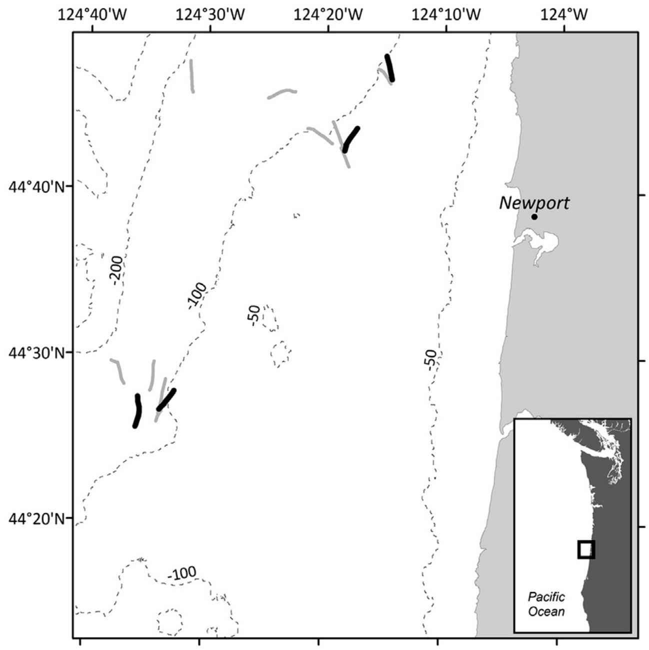

Fig. 2. Location of experimental tows conducted 23–24 August 2009 in the northeast Pacific Ocean, off Newport, Oregon. The four black lines indicate the locations of tows in which video data were analyzed. The gray lines indicate tows that were not analyzed due to poor visibility from various camera locations and angles.

calculated from the position data and the trawl's actual bottom time. Fish catches were sorted to species and weighed in aggregate using an electronic, motion-compensated scale (Marel, Reykjavik, Iceland). Total length (TL) in centimeters was measured for all flatfishes. Large catches of a single species were sub-sampled through random selection when necessary.

The sweeps were comprised of two sections of mud gear (distal from the trawl), including a bridle consisting of an upper and lower leg, where the lower leg functions as a second section of mud gear (proximal to the trawl), and a 7.6 m long "back strap" or "door leg extension" connecting the trawl doors to the mud gear. The mud gear and lower bridles were each 27.4 m long bearing point to bearing point (Fig. 1 and online supplement 2) and were made from 15.9 mm galvanized steel-core wire rope (Independent Wire Rope Core) covered by 88.9 mm rubber discs composed of either belt or punched tire material, with 203.2 mm rubber discs centered every 4.57 m sandwiched between two 152.4 mm rubber discs (online supplement 3).

2.2. Video camera system

A self-recording video camera system was positioned at one of four different locations along sections of the starboard sweep (Fig. 1). The video system consisted of a high-resolution, low-light (1.1 lux), color video camera (DeepSea Power and Light® [DSPL] model 2060 Multi-SeaCam® [75° horizontal × 60° vertical and 460 TV lines of horizontal resolution with NTSC]); and source of illumination (DSPL halogen Multi-Sealites® [~950 lumens]) (Fig. 3).

Video was captured with a time stamp using a Sony® digital camcorder on MiniDV tapes. The camcorder, battery packs, and controller (with associated pressure activation switch) were contained in a titanium pressure housing. The camera system was installed at four positions along the sweep. Position 1 provided a downward vertical (orthogonal) view from the top bridle directly over the junction of the sweep (lower bridle) and trawl footrope (Fig. 1). At position 2, the video system was also mounted on the top bridle, ~14 m forward of position 1, and oriented for two different

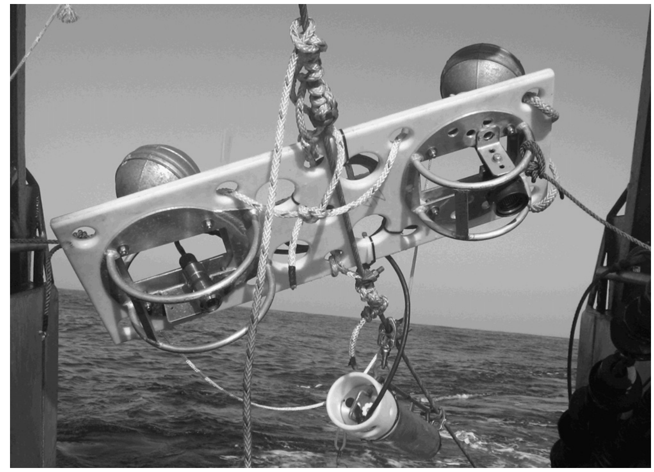

Fig. 3. Video camera system attached to top bridle prior to deployment. The high resolution, low light camera was placed on the right side of the mounting frame while the light source was on the left side. The pressure housing was hung beneath the frame.

views: downward vertical and forward oblique. Position 3 provided a forward oblique view of the first few meters of the aft section of forward segment of the sweep (mud gear), including the delta plate that joins the mud gear to both the upper and lower legs of the bridle. Position 4 provided a forward oblique view and was located approximately 14 m (midway) along the forward section of the mud gear. At positions 3 and 4, floats were attached to the camera frame and the pressure housing to keep them suspended over the gear. The camera was placed in positions 1 and 2 for five tows each, position 3 for two tows and position 4 for one tow. Video from the first tow at all four positions was reviewed immediately at sea for a qualitative determination of the usefulness of further deployments at each position. Our goal was to collect videos and associated catch data from at least four tows at each position, but it was obvious after reviewing the videos onboard from positions 3 and 4 that they would not be usable. Only one additional attempt was made at position 3 and no additional attempts were made at position 4.

2.3. Video analysis

Video was reviewed at two laboratories by two different readers. Double reads from twenty-two sections of randomly chosen video indicated that there was no significant reader bias (online supplement 4). Data were collected separately for gear and fish. Gear performance, including bottom contact, presence of a mud cloud, sweeps digging into the bottom, gear on bottom, relative changes in net speed (e.g. slow down or sped up), were recorded with a complete review of the video for each tow. Changes in gear performance were recorded and identified by time stamp.

Quantitative data were collected for all fish estimated to be ≥10 cm total length to determine if flatfishes were herded by the trawl sweep and how their length and distance from gear affected their behavior (Table 1). All measurements, including fish length, were estimated using the known diameter (8.9 cm) of the sweeps as a point of reference. A ten point divider was used to extrapolate the known dimensions of the sweep width within each video frame to measure fish length and distance from sweeps. The ten point divider was calibrated for each measurement by adjusting it to the known sweep diameter at the same distance up from the bottom of the screen of the video monitor as the fish to account for the differences in the field of view of the oblique image as compared to the vertical view. Species identification was not possible so each fish was assigned to a general flat or round fish category. Fish length was measured at the best view during the observation time

Table 1
List and description of quantitative and qualitative measurements made for each observed fish.

Measurement	Description
Time stamp fish first observed	hh:mm:ss
Species	Flat or round
Fish total length	5 cm increments
Orientation in relation to mud gear at first view	45° increments
Distance from mud gear at first view	5 cm increments, closest part of fish to gear
Fish movement during entire observation	Stationary or reacting
Distance from mud gear at first response	5 cm increments, closest part of fish to gear
If already moving, closest to mud gear	5 cm increments, closest part of fish to gear
Orientation when last seen	45° increments
Final distance from gear if stationary or stopped	5 cm increments, closest part of fish to gear
Escaped	Over or under
Time stamp last observed	hh:mm:ss

and recorded into 5-cm bins. Fish orientation at first and last view was determined in 45° increments by the direction a fish's head was pointing in relationship to the sweep. This coarse measurement was used to account for some uncertainty in estimating fish heading as well as to cover potential bias resulting from different camera angles. Zero degrees indicated a fish facing toward the boat and 90° indicated a fish facing directly away from the sweep. Each fish was classified as either reacting or stationary based on their response or lack of response to the sweep during the observation. A fish that reacted in a direction away from the sweep (heading between and including 0° and 180°) was considered herded. The distance at which a fish reacted to the sweep was recorded along with the closest distance a fish came to the sweep during the observation in 5 cm increments. It was possible for some fish to remain stationary without coming into contact with the sweep during the observation due to the angle of attack and the field of view from the camera. The distances of stationary fish from the sweep were recorded at the first and last view.

2.4. Data analysis

Length estimates from the video analysis of three tows were compared to lengths of flatfishes measured from the catch to investigate potential selectivity of the gear. Length data for both measurements were log transformed to meet assumptions of normality. A two-way ANOVA with tow and measurement type (video and catch) as explanatory factors was used to test for a significant difference. Length estimates from video were also used to test if there were any effects of size on behavior. Welch's two sample t-tests were used to compare the average length between reacting and stationary fish. A Pearson correlation coefficient was used to determine if there was an association between the length of a fish and the closest distance it came within the sweep and the distance at which stationary fish first reacted to the gear. Distance measurements were $\log(x+1)$ transformed and data from all tows was combined. A generalized linear model with a clog-log link was used to predict distance at which 50% of fish react to the gear. The proportion of reacting to stationary fish at the distance first measured for each from all tows was used to create this model.

Fish orientation was used to indicate if herding may have occurred prior to our observation and to determine the predominant direction that flatfishes reacted. Reacting fish with an orientation between and including 0° and 180° were considered to be displaying herding behavior. Fish orientation data were analyzed using the package 'circular' in R 2.12.1 (R Development Core Team, 2010). Kuiper's one sample tests of uniformity were used to examine fish orientation and Wilcoxon rank sum tests were used to compare mean orientations of stationary and reacting fish (Jammalamadaka and Rao SenGupta, 2001).

3. Results

Four out of 13 tows had camera placement and visibility that allowed for clear observation of fish behavior with minimal mud clouds obscuring the view. Camera placement was too high above the seafloor to get a clear view of fish responding to the gear at position 1 while intermittent mud clouds obscured much of the view at positions 3 and 4 (Fig. 1). All four tows that were deemed usable were recorded from camera position 2 (Fig. 1). The camera was facing downward and vertical during two tows and was facing obliquely forward along the sweep toward the door in the other two tows. The field of view for the vertical image at position 2 was approximately 145-cm (wide) × 109-cm (high), and the field of view for the oblique image was approximately 205-cm wide at the midpoint of the image. Depth, bottom temperature, trawl speed and net configuration were very similar for each tow (Table 2).

A total of 632 flatfishes were observed during 4 separate tows with a total of 53:54 (min:s) of bottom time (Table 2). Species identification from video was not possible, but flatfish catch was dominated by four species; English sole (*Parophrys vetulus*), Pacific sanddab (*Citharichthys sordidus*), petrale sole (*Eopsetta jordani*) and rex sole (*Glyptocephalus zachirus*), which comprised 16%, 60%, 12% and 8% of combined flatfish catch, respectively. The mean length of fish measured onboard was greater than estimated lengths from video (ANOVA, $p < 0.001$) (Table 2) and only one fish 15 cm or less in length was caught during all three tows. In contrast, 62% ($n = 241$), 5% ($n = 5$), 48% ($n = 32$) and 33% ($n = 23$) of fishes observed on video from tows 7, 8, 9 and 10 (respectively) were estimated within the 10 cm and at 15 cm size classes.

A majority of fish reacted during observation ($n = 421$) in comparison to those that remained stationary ($n = 211$). There was no significant difference between the mean length of fish that reacted during observation (18.8 cm ± 0.3 SE) versus those that remained stationary (19.2 ± 0.4 SE) (Welch t-test, $p = 0.29$). However, the ratio of reacting to stationary 10-cm fishes was greater than all other size classes. Eight fish out of 615 (1.3%) were observed escaping; five went under the gear, one went over and two were undetermined due to obstruction by mud cloud at sweep. There were 17 additional fish whose fate could not be determined due to an obstruction by a mud cloud. The mean length of the escaping fish was 16.3 cm (±1.8 SE). Flatfish length was weakly correlated to the closest distance at which a fish was observed next to the sweep ($r = 0.165$). There was no correlation between flatfish length and the distance at which a stationary fish first reacted ($r = -0.075$).

Stationary fish were initially observed at a mean distance from sweeps (75.5 cm ± 2.5 SE) which was significantly greater than that of reacting fish (43.4 cm ± 2.0 SE) (Welch t-test, $p < 0.01$). The mean distance that a fish first responded to the gear was 36.6 cm (±2.0 SE) and the closest distance that a reacting fish came to the gear was on average 41.8 cm (±2.2 SE). The length from the sweep in which 50% of observed fish were reacting was 73.8 cm (±3.4 SE) (Fig. 4).

The mean orientation of fishes at first observation, which could indicate previous herding behavior, varied from 95° to 118° between tows (Table 2). Fish were not randomly oriented and were most commonly oriented away from the gear (Kuiper's one sample test of uniformity, $p < 0.01$) (Fig. 5). At first observation, 95.0% of reacting and 83.9% of stationary fish were oriented between and including 0° and 180°. At last observation, 98.1% of reacting fish were oriented between and including 0° and 180°; stationary fish

Table 2
Summary statistics for tow, video analysis and catch. The percentage of total catch by numbers for the four dominate flatfish species are included.

	Tow 7	Tow 8	Tow 9	Tow 10
Tow summary				
Total time net on bottom (min)	13:51	15:16	10:25	14:22
Vessel speed (over ground)	1.29 m/s	1.42 m/s	1.40 m/s	1.36 m/s
Net height	5.4 m	5.1 m	5.0 m	5.1 m
Net width	12.9 m	13.4 m	13.2 m	13.4 m
Door width	39.8	41.1	37.4	41.4
Tow depth	101 m	90 m	104 m	117 m
Temperature at gear	7.61 °C	7.75 °C	7.72 °C	7.65 °C
Camera position	Down	Down	Forward	Forward
Video summary				
Total observation time (min)	10:11	13:54	08:48	11:10
Total number of flatfish	390	107	67	68
Fish per minute	38.3	7.7	7.6	6.1
Mean length (cm) ± SE	16.8 ± 0.3	25.3 ± 0.6	18.4 ± 0.7	21.2 ± 0.9
Mean orientation at first observation	108.9°	94.6°	118.0°	106.2°
Mean orientation at last observation	103.7°	111.3°	124.8°	103.1°
Percent escaped	0%	1.9%	7.5%	1.5%
Catch summary				
Total number of flatfishes caught	685	618	[a]	315
Mean length (cm) ± SE	25.4 ± 0.5 (n = 118)	25.3 ± 0.7 (n = 123)		28.5 ± 0.6 (n = 126)
English sole	11.9%	11.1%		22.3%
Pacific sanddab	51.8%	67.2%		15.1%
Petrale sole	1.4%	4.4%		48.4%
Rex sole	6.2%	7.7%		6.3%

[a] Catch data were not collected for tow 9.

had the same orientation as when first observed. Although most fish were oriented away from the gear, there was a significant difference in orientation between fish that reacted and those that remained stationary with reacting fish more likely to oriented directly away from the gear (Wilcoxon rank sum test, $p < 0.001$) (Fig. 6).

4. Discussion

This study provides the first *in situ* video of U.S. west coast flatfish behavioral responses to the sweeps of the NWFSC Aberdeen-style survey trawl. Evidence for herding behavior in response to the trawl sweeps was observed in the video and supported by the statistical analyses, advancing the ability to understand and interpret the area swept biomass estimates used in stock assessments. Flatfish herding behavior in response to the sweeps used on the NWFSC Aberdeen-style bottom trawl suggests that the distance between the leading edge of the trawl wings underestimates the width used in area swept calculations, essentially supporting estimates of a catchability coefficient, q, larger than 1 in stock assessments for these flatfishes.

Herding behavior along the trawl sweep was identifiable for both stationary and reacting fish through their orientation and direction of response. Over 80% of stationary fish were orientated in a roughly perpendicular position to the sweep indicating either a prior herding response or an adjustment in position toward the direction the fish intend to swim as described by Stickney et al. (1973). The roughly unidirectional orientation of stationary flatfish could be a response to environmental parameters such as current or an indication of the future direction of travel for migration or foraging (Gibson, 1997). However, it is unlikely that the orientation would be the same in respect to the sweep in all four tows

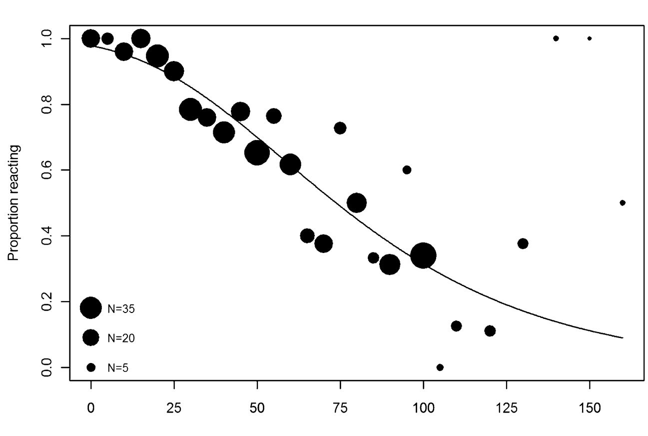

Fig. 4. Scatter plot showing the proportion of reacting fishes as a function of initial distance from gear. The diameter of each point represents sample size for a given distance. The data were fit with a generalized linear model ($p < 0.001$).

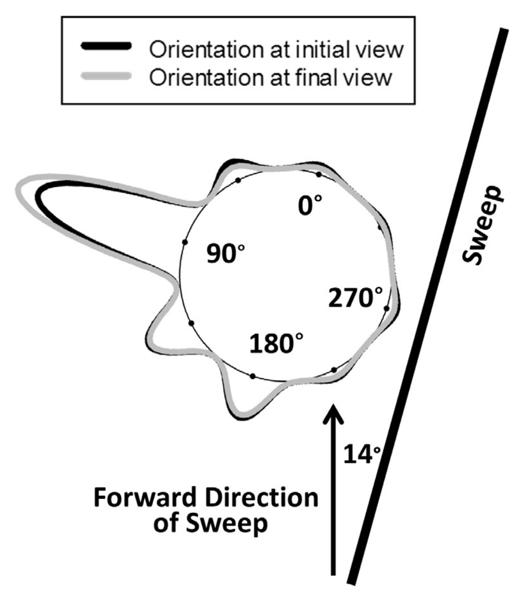

Fig. 5. Circular density plot of fish orientation density for all fish (stationary and reacting) at initial and final observation. The angle of incidence of the sweep was approximately 14° at camera position 2. The mean direction of fish at initial view was 162° compared to 164° at final view.

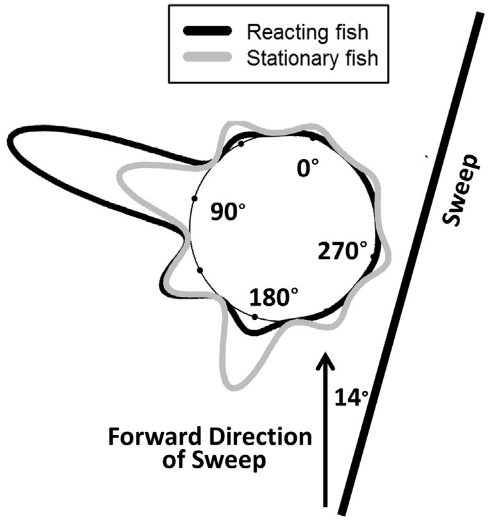

Fig. 6. Circular density plot of fish orientation at last view for reacting and stationary fish. The angle of incidence of the sweep was approximately 14° at camera position 2. The mean direction of reacting fish was 170° compared to 138° for stationary fish.

if factors other than the trawl were highly influential. Reacting fish overwhelmingly moved away from the sweep, a behavioral response noted in earlier work (Main and Sangster, 1981; Wardle, 1983). Data in support of flatfish herding by the sweeps of the NWFSC trawl are consistent with other studies that have manipulated sweep length to investigate herding in flatfish (Somerton and Munro, 2001; Somerton et al., 2007) as well as laboratory behavioral studies (Ryer et al., 2004; Ryer, 2008).

Although flatfishes herded by the sweeps of the NWFSC trawl appear to be an important contribution to the overall survey trawl catch, area swept calculations to estimate fish densities for stock assessments include only the area between the leading edge of the trawl wings and do not take into consideration the herding effects of the sweeps. The inclusion of a larger area swept for density calculations is warranted and would result in biomass indices at a scale that are more closely related to the actual population sizes estimated by stock assessments. The ideal width is likely to be some value between the distance between the wings and the distance between the doors dictated by bottom contact of the sweep (Somerton, 2003). This study does not have the appropriate data to produce such a measurement but it does provide evidence that the biomass estimate using the distance between the wings to calculate area swept will likely result in an over-estimate of density and thus a survey biomass estimate that is higher than absolute abundance.

Recent assessments for petrale sole (*E. jordani*) as well as English sole (*P. vetulus*) and rex sole (*G. zachirus*), produced estimates of a NWFSC survey *q* greater than one, 2.97, 1.22, and 1.79, respectively (Haltuch et al., 2011; J. Cope, pers. comm.). The distance between the trawl doors is over three times greater than the distance between the leading edge of the wings on the NWFSC trawl (Fig. 1), and since abundance data was expanded to the index of biomass using net wingspread, survey biomass estimates between 1 and 3 could be expected. Catchability in a stock assessment is solely used as a scalar and is difficult to interpret, but the observations of herding presented here illustrate one process that contributes to a larger than expected estimate of *q*.

Despite direct evidence of herding, expanding the area swept directly from net width to door width rests upon assumptions that are highly dependent on an over simplification of processes happening in the water. Herding efficiency is highly sensitive to subtle changes in fish behavior (i.e. swimming continuously versus periodic settling) (Winger et al., 2004). The decision to use door-to-door distance in area swept calculations is also dependent upon the angle of the sweeps (angle of incidence), amount of bottom contact and the speed of the trawl (Winger et al., 2010). Rose and Nunnallee (1998) showed that although geometrical corrections for swept area can be useful, they do not necessarily take into account fish behavior. Several quantitative measurements from this study can aide future modeling of the herding behavior of flatfishes (Dickson, 1993; Ramm and Xiao, 1995; Somerton and Munro, 2001; Somerton et al., 2007). Mean direction of movement and the distance at which 50% of fish react (provided here) along with estimates of swimming speed (Winger et al., 1999, 2004) can be used to calculate the number of encounters with the gear if the angle of incidence along the entire sweep is known. An escape probability at each encounter with the sweeps can be used to estimate catchability before encountering the footrope at the trawl mouth. Unfortunately, behavior was only observed at one section of the sweep limiting the ability to expand these behaviors along the entire sweep.

One behavioral issue that was not quantified and could complicate the modeling of behavior along the sweeps is the effect of density-dependent behavioral responses (Godø et al., 1999). Qualitative observations suggested that higher fish densities often elicited greater herding activity but there was not enough contrast in density data to make statistical comparisons. On several occasions fish that were stationary and apparently un-responsive to the gear were herded when contacted by another reacting fish.

Additional concerns for both area swept calculations and catchability modeling include species specific differences in herding behavior and possible effects of ambient light (Ryer et al., 2010). Although a majority of flatfish species observed during this study and caught in the NWFSC groundfish bottom trawl survey are likely herded by sweeps, individual species identifications could not be made from the video. Therefore, orientation, reaction distances and overall herding behavior were estimated for all species pooled. In addition, the NWFSC groundfish trawl survey collects data for several species that were not present in the catches from this study. If herding behavior is different among species, it would be important to have species-specific area swept calculations. The trawl survey encompasses both the continental shelf and slope from 55 to 1280 m depth, yet tows analyzed in this study fell within a small portion (90–117 m) of the overall depth range. Ambient light has been shown to influence flatfish behavior; at low light levels the herding response was replaced with a rise off the bottom that may cause the sweep to pass beneath the flatfish (Ryer and Barnett, 2006). Therefore, the herding response quantified in our research may not represent fish behavioral responses to the NWFSC survey trawl at greater depths. Additional research tows with a similar camera system could improve our understanding of the response behavior at varying depths. Although there are likely species specific differences in behavioral responses to artificial light, we assumed (Albert et al., 2003; Walsh and Hickey, 1993; Weinberg and Munro, 1999) that our video lights had a minimal effect on the observed fishes responses.

The significant differences in mean length between video observations and catch suggest gear selectivity. One factor contributing to these differences is the lack of 10–15-cm fish in the catch. These smaller fish are likely escaping at the footrope (Walsh, 1992) as there was no significant effect of fish length on herding along the sweeps. However, 10-cm fish tended to get closer to the gear and were observed reacting more often than larger fish. This difference is partially due to their swimming behavior which does not allow for as long of a settling period as larger fish (Winger et al., 2004), but did not influence escapement at the sweep. These results are similar to those of Somerton and Munro (2001) and Somerton et al. (2007) who found no significant effect of length on herding for 5 out of 7 and 4 out of 4 fish species, respectively.

Understanding the herding behavior of flatfishes can assist in resolving the relationship between the estimated biomass and absolute biomass in stock assessments. Although it is premature to adopt a survey-wide increase in the area swept calculation to include a door to door distance, the net wing to net wing measurement currently used clearly underestimates the true area swept for some species. Even with additional data along other sections of the sweep, it may be necessary to use herding models instead of area swept calculations to improve density estimates and survey accuracy (Ramm and Xiao, 1995). It is important to note that the larger than expected catchability coefficients estimated in some assessments are not due to faulty survey design or data collection, but are a result of the post-survey expansion of the raw data. These results show that flatfishes are herded in the NWFSC trawl survey and herding is one of the processes that can lead to larger than expected estimates of catchability in a stock assessment. Furthermore, additional research investigating these behavioral responses, focused on an increased number of species, trawl depths and sections of the sweeps would be beneficial to better understand how best to expand survey data and how to interpret catchability estimates from stock assessments.

Supplemental materials

Three figures and an analysis of video double reads have been referred to above and submitted as online supplements.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.fishres.2014.02.007.

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