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Reducing variability in bottom contact and net width of a survey trawl by restraining door movement and applying a constant ratio of warp length to depth

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Abstract—A field study was conducted to examine methods to reduce varying geometry of a demersal survey trawl net caused by changing depth and trawling speed and that could result in variable sampling efficiency. A reduction in varying trawl net geometry is important because variance in indices of abundance is the result of variability in sampling efficiency, as well as animal density. Trawl performance measures considered were door and wing spread and the contact of the footrope and lower bridles with the seabed. Three treatments were tested for their effects on these measures: 1) standard towing procedures, 2) door spread restrained by a restrictor line attached between the trawl warps ahead of the doors, and 3) doors similarly restricted in conjunction with a modified scope ratio. Generalized linear modeling showed that both depth and trawl speed significantly affected trawl measures in nearly all cases. The restrictor line reduced the effect of depth on spread and, to a lesser extent, on bottom contact of the footrope; however, it was ineffective at reducing the effect of trawl speed over the speed range observed. The combination of a restrictor line and modification of the scope ratio to achieve a consistent upward pull on the doors was most effective in maintaining trawl shape to our target dimensions.

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Demersal otter trawls used in both commercial fisheries and resource assessments lack a rigid frame; instead, sheer on the trawl doors and various operational factors (e.g., warp length and towing speed) are used to hold them in their fishing configuration. From the perspective of commercial fisheries, the lack of a rigid frame is convenient because it allows for easy stowage of the trawl when it is on deck. However, from the perspective of resource assessment, this flexibility contributes to variability in trawl shape and likely has a subsequent effect on sampling efficiency (Godø and Engås, 1989; Koeller, 1991; Walsh, 1992; Weinberg et al., 2002). This idea challenges a fundamental assumption with bottom trawl surveys for estimating indices of population abundance for stock assessments. That assumption is that the sampling efficiency of the trawl remains the same from tow to tow, across the survey area, and over time so that the survey-estimated catch per unit of effort accurately reflects changes in the distribution and abundance of fish stocks.

The relationship between trawl shape and its sampling efficiency is directly affected by 3 common processes: 1) horizontal herding, defined as the horizontal movement of fish into or out of the net path, 2) vertical herding, defined as the vertical movement of fish into or out of the net path, and 3) escapement, defined as and limited here to fish passage beneath the footrope. The effectiveness of horizontal herding can be affected by shifts in the bridle angle of attack due to changes in door and wing spread. This region of the trawl is critical for capture efficiency because it generates both visual and tactile stimuli (Main and Sangster, 1981) that, along with other factors such as temperature (Ryer and Barnett, 2006) and trawl speed, will determine whether fish (particularly flatfishes) are herded into the path of the net or, conversely, elude capture by passing over, under, or through the bridles (Somerton and Munro, 2001). The effectiveness of vertical herding can be affected by changes in the height of the net opening that make it possible for fish above the headrope to pass over the top or swim down into the trawl opening. For semipelagic species, additional visual, auditory, and pressure cues from the vessel, warps, doors, bridles, and wing mesh contribute to this process

(Engås and Godø, 1989a; Somerton, 2004; De Robertis and Wilson, 2006; De Robertis and Handegard, 2013). The effectiveness of a bottom trawl footrope, in relation to fish escapement beneath it (particularly in relation to escapement of flatfishes), can be affected by changes in the distance from the bottom during periods when it loses contact (Engås and Godø, 1989b; Walsh, 1992). For these reasons, we suspect that minimizing changes in trawl geometry should lead to better consistency in trawl efficiency and, hence, to more precise estimates of abundance.

Of the environmental and operational factors that affect net geometry, towing depth, towing speed, warp length, and substrate type are most important (Godø and Engås, 1989; Weinberg and Kotwicki, 2008). Changes in these factors generally produce changes in the horizontal spread of the trawl doors and net width. For many trawl designs, increasing the horizontal opening results in a decrease in the vertical opening and can increase the distance of the footrope from the seabed (von Szalay and Somerton, 2005). One method that has been shown to successfully reduce the spread of a trawl is to deploy a restrictor line (Fig. 1)—a line attached between trawl warps ahead of the trawl doors to restrain door movement (Engås and Ona[1,2]).

In May 2005, the Alaska Fisheries Science Center (AFSC) of the U.S. National Marine Fisheries Service conducted an experiment with a restrictor line on the standardized trawl gear that is used in the annual bottom trawl survey in the eastern Bering Sea (hereafter referred to as *the survey*). In this study, we extended the work of Engås and Ona[1,2] by using generalized linear modeling (GLM) to analyze the effects of the restrictor on footrope and bridle contact with the seabed. More specifically, using the trawl performance criteria of 1) consistent door and wing spread, and 2) reduced distances of the footrope and lower bridles from the seabed, we examined which of 3 towing treatments best minimized changes in trawl geometry.

Materials and methods

Vessel, trawl gear, and instrumentation

Trawling operations were conducted aboard the 40-m stern trawler FV *Aldebaran* that was chartered for the 2005 survey of crab and groundfish resources in the eastern Bering Sea (Lauth and Acuna[3]). This vessel is equipped with raised, split trawl winches filled with compacted, solid-core trawl warps 28.6 mm (1.125 in) in diameter. Warps were measured and marked in accordance with standardized survey procedures (Stauffer, 2004).

The 83-112 bottom trawl used in this study is the same as the one used in the annual AFSC resource assessment surveys. It is a low-rise, 2-seam flatfish trawl characterized by a headrope that is 25.3 m (83 ft) long and a simple footrope that is 34.1 m (112 ft) long. The footrope is 5.2 cm in diameter and is composed of steel cable wrapped in a split rubber hose for protection. It is weighted with 75 kg of chain to which the netting is attached. The nylon net is made of 102-mm stretch-mesh panels forward of the intermediate section, 89-mm stretch-mesh throughout the remainder of the net, and has a 32-mm mesh liner inside the codend. It connects on each side to a steel V-door, which is 1.8×2.7 m and weighs 816 kg (in air), by a pair of 3-m-long door legs, a 12.2-m-long door leg extension, and a pair of 54.9-m-long bare cable bridles.

Our restrictor line, with a length of 10.5 m, was nearly 2 m longer than the 8.6-m distance between the trawl blocks to facilitate deployment over the stern with the trawl doors in the water and beginning to spread. It consisted of 3 lengths of braided Spectra[4] line (each 12.7 mm in diameter): a 6-m-long middle section capable of bridging the stern ramp and a pair of detachable 2-m-long end sections for tethering each side to the trawl warps. Quick assembly of the 3 sections was accomplished by using a combination of hammerlocks, G-hooks, and flat links. The starboard side of the restrictor connected to a loop of 25.4-mm-diameter Duralon braid sheathing tied directly to the starboard warp with a variant of the hitch knot that is slip-free yet easy to untie. The port side of the restrictor terminated with a large slip hook that snapped loosely around the warp, allowing it to slide freely and, therefore, preventing the restrictor from parting if the net was askew during deployment or while towing.

Time-synchronized data were collected from numerous shipboard and trawl-mounted instruments. Vessel position and speed over ground (hereafter referred to as *towing speed*) were measured at 2-s intervals with GPS satellite navigation. The speed of the trawl as it moved through the water (hereafter, referred to as *trawl speed*) was measured along the trawl axis to the nearest 0.1 kn, at approximately 20-s intervals, with a Scanmar acoustic trawl speed sensor (TrawlSpeed HC4-TSS, Scanmar AS, Åsgårdstrand, Norway) mounted to the center of the headrope. Wing spread and door spread were measured acoustically to the nearest 0.1 m, at 4-s intervals, with NetMind sensors (Northstar Electronics Inc., Vancouver, Canada). The distance of the footrope from the seabed was measured to the nearest centimeter at 0.5-s intervals with bottom con-

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[1] Engås, A. and E. Ona. 1991. A method to reduce survey bottom trawl variability. ICES Council Meeting (C.M.) Documents 1991/B:39, 6 p.

[2] Engås, A. and E. Ona. 1993. Experiences using the constraint technique on bottom trawl doors. ICES Council Meeting (C.M.) Documents 1993/B:18, 10 p.

[3] Lauth, R. and E. Acuna (compilers). 2007. 2005 bottom trawl survey of the eastern Bering Sea continental shelf. AFSC Processed Rep. 2007-1, 164 p. [Available from Alaska Fish. Sci. Cent., NOAA, Natl. Mar. Fish. Serv., 7600 Sand Point Way NE, Seattle, WA 98115.]

[4] Mention of trade names or commercial companies is for identification purposes only and does not imply endorsement by the National Marine Fisheries Service, NOAA.

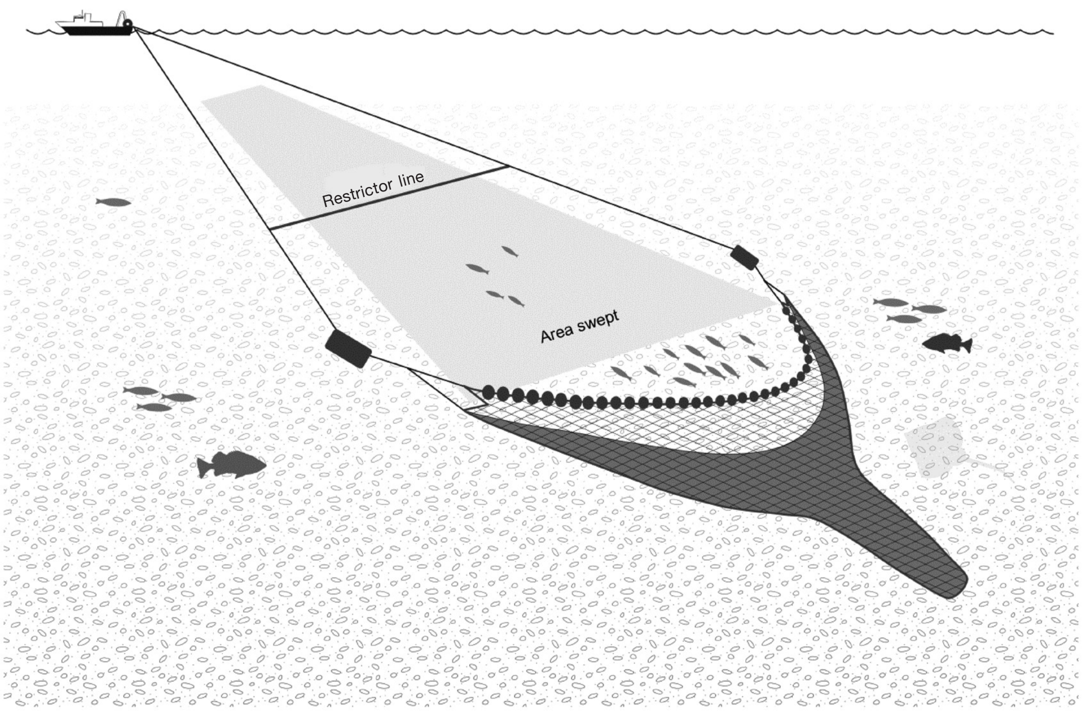

Figure 1

Depiction of the area swept between trawl wing tips with a restrictor line attached to the warps for constraining door spread.

tact sensors and used in our calculation of footrope performance (Somerton and Weinberg, 2001). Sensors were placed in 5 positions along the footrope: one at the center and one each at both port and starboard corners of the trawl mouth (located 3 m to either side of the center) and at both wing ends (located 1 m aft of the wing end). Similarly, 4 sensors were used to measure lower bridle performance, with 1 sensor suspended at each of 2 positions, 30 and 40 m forward of the wing end, on both (the port and starboard sides, according to Somerton (2003). Bottom contact sensors are self-contained units consisting of an analog tilt meter capable of measuring angle to the nearest 0.5° and a data logger housed in a watertight stainless steel container that fits inside a steel sled. Fluctuations in the distance of the footrope or bridle from the bottom produce changes in the recorded tilt angle. Tilt angles were converted to distances from the bottom for each sensor by using separate quadratic functions derived from previous calibrations (Somerton and Weinberg, 2001).

Experimental design

Three independent experimental towing sites were selected spanning the range of trawling depths covered by the survey. The shallow depth site (59°17′N, 165°37′W) was located at a depth of 21 m, the middle depth site (56°38′N, 167°25′W) at 104 m, and the deep site (54°55′N, 166°24′W) at 150 m. Depths were determined by the ship's echosounder.

Towing was conducted according to standardized survey procedures: a 3-kn tow speed over ground with a fixed amount of warp as called for by the survey scope table (137 m at the shallow site, 274 m at the middle site, and 457 m at the deep site). The codend remained open to eliminate variable effects of changes in catch size on trawl geometry. With the codend open, the total number of possible tows was increased and time was saved because the codend did not need to be emptied after each treatment. Experimental hauls consisted of 3 towing treatments:

1) No restrictor line and use of the standard survey scope ratio (control treatment);
2) Restrictor line and use of the standard survey scope ratio; and
3) Restrictor line and use of a modified scope ratio.

Tow duration for each treatment was 10 min, after a 5-min stabilization period. Treatments were randomized at each site to reduce biases introduced by sea state, wind, and tidal currents on trawl performance.

Determining position of the restrictor line and target wire angle

En route to the first study site, we conducted a limited number of test tows at an opportune depth of 71 m, experimenting with 3 differing restrictor positions while also testing 3 different warp lengths or scope ratios, our proxy for varying vertical wire angles, for their effect on wing spread. A review of the survey database showed that for the most recent 5 years before this experiment, 95% of tows had an average wing spread of at least 15 m (Fig. 2A). Of the more uncommon tows with wing spreads <15 m, most occurred in shallower water (depths <39 m) and had a warp length of 137 m, the shortest length permitted by the survey (Fig. 2B). For the purpose of this study, we considered 15 m to be the effective minimum survey wing spread. Therefore, because the primary objective of this study was to keep trawl geometry constant across survey depths, we targeted a 15-m wing spread for all tows in which the restrictor was deployed. With the trawl doors at the surface, 3 restrictor positions of 70, 116, and 162 m forward of the doors were explored. Testing resulted in the position at 116 m yielding wing spreads closest to our target spread of 15 m.

Our third experimental treatment, in which the restrictor line and a modified scope ratio were used, called for setting an appropriate amount of trawl warp to minimize the variability in the upward pulling force on the trawl door. A constant upward pulling force at all depths was considered desirable because it would ensure that the door weight in contact with the bottom was equal, regardless of depth, enabling more consistent ground sheer of the doors necessary to spread the trawl. The pulling forces exerted on a trawl door are divided into vertical (upward pulling force; *U*) and horizontal (forward pulling force; *F*) forces that can be related to each other with this equation:

$$U = F \times \tan(v), \qquad (1)$$

where v = the angle between the trawl warp and the seabed.

This equation indicates that, to achieve constant *U*, it is necessary to keep *F* and *v* constant. *F* depends on trawl speed and the friction force produced by door contact with the substrate. Other than maintaining a constant vessel speed over ground, we were unable to control for either one of these variables in the experiment. However, angle *v* was controlled in the third treatment by setting an appropriate length of wire to keep *v* constant and minimize the variability in *U*. The length of warp needed at each depth location was determined with this equation:

$$Warp\ length = depth \ / \ \sin(v). \qquad (2)$$

We tested 3 different warp lengths, 229, 274, and 366 m, at the depth of 71-m, that represented 3 different wire angles, 11.2°, 15.1°, and 18.2°. The 274-m warp length or 15.1° wire angle gave the most constant wing spreads near our 15-m target and coincidentally was closest to the 14.7° angle used by Engås and Ona[1] to keep approximately two-thirds of the door weight in contact with the bottom. On the basis of this equation:

$$Warp\ length = depth \ / \ \sin(15.1°), \qquad (3)$$

our 3 depth sites (21, 104, and 150 m) required the use of 81, 400, and 576 m of trawl warp, respectively, approximating a 3.8:1 scope ratio. Because the treatment that used a restrictor with a modified scope ratio called for 81 m of warp at our shallow experimental depth site and our restrictor position was 116 m forward of the doors, no restrictor was used and the trawl blocks served as the restrictor instead.

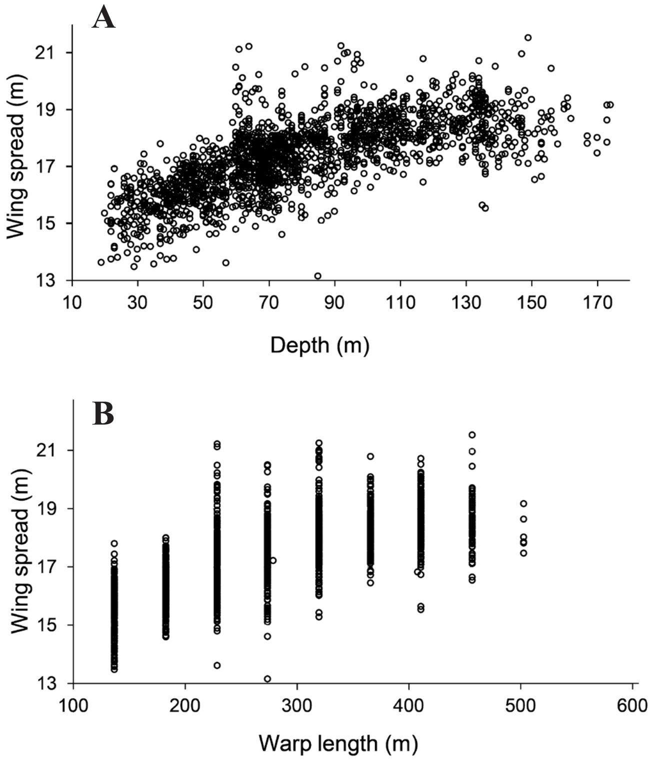

Figure 2

Mean wing spread data by (**A**) depth and (**B**) warp length from the eastern Bering Sea bottom trawl surveys conducted by the Alaska Fisheries Science Center during 2000–2004.

Data analyses

For any given trawl measure, all 3 towing treatments in a haul were excluded from analyses if one or more of the treatments produced unusable data. Examples of events that produced unusable data include sensor malfunction or suspected trawl failure caused by the collapse of a door or the encounter of a derelict crab pot. The remaining treatment data were screened for outliers by using a standardized sequential outlier rejection routine (Kotwicki et al., 2011). Arithmetic means were then calculated by treatment for each trawl performance measure and for trawl speed. Because of the symmetrical placement (port and starboard) of all but one bottom contact sensor, the number of data sets produced that could be used to calculate means were double for the distances from the seabed to the footrope corners and wing ends and to 2 positions along the lower bridles than for the distance from the seabed to the center of the footrope (which was collected with a single sensor), or for acoustic measurements of door and wing spreads.

Generalized linear models were used to compare the effects of different depths on our net performance measures between the 3 towing treatments. Because we could not control for effects of current on trawl speeds but we suspected speed has an effect on wing spread (Weinberg et al., 2002), we included trawl speed in the model to account for any confounding effects it might have on the analyses in this study. Also, because wing spread directly correlates with headrope height with this low-opening style of net, we elected not to include the vertical opening of the trawl in the modeling process. Mean door and wing spread and mean distance off bottom at each position were treated as independent variables (V_i) in the following model:

$$\begin{aligned} Vi \sim & \, \mathit{depth} + \mathit{trawl\ speed} + \mathit{treatment} \\ & + \mathit{depth{:}treatment} + \mathit{trawl\ speed{:}treatment}, \end{aligned} \tag{4}$$

where the “treatment” term accounted for possible differences in the intercepts between treatments, and interaction terms accounted for possible differences in the slopes between treatments. Significance of the treatment term indicates difference in magnitude of the V_i. Significance of the interaction term indicates differences between treatments on the effects of depth or trawl speed on V_i.

Terms in both models were selected with the help of the glmulti package, vers. 1.0.6 (Calcagno, 2012), in R, vers. 2.15.1 (R Core Team, 2012) by running each model with all possible combinations of terms and choosing the one with the smallest Akaike’s information criterion corrected for finite sample size (AICc; Burnham and Anderson, 2002).

Results

Of the 38 experimental hauls that were completed, 14 occurred at the shallow site, 10 were conducted at the middle site, and 14 occurred at the deep site. The number of successful treatments used in the analyses of this study varied for each performance measure as a result of instrument failures and gear conflicts. Table 1 summarizes the successful efforts of the experiment. Although the target towing speed was 3.0 kn, tidal currents and weather affected the speed of the trawl at it moved through water such that the average trawl speed per treatment varied between 2.1 and 3.3 kn.

Door spread

For our control treatment, mean observed door spreads increased 52% across depths from 46 m at the shallow site to 70 m at the deep site (Table 1). The GLM showed that each treatment affected the relationship between door spread and depth differently (Table 2, Fig. 3). Treatments with the restrictor line were quite effective at mitigating the effect of depth on door spread; the slope of the standard survey scope ratio was slightly positive and the slope of the modified scope ratio was slightly negative across depths. On average, observed door spreads for the treatment with the restrictor line and standard scope ratio ranged between 45 and 51 m, and the treatment with the restrictor line and a modified scope ratio held door spread nearly constant, between 44 and 45 m (Table 1). The effect of trawl speed was small and positive for all 3 treatments. The significance of the interaction term between trawl speed and treatment indicated differences between the trawl speed effects among treatments, but the magnitude of these differences were small, positive, and ineffective in mitigating the effect of trawl speed (Table 2).

Wing spread

For our control treatment, mean observed wing spread increased 20% across depths from 15.1 m at the shallow site to 18.1 m at the deep site (Table 1). The GLM showed that each treatment affected the relationship between wing spread and depth differently (Table 2, Fig. 4). As with door spread, treatments with the restrictor line were very effective at mitigating the effect of depth on wing spread; the modified scope ratio performed slightly better than the standard survey scope ratio. On average, observed wing spreads for the treatment with the restrictor line and standard scope ratio ranged between 14 and 16 m, and the treatment that used the restrictor and modified scope ratio held wing spread nearly constant, between 14 and 15 m (Table 1). The effect of trawl speed was small and positive for all treatments, but no differences between treatments were detected (Table 2).

Distance of the footrope off bottom

Changes in mean distances of the footrope off bottom were relatively small, 3.5 cm maximum across all depth sites. For our control treatment, mean observed distances off bottom across depth sites ranged from 1.8 to 5.3 cm at the footrope center to 2.7 to 5.1 cm at the footrope corner and 3.4 to 4.1 cm at the wings (Table 1). The GLM indicated that both depth and trawl speed positively affected distances of the footrope off bottom at the center position, albeit to a small extent, but increased with increasing depth and speed; but only depth, and not speed, positively affected distances of the footrope corners and wings from the bottom (Table 2). The use of the restrictor line and modified scope

Table 1

Means and standard deviations (SD) by trawl performance measure, depth of site (shallow, middle, and deep), and towing treatment observed during the eastern Bering Sea study conducted by the Alaska Fisheries Science Center in 2005 to reduce variability in the geometry of a demersal survey trawl. Treatments included standard survey procedure, adding a restrictor line to constrain door movement, and adjusting scope ratio with the restrictor line in place. Trawl spreads were measured in meters, and the distances of the footrope and lower bridle from the seabed were measured in centimeters at various points along their lengths (fwd=forward of wingends).

	Treatment 1: no restrictor, standard survey scope								
	Shallow (*n*=28)			Middle (*n*=20)			Deep (*n*=28)		
Trawl measure	Mean	SD	*n*	Mean	SD	*n*	Mean	SD	*n*
Door spread (m)	46.44	2.23	7	66.88	2.47	4	70.44	1.59	10
Wing spread (m)	15.15	0.76	9	17.88	0.24	4	18.05	0.13	5
Headline height (m)	3.28	0.16	12	2.96	0.12	8	2.77	0.11	14
Footrope center (cm)	1.84	0.14	9	3.36	0.05	4	5.33	0.36	10
Footrope corner (cm)	2.73	0.28	17	3.27	0.15	8	5.09	0.31	19
Footrope wing (cm)	3.44	0.74	17	3.41	0.49	8	4.14	0.52	17
Bridle, 30 m fwd (cm)	3.16	0.66	15	2.52	0.21	6	4.45	1.61	17
Bridle, 40 m fwd (cm)	2.59	0.71	12	2.46	0.45	6	3.75	0.71	19

	Treatment 2: restrictor, standard survey scope								
	Shallow (*n*=28)			Middle (*n*=20)			Deep (*n*=28)		
Trawl measure	Mean	SD	*n*	Mean	SD	*n*	Mean	SD	*n*
Door spread (m)	45.19	4.59	12	51.11	3.82	4	50.59	0.61	10
Wing spread (m)	14.49	0.78	12	15.37	0.54	4	15.98	0.71	8
Headline height (m)	3.40	0.23	14	3.25	0.20	8	3.16	0.12	14
Footrope center (cm)	1.79	0.16	12	2.84	0.34	4	5.10	0.26	9
Footrope corner (cm)	2.75	0.46	23	3.39	0.32	8	5.17	0.53	20
Footrope wing (cm)	3.22	0.71	21	3.30	0.63	7	4.12	0.58	20
Bridle, 30 m fwd (cm)	3.06	0.65	19	2.50	0.28	7	4.37	1.33	18
Bridle, 40 m fwd (cm)	2.42	0.60	16	2.27	0.24	6	3.67	1.06	15

	Treatment 3: restrictor, modified scope								
	Shallow (*n*=28)			Middle (*n*=20)			Deep (*n*=28)		
Trawl measure	Mean	SD	*n*	Mean	SD	*n*	Mean	SD	*n*
Door spread (m)	43.57	0.80	9	45.00	5.93	4	44.08	2.45	9
Wing spread (m)	14.46	0.43	12	14.32	0.93	4	15.07	0.63	6
Headline height (m)	3.38	0.16	14	3.27	0.25	7	3.13	0.17	13
Footrope center (cm)	1.78	0.11	11	2.71	0.29	4	4.82	0.41	9
Footrope corner (cm)	2.61	0.37	23	3.19	0.20	8	5.20	0.56	18
Footrope wing (cm)	3.44	0.77	22	3.28	0.75	7	4.03	0.63	15
Bridle, 30 m fwd (cm)	3.03	0.68	17	2.48	0.25	8	4.03	1.44	16
Bridle, 40 m fwd (cm)	2.49	0.44	18	2.17	0.25	6	4.25	1.63	13

ratio was slightly more efficient than the use of the restrictor line with the standard scope ratio at mitigating the depth effect at the center of the footrope (Table 2, Fig. 5). The effect of trawl speed was small and positive for all treatments. The interaction term, between trawl speed and treatment, was not significant, indicating no difference in the effect of trawl speed between treatments (Table 2).

Distance of the bridle off bottom

Changes in mean distances of the bridle off bottom were nominal, less than 2 cm across all 3 depth sites. For our control treatment, mean observed distances off bottom ranged from 3.2 to 4.4 cm and from 2.6 to 3.8 cm for the 30 and 40 m positions, respectively (Table 1). The GLM indicated that both depth and trawl speed

Table 2

Generalized linear model coefficients from the eastern Bering Sea study conducted by the Alaska Fisheries Science Center in 2005 on variation in trawl geometry by towing treatment, no restrictor, survey standard scope (NRSS); presence of a restrictor line, survey standard scope (RSS); and presence of a restrictor line, modified scope (RMS), describing the relationship between the mean net performance measures as affected by depth and trawl speed. Only coefficients from models found to be significant are shown. Coefficients of multiple determination (R^2) expressed as a percentage also are presented. Common intercepts and slopes indicate that we did not detect significant differences between treatments, respectively.

	Door spread		Wing spread		Footrope center		Footrope corner		Footrope wing		Lower bridle 30 m		Lower bridle 40 m	
	Depth	Speed	Depth	Speed	Depth	Speed	Depth	Speed	Depth	Speed	Depth	Speed	Depth	Speed
Common intercept			10.9416		−0.2354		2.0952		3.1684		0.0550		−1.3598	
Common slope			1.3135			0.4942	0.0188		0.0054		0.0067	1.0321	0.0074	1.3755
NRSS intercept	37.7859	37.7859												
NRSS slope	0.1878	1.8372	0.0253		0.0265									
RSS intercept	16.5546	16.5546												
RSS slope	0.0258	10.8316	0.0084		0.0244									
RMS intercept	22.2891	22.2891												
RMS slope	−0.0248	8.9876	0.0014		0.0226									
R2 percentage	95.27		84.79		93.59		80.68		18.06		20.89		38.40	

positively affected distances off bottom at the 2 bridle positions, increasing with increasing depth and speed, but no differences between treatments were detected (Table 2).

Discussion

Horizontal herding

Our primary objective was to reduce the effects of depth and coincidental changes in trawl speed on the geometry of our survey trawl. Specifically, we wanted to determine which of 3 towing methods would best control the variability in the spread of the doors and wings to achieve the average minimum 15-m wing spread seen in recent surveys. We found that attaching a restrictor when we used the standard survey scope ratios successfully reduced the variability in mean wing spread to within 1.7 m across the typical range in survey depths—considerably less than the 8.3-m range seen during surveys (Fig 2A). Best results were obtained when a restrictor line was used with a modified scope ratio (3.8:1) to provide a constant upward pulling force on the trawl doors.

With mean door and wing spread data, we were able to estimate bridle angles of attack at each depth site and for each treatment. Maintaining consistent bridle angles minimizes inconsistencies in fish-size and species-specific selectivity inherent in the horizontal

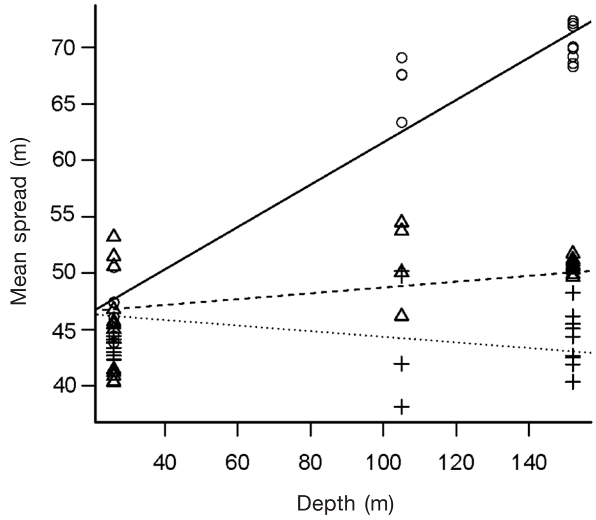

Figure 3

The effect of depth on mean door spread during the eastern Bering Sea field experiment conducted by the Alaska Fisheries Science Center in 2005 to reduce the variability in a survey trawl's geometry. Data were fitted with a generalized linear model. Three towing treatments were applied: no restrictor line with standard scope (circle, solid line), restrictor line with standard scope (triangle, dashed line), and restrictor line with modified scope (plus sign, dotted line).

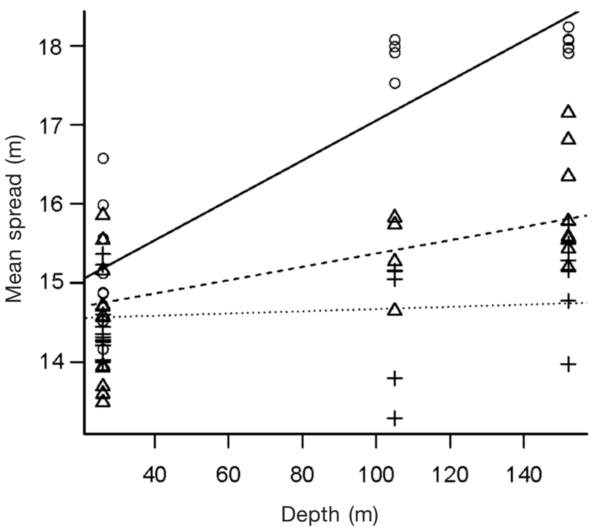

Figure 4

The effect of depth on mean wing spread during the eastern Bering Sea field experiment conducted by the Alaska Fisheries Science Center in 2005 to reduce the variability in a survey trawl's geometry. Data were fitted with a generalized linear model. Three towing treatments were applied: no restrictor line with standard scope (circle, solid line), restrictor with standard scope (triangle, dashed line), and restrictor with modified scope (plus sign, dotted line).

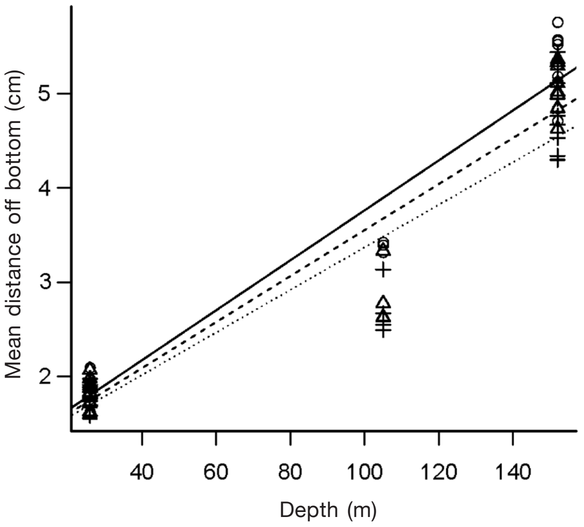

Figure 5

The effect of depth on mean distance of the center of the footrope off bottom during the eastern Bering Sea field experiment conducted by the Alaska Fisheries Science Center in 2005 to reduce the variability in a survey trawl's geometry. Data were fitted with a generalized linear model. Three towing treatments were applied: no restrictor line with standard scope (circle, solid line), restrictor line with standard scope (triangle, dashed line), and restrictor line with modified scope (plus sign, dotted line).

herding process (Engås and Godø, 1989a; Somerton and Munro, 2001), thereby, reducing systematic bias in the abundance estimates. For example, bias may occur when a particular area produces lower sampling efficiency than other survey areas, such as may happen at different depths where trawl bridle angles of attack vary. Changing angles have an effect on fish-size–specific reactions to the bridles and on the swimming stamina of a fish: the greater the angle, the greater is the potential that herded fish will have to swim longer and farther to enter the path of the net before tiring. As a result, false interpretations of a species' spatial distribution over the whole survey area can occur because, in reality, part of the distributional variability is caused by differences in the trawl sampling efficiency.

We found that when the restrictor line was not used, mean bridle angles varied from 13° to 20° across depths. These angles were reduced to a range from 12° to14° when the restrictor line was used with a standard survey scope ratio and to a constant 12° when the restrictor was used with a modified scope ratio. Therefore, we conclude that the use of a restrictor during our bottom trawl survey would ensure more constant trawl geometry across the entire survey area, reducing the variability in horizontal herding that may be associated with changing bridle angles. This deduction is consistent with our objective of ensuring that the changes in observed trawl catch abundance are representative of actual shifts in abundance.

Contact of the lower bridle with the seabed also contributes to the herding of fish, particularly flatfishes. Whereas our study showed that bridle contact decreased as a result of increasing depth and towing speed, the addition of the restrictor line did not affect these relationships and, therefore, likely would not contribute to any significant improvement in the variability in survey horizontal herding owing to bridle contact, at least given the conditions observed during this experiment.

Vertical herding

Although we did not measure net height directly, our survey data show that by keeping net spread constant we achieve a more constant net height that, therefore, sweeps a more constant volume of water and presumably stabilizes the effect of the net on vertical herding of fish near the bottom. The 83-112 bottom trawl was designed to catch flatfish and semipelagic species, such as walleye pollock (*Gadus chalcogrammus*) and Pacific cod (*Gadus macrocephalus*), that have near-bottom distributions. The vertical herding of benthic species with this trawl is perceived to be negligible. Conversely, the vertical herding of semipelagic species like walleye pollock is recognized (De Robertis and Wilson, 2006), although the quantifiable extent to which it occurs is not well understood.

Research with acoustics has shown that fish behavioral tactics to avoid vessels and trawls, usually in the form of diving, are used by a variety of pelagic and semipelagic species in advance of an approaching vessel (Vabø et al., 2002) and on through the time that a trawl arrives (Ona and Godø, 1990; Handegard et al., 2003; Kaartvedt et al., 2012). This diving behavior accounts for a considerable increase in the number of fish available to the trawl, an increase that can bias survey results (Aglen, 1996; Hjellvik et al., 2003; Handegard and Tjøstheim, 2009), particularly if the vertical herding is size- or age-related (De Robertis and Wilson, 2006). Auditory stimuli, such as that of vessel noise (Mitson and Knudsen, 2003), of vessel induced pressure waves (Mitson, 1995), and of warp vibration (Handegard and Tjøstheim, 2009), are attributed most often to fishes with diving behavior. Additionally, light levels at depth (Misund, 1997) and density dependence play a role in vertical herding for some species (Hoffman et al., 2009; O'Driscoll et al., 2002).

As shown in this study, the addition of a restrictor line reduces the trawl footprint; however, it also introduces uncertainty to our current knowledge of the relationship between fish behavior and trawl sampling efficiency. The effect of this tool on vertical herding and the resultant catch rates for species of the Bering Sea is unknown. To better understand the potential of this effect, knowledge of the height of the restrictor line above the seabed is critical. Because of instrument failure, we were unable to collect such data, but we can still estimate the height of the restrictor line, as the product of bottom depth and 116 m (the position of the restrictor line forward of the doors), divided by warp length, assuming that the warps form a straight line from the trawl doors to the vessel. In actuality, the restrictor heights off bottom would be somewhat less than our predicted heights because of a narrow degree of natural warp catenary.

If the above relationship and our standard survey scope ratios had been used, restrictor heights would have been 18, 44, and 38 m at our 3 depth sites, compared with a constant 30 m off bottom when the scope ratio was modified. Although the average headrope height of the 83-112 trawl is 2–3 m during standard survey operations, a recent study by Kotwicki et al. (2013) reported that the effective fishing height of this trawl for walleye pollock that display the diving response was, on average, 16 m. Although our predicted restrictor heights were all above the 16-m effective fishing height calculated by Kotwicki et al. (2013), the vibrations of the restrictor line, along with bringing the trawl warps closer together, could contribute to fish disturbance, and hence inconsistencies in sampling efficiency.

A better understanding of the effect of a restrictor line on fish behavior and catch rates is required before it can be considered an accessory to standardized survey trawl gear. If it were incorporated, a means for correcting our 30-year survey time series (before and after the use of a restrictor line) would also have to be developed. We are aware of one bottom trawl survey during which a restrictor line is regularly deployed: Norway's Institute of Marine Research (IMR) Barents Sea Cod Survey. In the case of that survey, the restrictor line was introduced over a 2-year period (one-third of tows during the first year and half of the survey tows during the next year). In those trials, evidence of increased catch rates for smaller Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*), but not larger fishes, was observed. In additional studies at IMR, when a transducer was mounted to the restrictor line, IMR found evidence of pelagic distributions of adult Atlantic cod and haddock diving to avoid the restrictor line (Aglen[5]). We suggest that a large-scale study should be initiated to examine the changes in species-specific catch rates before a restrictor line is incorporated as a standard tool for the eastern Bering Sea survey.

Our most promising towing treatment to reduce variability in trawl geometry involved a fixed ratio of depth to warp length. Given the relatively shallow depth range of the eastern Bering Sea survey (<200 m), this method proved successful. Surveys where deeper waters are sampled may not achieve success with a fixed ratio of depth to warp length because the degree of warp catenary, particularly in the warp's lower half, increases at greater depths, thereby transferring pulling forces from upward to horizontal[6]. Too much horizontal pull will lead to imbalance as evidenced by doors collapsing and warp dragging through sediment. Polishing of trawl warps ahead of the doors and on the doors in unexpected places are clear indications of excess warp ratios.

Escapement

We found that the use of a restrictor line allowed us to achieve a modest reduction in the effect of depth on the distance off the bottom of the relatively light weight footrope of the 83-112 trawl. The use of the restrictor line, we believe, would result in a reduction in the variability in fish escapement under the footrope and a more uniform catching efficiency (Engås and Godø, 1989b; Walsh, 1992). That there was still an effect of depth with the restrictor line was unexpected. Von Szalay and Somerton (2005) described increases in the distance of the footrope off bottom to be a function of increasing wing spread in which the footrope tension increases and, therefore, lifts the rope from the bottom. If this were the case, then one would expect no differences in footrope height off bottom when wing

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[5] Aglen, A. 2013. Personal commun. Inst. Mar. Res., 5817 Bergen, Norway.

[6] Dickson, W. 1973. Warp length in deep water, 19 p. MIR/UNDP/FAO/Polish/UNSF Highseas Fisheries Research Project, Gydnia, Poland.

spread is constant. One explanation for bottom contact sensor angles (our proxy for increasing distances of the footrope off bottom) increasing with increasing depth when the restrictor limited spread could be that the sensor housing penetrated the softer bottom substrate. If the edge of the bottom contact sensor had been sinking into the seabed, recorded angles would have been higher and our function for transforming angles into distances off bottom, which was derived from a separate experiment performed on a hard surface, would be incorrect. In retrospect, we compared the locations of our towing sites with locations from a sediment map of the Bering Sea (Smith and McConnaughey, 1999) and observed that our deepest site occurred in a soft, muddy region of the Bering Sea where the sensor could possibly penetrate the substrate. Use of this tool for predicting footrope performance may best be limited to areas of comparable substrate, and data collected over an entire survey area should be used cautiously.

In conclusion, reduced variability in net spread and bottom contact of our survey trawl was best achieved by affixing a restrictor line between the trawl warps to constrain the spread of the otter doors in conjunction with the use of a 3.8:1 ratio of warp length to depth. The stabilization of trawl shape across a survey area will reduce the variability in horizontal herding and fish escapement, leading to more precise estimates of abundance for stock assessments. Before inclusion of a restrictor line as part of standardized survey equipment, we recommend that further experimentation be conducted with retention of the catch to quantify the effect of the restrictor line on horizontal and vertical herding. These studies would be most meaningful for the eastern Bering Sea semipelagic gadoids walleye pollock and Pacific cod. With a clearer understanding, catch coefficients could be developed and applied to historical survey data.

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