Whole-gear efficiency of a benthic survey trawl for flatfish

David A. Somerton (contact author)
Peter T. Munro
Kenneth L. Weinberg
National Marine Fisheries Service, NOAA
Alaska Fisheries Science Center
7600 Sand Point Way NE
Seattle, Washington 98115
Email address for D. A. Somerton: david.somerton@noaa.gov

Abstract—Whole-gear efficiency (the proportion of fish passing between the otter doors of a bottom trawl that are subsequently captured) was estimated from data collected during experiments to measure the herding efficiency of bridles and doors, the capture efficiency of the net, and the length of the bridles sufficiently close to the seafloor to elicit a herding response. The experiments were focused on four species of flatfish: arrowtooth flounder (*Atheresthes stomias*), flathead sole (*Hippoglossoides elassodon*), rex sole (*Glyptocephalus zachirus*), and Dover sole (*Microstomus pacificus*). Whole-gear efficiency varied with fish length and reached maximum values between 40% and 50% for arrowtooth flounder, flathead sole, and rex sole. For Dover sole, however, whole-gear efficiency declined from a maximum of 33% over the length range sampled. Such efficiency estimates can be used to determine catchability, which, in turn, can be used to improve the accuracy of stock assessment models when the time series of a survey is short.

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Fish density can be estimated from bottom trawl catch-per-swept-area data if there is knowledge of the whole-gear efficiency (the proportion of fish that are captured within the area spanned by the trawl doors). One approach to the estimation of whole-gear efficiency is to consider it as a function of three separate and underlying trawling processes: vertical and horizontal herding of fish, retention of fish by the net, and escapement of fish beneath the trawl footrope, which are often more tractable to field experimentation and estimation. Perhaps the earliest example of this approach was the development of a mathematical model by Dickson (1993a) for the efficiency of trawl gear in capturing fish and the application of this model for capturing Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus;* Dickson, 1993b) with the use of experimental data on herding (Engås and Godø, 1989a) and on escapement under the footrope (Engås and Godø, 1989b). Somerton and Munro (2001) proposed a modification to Dickson's (1993a) model for application to flatfish to account for the observation that flatfish herding is restricted to the length of the lower bridle that is sufficiently close to the bottom to elicit a behavioral response (Main and Sangster, 1981b). A variant of this model was then applied to seven species of North Pacific flatfish to estimate the efficiency of the capture process that was due to herding (Somerton and Munro, 2001). Although this application was followed by experiments to estimate escapement under the footrope for some of the same flatfish species (Munro and Somerton, 2002), the flatfish efficiency model was never used to combine the herding and escapement estimates and thereby produce an estimate of whole-gear efficiency. In this article, we again use the flatfish trawl efficiency model, extended by developing an estimator for the variance of efficiency, and apply the model to new experimental data for four flatfish species (flathead sole [*Hippoglossoides elassodon*], rex sole [*Glyptocephalus zachirus*], Dover sole [*Microstomus pacificus*], and arrowtooth flounder [*Atheresthes stomias*]) to estimate whole-gear efficiency for the Poly Nor'eastern trawl, which is used by the Alaska Fisheries Science Center (AFSC) on its bottom trawl surveys of the Gulf of Alaska and the Aleutian Islands region.

Materials and methods

The Poly Nor'eastern trawl

The Poly Nor'eastern trawl, pictured in Figure 1 and detailed in the Appendix, has the following basic features: the net has a four-seam design and has a 27.2-m headrope and a 36.5-m footrope equipped with 36-cm diameter bobbins to allow operation on moderately rocky terrain. The trawl doors are "V" style measuring 1.8 m by 2.7 m and weighing 816 kg each. Tailchains constructed of two 3-m

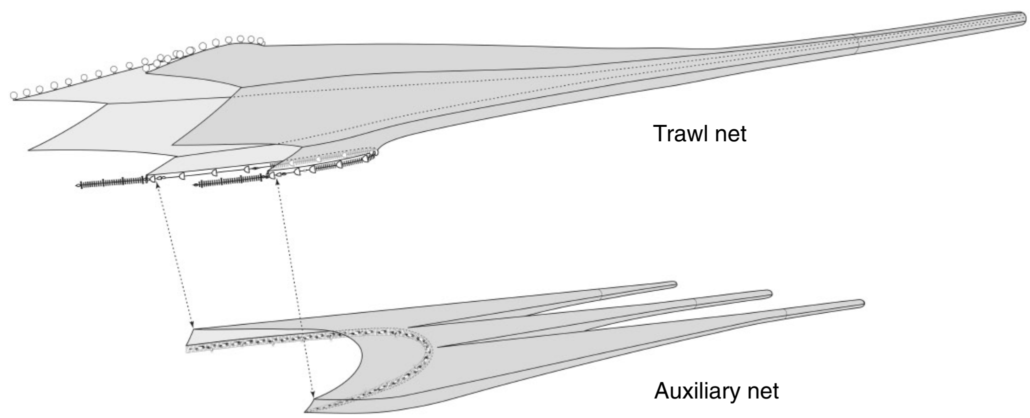

Figure 1
A diagram of the Poly Nor'eastern trawl net and the auxiliary net that was attached beneath the trawl net to capture fish escaping under the trawl footrope. Details on the construction of these nets can be found in the Appendix.

lengths of 13-mm long-link chain are joined to a single 19-mm diameter steel cable, known as the tailchain extension, that is varied in length to suit the needs of each vessel. Tailchain length is the combined length of the chain and extensions. Tailchain extensions are connected to the leading edge of each wing with three bridles measuring 54.9 m in length and constructed of 16-mm steel cable. The net mesh in the lower section of each wing ends 6.1 m behind the end of the footrope (Fig. 1; Appendix); the footrope in this section will be referred to as the wing extension.

Trawl efficiency model for flatfish

For flatfish, which are unlikely to escape through the small-mesh, codend liner, or over the headrope, the catch of a trawl (N) can be expressed as the sum of the catches of fish originating from the net and bridle paths (Dickson, 1993a; Somerton and Munro, 2001)[1]:

$$N = k_n DLW_n + k_n hDLW_{on}, \tag{1}$$

where D = fish density;
L = tow length;
W_n = the width of the net path;
W_{on} = the width of the bridle path contacted by the bridle;
k_n (net efficiency) = the proportion of fish within net path that are captured; and
h (herding coefficient) = the proportion of fish within the bridle contact path that are herded into the net path.

Because h is relative to W_{on}, which will vary with trawl design, for comparative purposes a more convenient measure of herding is the bridle efficiency (k_b) or the proportion of fish that are herded from the entire bridle path (Dickson, 1993a). Bridle efficiency can be calculated from the herding coefficient by using

$$k_b = \frac{hW_{on}}{W_d - W_n}, \tag{2}$$

where W_d = the width of the door path.
k_b = the average bridle efficiency in the area swept by the entire bridle (i.e., wing tip to door); and
h = the bridle efficiency only in the area actually contacted by the lower bridle.

Trawl efficiency (E) can then be derived from Equation 1 by dividing by the total number of fish within the door path (i.e., DLW_d).

$$E = \frac{k_n(W_n + hW_{on})}{W_d}. \tag{3}$$

Of the five quantities needed to evaluate this expression, two (W_n, and W_d) are routinely measured on bottom trawl surveys, but three (k_n, h, and W_{on}) require separate field experiments for their estimation. In this study, k_n was estimated with the data obtained from a net efficiency experiment which consisted of attaching

[1] In Somerton and Munro (2001) the parameter W_{on} in Equation 1 was instead represented by the equivalent, but more complex, expression: $W_d - W_n - W_{off}$, where W_{off} is the width of the bridle path not contacted by the bridle.

an auxiliary net under the trawl net to capture those fish escaping beneath the footrope—a method similar to that used in the studies of Engås and Godø (1989a), Walsh (1992), and Munro and Somerton (2002). Bridle efficiency (k_n) and the herding coefficient (k_n) were estimated from the data obtained from a herding experiment which consisted of repeatedly conducting trawl hauls where W_d was varied by varying the length of the bridles as has been done in the studies of Engås and Godø (1989b), Ramm and Xiao (1995), and Somerton and Munro (2001). The width of the area contacted by the bridle was estimated from the data obtained from an experiment by using bottom contact sensors to measure the off-bottom distance along the lower bridle—a distance that was reported for the Poly Nor'eastern trawl in Somerton (2003).

Net efficiency experiment

The net efficiency experiment was conducted during 2–10 July 1996 in the Gulf of Alaska, off the southeast side of Kodiak Island (58°30′N, 149°30′W) at 135–151 m depth with a 45-m chartered stern trawler, the FV *Golden Dawn*. An auxiliary net, described in the Appendix and patterned after those described in Engås and Godø (1989b) and Walsh (1992), was attached under the trawl net (Fig. 1). Trawling procedures followed normal survey protocols that included towing only during daylight hours for 15 minutes at a vessel speed of 1.5 m/sec. Catches from the trawl and the auxiliary net were kept separate, sorted by species, weighed, and all individuals were measured for total length (TL) in centimeters.

The auxiliary net, which was constructed of smaller 10.2-cm stretch mesh polyethylene netting, had a 24.8-m long headrope that was lashed directly to the fishing line of the trawl net (i.e., the forward edge of the netting) excluding the wing extension sections of the trawl footrope. The auxiliary net also had a 28.0-m long, 1.3-cm diameter chain footrope, strung with 12.7-cm rubber disks (Fig. 1), that was attached to the trawl footrope at the junctions of the roller gear and wing extensions, thus allowing the auxiliary footrope to move independently of the trawl footrope and to follow it with a separation distance of approximately 1–2 m at its center. The auxiliary net was designed so that the common intermediate section was attached to three separate codends, each having a 3.2-cm stretch mesh liner.

Experimental tows to verify that trawl performance was not altered by the attachment of the auxiliary net preceded the tows used for the measurement of net efficiency. During all of the experimental tows, a video camera, supplied with a 50 W light, was positioned in front of the footrope along the centerline of the trawl so that it had an oblique view and allowed an approximate measurement of the distance between the center of the footrope center and the sea floor. Initially, 10 tows were made with the trawl without the auxiliary net attached. When the same procedure was used for the trawl with the auxiliary net attached, the video recording indicated that the off-bottom distance of the footrope at its center was greater. By trial and error, additional weight (chain) was attached to the center of the footrope until the off-bottom distance appeared equal to that of the trawl footrope without the auxiliary net. A total of 53.4 kg of chain was attached across the centermost 6.1 m of the footrope.

Estimating k_n from the experimental data

Net efficiency, k_n, was estimated as a function of fish length, l, by fitting an analytical model to the capture probability, P (i.e., proportion of fish passing between the trawl wing tips that are caught), and fish length data pooled over tows. Four competing models, each representing a different capture process, were considered (Munro and Somerton, 2001). The first three are parametric models, which, in order of increasing complexity, are expressed as

$$\text{2-parameter logistic,} \quad P = \frac{1}{1+e^{-(\alpha+\beta l)}}, \tag{4}$$

$$\text{3-parameter logistic,} \quad P = \gamma\left(\frac{1}{1+e^{-(\alpha+\beta l)}}\right), \tag{5}$$

4-parameter logistic,

$$P = \gamma\left(\frac{1}{1-\delta}\right)\left(\frac{1-\delta}{\delta}\right)^{\delta}\left(\frac{e^{-\delta(\alpha+\beta l)}}{1+e^{-(\alpha+\beta l)}}\right), \tag{6}$$

where α, β, γ, and δ are free parameters to be estimated.

The maximum likelihood procedure for fitting these models, detailed in Munro and Somerton (2001), was based on the assumption that the entry of individual fish into either the trawl net or the auxiliary net could be described as a binomial statistical process. The fourth model is a nonparametric model, the cubic spline, which was fitted by using an S+ (S-PLUS, Insightful Corporation, Seattle, WA) function that determined the effective number of parameters of the spline function with cross validation (Venerables and Ripley, 1994). Of the four competing models, the best fitting model was selected as the one producing the lowest value of the Akaike Information Criterion (AIC; Burnham and Anderson, 1998). Ninty-five percent confidence intervals about the capture probabilities as a function of fish length were estimated by using the bootstrapping method (Efron and Tibshirani, 1993) where entire hauls were used as the units of data resampled.

Herding experiment

The herding experiment was conducted 10–19 May 1998 aboard a 30.6-m stern trawler, the FV *Hickory Wind*, near Kodiak Island in the Gulf of Alaska at depths ranging from 126 to 183 m. A blocked sampling design was used to minimize the effects of the spatial variation in fish density on catch. In each geographical block, three nearby, but nonoverlapping, trawl hauls were made with each of three bridle lengths (chosen in random order). Bridles lengths measured 36.6 m, 54.9 m (the standard used on AFSC bottom trawl surveys), and 73.1 m. Tailchain length was 6.1 m. Trawling was conducted during daylight hours for 30 min at 1.5 m/sec. On all hauls, door spread, wing spread, and headrope height were measured simultaneously and continuously with an acoustic trawl mensuration system. Tow length was measured as the straight-line distance between the GPS positions of the first and last footrope contact with the bottom; this distance was determined by using a bottom contact sensor (Somerton and Weinberg, 2001) attached to the center of the footrope. The catch from each haul was first sorted to species, weighed in the aggregate, and then all flatfish were measured for TL in centimeters.

Estimates of W_{on} for the three bridle lengths were calculated from the estimates of the length of bridle contact with the bottom, L_{on}, provided by the bridle contact experiment described in Somerton (2003). Although the lengths of the bridles in this experiment were the same as those in the herding experiment, the length of the tailchains was 10.4 m longer because the length of the tailchain extensions vary with the size of a vessel. Consequently, the distance between the wing tip and the door differed between experiments. Because the cable used for the tail chain extension is quite similar in diameter to that used for the bridles (i.e., 19 mm [tail chain] vs. 16 mm [bridle]), the resulting difference in length is essentially the same as a constant addition to the three bridle lengths. We assumed that the effect of such a change in total bridle length was reflected only in L_{on} and that the portion of the bridle that was off bottom, L_{off}, did not differ between the bridle measurement and herding experiments. Thus L_{on} for the herding experiment was estimated as the total bridle length (bridle length + tail chain length) for the herding experiment minus L_{off} from the bridle contact experiment. A value of W_{on} was then estimated for each bridle length as

$$W_{on} = 2\sin(\alpha)\, L_{on}, \tag{7}$$

where α = the average bridle angle at each bridle length during the herding experiment.

Sin(α) was computed for each haul as

$$(W_d - W_n)/2L_t,$$

where L_t = the total length of the bridle plus the tailchain (i.e., wingtip to door distance); and
W_d and W_n = the haul mean values of door and wing spread.

Variance of W_{on} was estimated by using the delta method (Seber, 1973) and assuming no covariance between sin(α) and L_{on}. This variance is expressed as

$$Var(W_{on}) = 4\left(\sin(\alpha)^2 Var(L_{on}) + L_o^2\ Var\left(\sin(\alpha)\right)\right). \tag{8}$$

Var(sin(α)) for each bridle length was calculated as the between-haul variability in sin(α), and Var(L_{on}) was obtained from Somerton (2003).

Estimating *h* from the experimental data

The herding coefficient was estimated by fitting a modified version of Equation 1 to the experimental data on W_n, W_{on}, and catch (in numbers). The first modification, which is considered more fully in Somerton and Munro (2001), consists of introducing a new parameter, k, defined as the product of D and k_n, that is allowed to vary among blocks. The second modification is to allow length dependency in k and h. The modified equation is

$$N_{ijk} = k_{ik}(LW_n)_{ij} + k_{ik}h_k(LW_{on})_{ij} + \varepsilon_{ijk}, \tag{9}$$

where subscript i refers to block number, j to bridle length within block, k to fish length class, and ε_{ijk} is a normally distributed error term.

For each fish-length class, fitting Equation 9 to the herding data required estimation of n+1 parameters, where n is the number of blocks sampled (i.e., a unique value of k for each block and a common value of h for all blocks). Because the model is nonlinear in the parameters (h and k are multiplied together), it was fitted to data by using nonlinear regression (Venables and Ripley, 1994). Fish length classes used in the calculations were chosen such that the number of observations of length was approximately equal among classes, and differed among species due to differences in the number and size range of sampled fish. After h was estimated, k_b was calculated for the standard bridle length with Equation 2.Variance of k_b was estimated by using a bootstrapping process designed to include among-block variability in catch and trawl measurements as well as the uncertainty in the estimated value of W_{on}. First, a bootstrap replicate of catch and trawl measurement data was obtained by randomly choosing, with replacement, blocks of data, each containing a single haul at each bridle length, from the n blocks sampled (blocks rather than hauls were randomized to preserve the within-block correlation in catch). Second, for each bridle length, a value of W_{on} was computed by using a normal random number generator with values of the mean and variance of W_{on} reported in Somerton (2003). Third, h was then estimated by fitting Equation 9 by using nonlinear regression, and k_b was estimated from h by using Equation 2. Fourth, the process was repeated 100 times and the variance of k_b was estimated as the variance among the replicates. Although the model that we used allows for length-dependent herding, herding may not be a length-dependent process in all species. To determine if k_b varied with fish length, the estimated length-specific values of k_b were regressed on the midpoints of the length intervals.

Table 1

Selectivity model selection and estimated parameters of the best fitting model. The value of the Akaike Information Criterion (AIC) is shown for each of four possible models described in Munro and Somerton (2001): 2-parameter logistic, 3-parameter logistic, 4-parameter logistic, and cubic spline models. The estimated parameters of the best fitting model, that is, the one with the lowest value of the AIC, are shown. Parameter notation (α,β,γ) is the same as in Equations 4–6 in the text. Although, for arrowtooth flounder (*Atheresthes stomias*) the best fitting model is the cubic spline, the parameters of the best fitting parametric model are also included for use at lengths >20 cm.

	AIC				Estimated parameters		
Species	2-parameter logistic	3-parameter logistic	4-parameter logistic	Cubic spline	α	β	γ
Arrowtooth flounder (*Atheresthes stomias*)	6568.8	6502.0	6504.0	6382.7	–2.65	0.156	0.966
Flathead sole (*Hippoglossoides elassodon*)	1804.3	1794.7	1796.7	1863.4	–3.66	0.208	0.861
Rex sole (*Glyptocephalus zachirus*)	1642.8	1594.0	1596.0	1634.9	–7.45	0.376	0.873
Dover sole (*Microstomus pacificus*)	1245.9	1247.9	1249.9	1256.6	2.27	–0.055	

Estimating whole-gear efficiency

Estimates of trawl efficiency, by 1 cm length categories, were obtained by substituting into Equation 3 the estimates of mean W_n and W_d for the standard bridle length from the herding experiment, k_n from the net efficiency experiment, h from the herding experiment, and W_{on} from the bridle measurement experiment. Variance of E, which was derived from Equation 2 by using the delta method (Seber, 1973) and by assuming no covariance between any of the parameters, was calculated as

$$V(E)=\left(\frac{W_n+hW_{on}}{W_d}\right)^2 V(k_n)+\left(\frac{k_n}{W_d}\right)^2 V(W_n)+ \left(\frac{k_nW_{on}}{W_d}\right)^2 V(h)+\left(\frac{k_nh}{W_d}\right)^2 V(W_{on})+ \left(\frac{k_n(W_n+hW_{on})}{W_d^2}\right)^2 V(\quad_d). \tag{10}$$

The variance variables $V(W_n)$, and $V(W_d)$ were estimated as the variance of these dimensions during the herding experiment. Variance variables $V(k_n)$, $V(h)$, and $V(W_{on})$ were calculated as described earlier.

Results

Net efficiency experiment

All four species of flatfish were present in each of the 34 tows successfully completed. Total number and size range of measured fish were the following: 9512; 5–84 cm TL (arrowtooth flounder); 1701; 6–45 cm TL (flathead sole); 2142; 10–61 cm TL (rex sole); and 949; 30–57 cm TL (Dover sole).

Estimates of k_n

The best fitting model of k_n as a function of length differed among the four flatfish species. For arrowtooth flounder, the best fitting model was the cubic spline (Table 1, Fig. 2), primarily because of its flexibility to fit the selectivity of small (<20 cm TL) fish. At larger sizes (>20 cm TL), however, the best fitting parametric model was the 3-parameter logistic model. The cubic spline model fitted almost equally well (Fig. 2); therefore, we have also included the parameter estimates of this model in Table 1. For flathead sole and rex sole, the best fitting selectivity model was the 3-parameter logistic with a maximum capture probability substantially below that for arrowtooth flounder (Table 1; Fig. 2), indicating that the escapement beneath the footrope for these species is substantial even at the largest sizes. For Dover sole, the best fitting model was the 2-parameter logistic model, with the parameters chosen such that the predicted capture probability decreased monotonically, and nearly linearly, over the observed length range of fish.

Herding experiment

Seventeen geographic blocks, each containing three hauls, were successfully completed. For arrowtooth flounder, 11,510 fish were measured and all 17 blocks had nonzero catches at all bridle lengths. For the remaining species, the statistics are as follows: flathead sole (6632 measurements, 17 blocks), rex sole (620 measurements, 13 blocks), and Dover sole (392 measurements, 12 blocks).

The width of the area contacted by the bridles (W_{on}) increased dramatically with increasing bridle length (Table 2), primarily because of the increase between the short and standard bridle length. At the shortest bridle length, the estimated value of W_{on} indicated that the lower bridle was typically lifted off the bottom along its entire length. Other aspects of trawl geometry changed with increasing bridle length. Wingspread

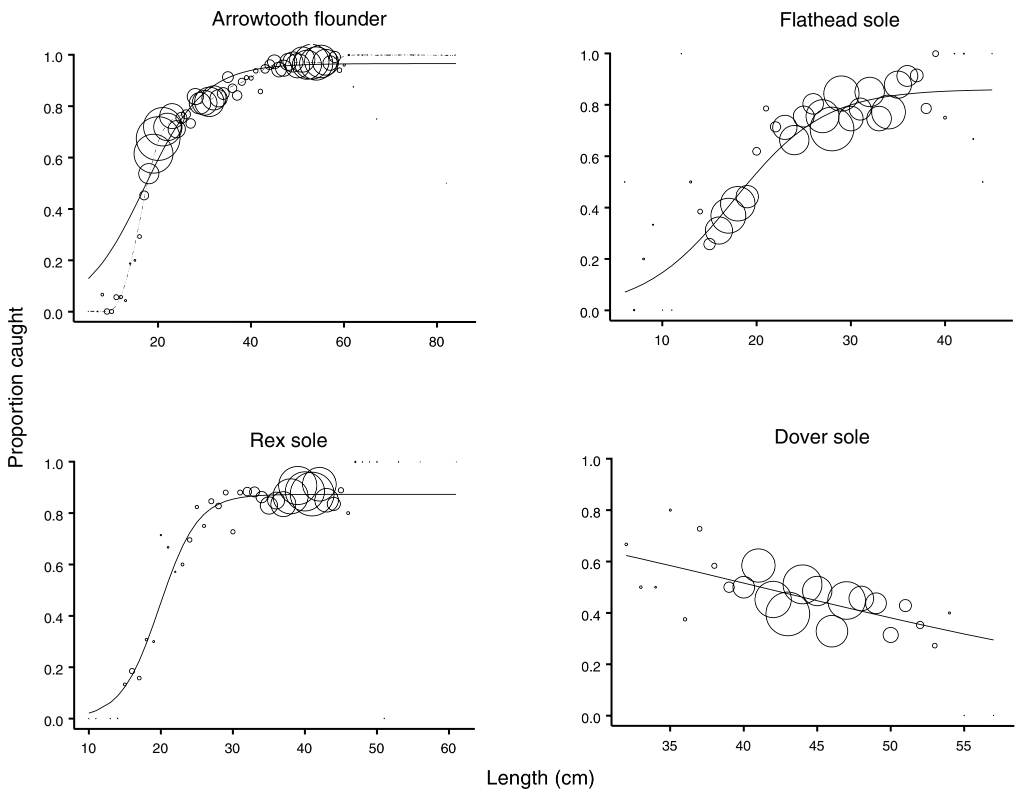

Figure 2

Proportion caught as a function of body length for four species of flatfish: arrowtooth flounder (*Atheresthes stomias*), flathead sole (*Hippoglossoides elassodon*), rex sole (*Glyptocephalus zachirus*), and Dover sole (*Microstomus pacificus*). For each species, the fit of the best fitting parametric model is shown with a solid line. However, for arrowtooth flounder (*Atheresthes stomias*), a nonparametric model, the cubic spline, fitted the data even better and is shown with a dashed line. Relative abundance by size group is indicated by the radius of the circles.

decreased slightly (0.4 m; Table 2) as bridle length increased, but the decrease was not significant; bridle angle (i.e., the angle between the bridles and the direction of travel (α) decreased significantly with increasing bridle length.

Estimates of k_b

Tests for length dependency in the herding process, based on the linear regression of k_b on fish length, indicated that the slopes were positive in all four cases (Table 3; Fig. 3), but significant only for arrowtooth flounder. Because the significance of the relationship for arrowtooth flounder is primarily due to the conspicuously lower value of k_b at the smallest length class (Fig. 3), we consider the evidence for an increase in k_b with size as credible, but still equivocal.

Length dependency in the herding process should lead to differences in the size distribution as bridle length is changed; however, size distributions for each species appeared quite similar for each of the three bridle lengths (Fig. 4) and none of the species had a significant (P<0.05) difference in mean size among bridle lengths. Consequently, k_b was considered as length invariant in the calculation of efficiency for all four species.

Length-invariant estimates of k_b were similar for the three sole species, ranging from 0.22 for rex sole to 0.24 for Dover sole (Table 4). These values are slightly larger than the estimated value of 0.17 for arrowtooth flounder. The values of the herding coefficient (h), or the herding efficiency in relation to the area swept by the lower bridle, were considerably higher than the values of k_b. For the three sole species, h ranged from 0.53 for rex sole to 0.58 for Dover sole. Again, these values were higher than the h estimate of 0.39 for arrowtooth flounder. Thus, roughly 40–50% of the flatfish encountering the lower bridle were ultimately herded into the path of the net.

Whole-gear trawl efficiency

Trawl efficiency estimates for arrowtooth flounder, flathead sole, and rex sole increased with increasing fish length and reached maxima of 0.45, 0.42, and 0.43,

Table 2

Trawl configuration parameters for the herding experiment. Included are the bridle lengths that were used, the means (and standard deviations) of the door width (W_d), wing width (W_n), bridle angle (α), bridle width (W_d–W_n), and bridle width in contact with the bottom (sea floor) (W_{on}).

Bridle length (m)	Door width (m) W_d	Wing width (degrees) W_n	Bridle angle (m) α	Bridle width (m) $W_d - W_n$	Bridle width on bottom (m) W_{on}
73.1	54.1 (3.4)	15.9 (0.6)	13.9 (1.0)	38.2 (2.8)	16.7 (2.1)
54.9	47.8 (2.7)	16.1 (0.6)	15.0 (1.0)	31.6 (2.1)	13.5 (2.5)
36.6	39.8 (1.8)	16.3 (0.5)	16.0 (1.0)	23.5 (1.4)	0.0 (0.0)

Table 3

Fit of a linear model to estimates of the bridle herding coefficient (k_b) as a function of fish length. The number of fish length bins, the slope of the regression line fit to k_b and length data, and the probability that the slope equaled zero is shown for each species. Significance of the slope (P<0.05) indicates that herding changes with fish size.

Species	Number of length bins	Slope of regression line	P(slope=0)
Arrowtooth flounder (*Atheresthes stomias*)	8	0.0035	0.039
Flathead sole (*Hippoglossoides elassodon*)	6	0.0033	0.616
Rex sole (*Glyptocephalus zachirus*)	5	0.0057	0.554
Dover sole (*Microstomus pacificus*)	4	0.0184	0.150

Table 4

Estimates of r^2 for the fit of the model (Eq. 9) without length dependency, and the values of h, k_b (Eq. 2), and the standard deviation (SD) of K_b for each of the four species of flatfish.

Species	r^2	h	k_b	SD(k_b)
Arrowtooth flounder (*Atheresthes stomias*)	0.71	0.391	0.167	0.038
Flathead sole (*Hippoglossoides elassodon*)	0.98	0.555	0.237	0.047
Rex sole (*Glyptocephalus zachirus*)	0.84	0.531	0.222	0.066
Dover sole (*Microstomus pacificus*)	0.62	0.576	0.239	0.162

respectively (Fig. 5), indicating that slightly more than 40% of the largest individuals that passed between the doors of the trawl were ultimately caught. In contrast, the efficiency estimates for Dover sole were considerably lower over the sampled size range and monotonically decreased with increasing fish length.

Discussion

Net efficiency

For three of the four flatfish species (i.e., arrowtooth flounder, flathead sole, rex sole), net efficiency (k_n) increased monotonically with fish size. For Dover sole, however, net efficiency declined over the sampled size range and was considerably lower than that for the other species in the larger commercial sizes. This unusual pattern is likely the result of two factors. First, small individuals, which are likely better at escaping under the footrope, were not sampled; consequently, the left-hand, ascending, portion of the selection curve is not defined. Second, the decline in capture probability with increasing size indicates that this species is behaviorally more adept at escaping under the footrope, probably by swimming ahead of the footrope, then dropping to the bottom, and allowing the footrope to pass over. Although distinct species-specific escape responses to a footrope

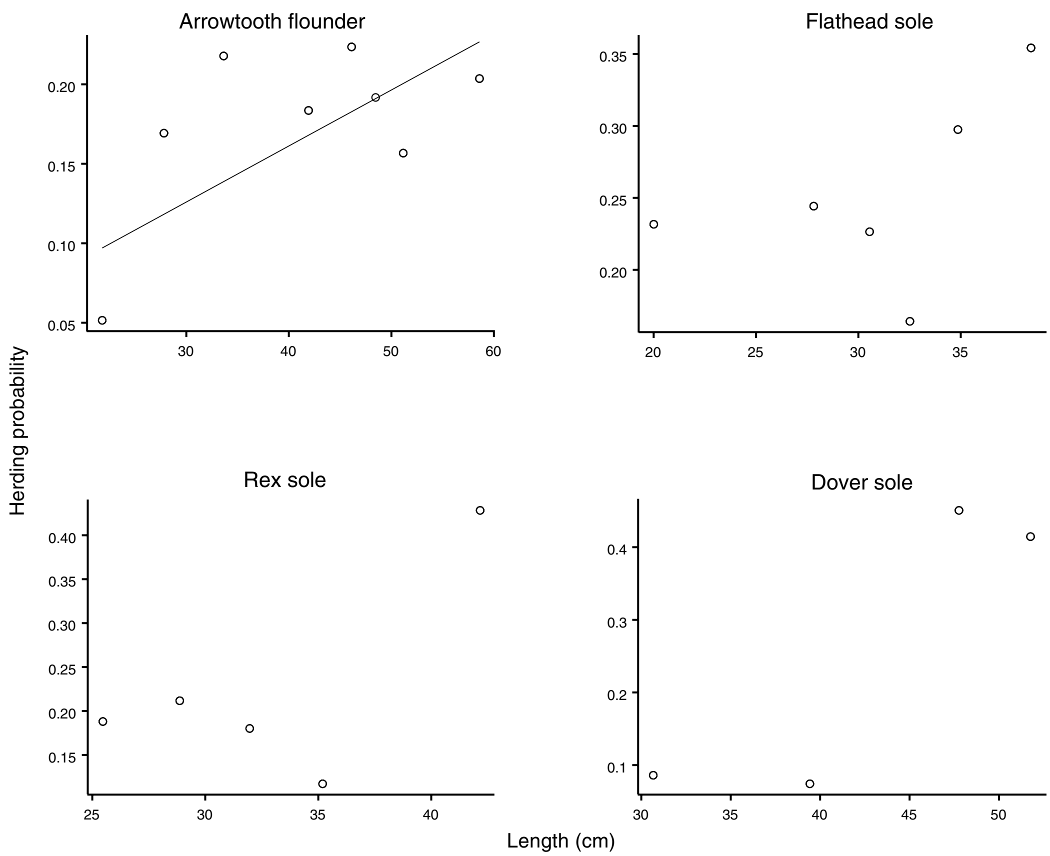

Figure 3

The herding probability (h) plotted against fish length for four species of flatfish: arrowtooth flounder (*Atheresthes stomias*), flathead sole (*Hippoglossoides elassodon*), rex sole (*Glyptocephalus zachirus*), and Dover sole (*Microstomus pacificus*). The herding probably increased significantly with length only for arrowtooth flounder (*Atheresthes stomias*). This relationship is shown with a solid line.

have been reported (Bublitz, 1996), our video recordings were insufficiently clear for us to distinguish species and therefore we could not determine the mechanism leading to the decline in capture probability. Regardless of the mechanism, a decline in net efficiency with increasing size has been previously reported for another flatfish (i.e., yellowtail flounder, *Limanda ferruginea*; Walsh, 1992).

Assumptions with the net efficiency experiment

The auxiliary net did not extend across the full width of the trawl net, but only across the center 78% of the width where the mesh of the trawl net attaches to the footrope. Our use of the estimated net efficiency in this section as a proxy for that of the total net spread, which is measured at the junction of the upper bridle and wing tip, is based on the assumption that the average escapement in the unsampled section is the same as that in the sampled section. From video observations (K. Weinberg, unpubl. data), it is evident that flatfish encountering these outer portions of the footrope tend to be herded toward the center of the footrope rather than pass under or over the footrope. Although we have no quantitative data on the change in escapement rate across the width of the trawl, we believe that our extrapolation of the measured escapement rate into the unsampled portion of the net spread potentially results in a slight underestimate of net efficiency.

Herding

One would expect herding to be a length-dependent process because the swimming endurance of fish, and therefore their ability to maintain position in front of the bridle, increases with body size (Winger et al., 1999). Our evidence for length-dependent herding, however, is equivocal. All four of the species had a positive slope in the regression of k_b on body length (Table 2), but in only one case, arrowtooth flounder, was

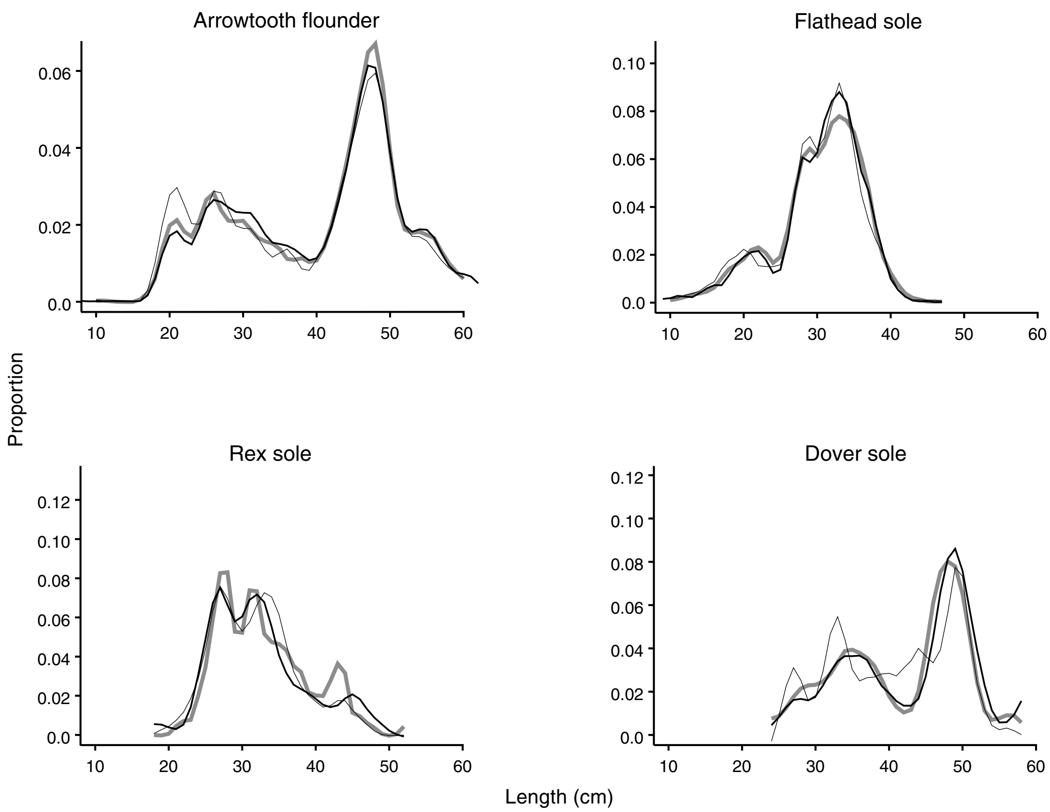

Figure 4

Length-frequency distributions, expressed as the proportion caught at each length, for each of the four flatfish species (arrowtooth flounder (*Atheresthes stomias*), flathead sole (*Hippoglossoides elassodon*), rex sole (*Glyptocephalus zachirus*), and Dover sole (*Microstomus pacificus*)) averaged over all hauls taken in the herding experiment are shown for three bridle lengths: short (thin line), standard (medium line), and long (thick line).

the slope statistically significant and this significance was dependent on the relatively low value of k_b in the smallest size interval. In previous studies, evidence for length-dependent herding has been inconsistent. Although Engås and Godø (1989a) observed increases in bridle efficiency with fish length for Atlantic cod and haddock, Somerton and Munro (2001) found either no change or decreases in bridle efficiency for seven species of flatfish, and Ramm and Xiao (1995) found no evidence of length dependent herding for any of a variety of species.

An alternative way of detecting length-dependent herding is through the changes in mean length of the catch as bridle length is changed, because the processes leading to the differences in herding ability with fish size would be intensified with increases in bridle length. Although Engås and Godø (1989a) and Andrew et al. (1991) found an increase in fish length with increasing bridle length, Somerton and Munro (2001) found a decrease in fish length. Because, in the present study, we observed no significant changes in mean size with bridle length (Fig. 4), even for arrowtooth flounder, which had a significant increase in k_b with length, length-dependency in the herding process is, at best, weak for flatfish sampled with the Poly Nor'eastern trawl and is therefore unlikely to contribute substantially to size selectivity.

Although estimates of k_b for the four species were pairwise not significantly different from each other, the estimates for flathead sole, rex sole, and Dover sole were very similar (Table 3), but considerably greater than the estimate for arrowtooth flounder. From an ecological perspective, similarity in the herding coefficients for the three sole species makes sense because all eat sessile or slow moving prey taken from the bottom and are likely relatively slow swimmers that stay close to the bottom when herded, whereas arrowtooth flounder eats relatively large pelagic fish (Yang and Nelson, 2000) and is likely a stronger, more agile swimmer that readily leaves the bottom.

The k_b estimates for the three sole species are also quite similar to the estimates that we obtained previously for the 83-112 Eastern trawl (flathead sole, 0.24; rex sole, 0.22; Dover sole, 0.27; Somerton and Munro,

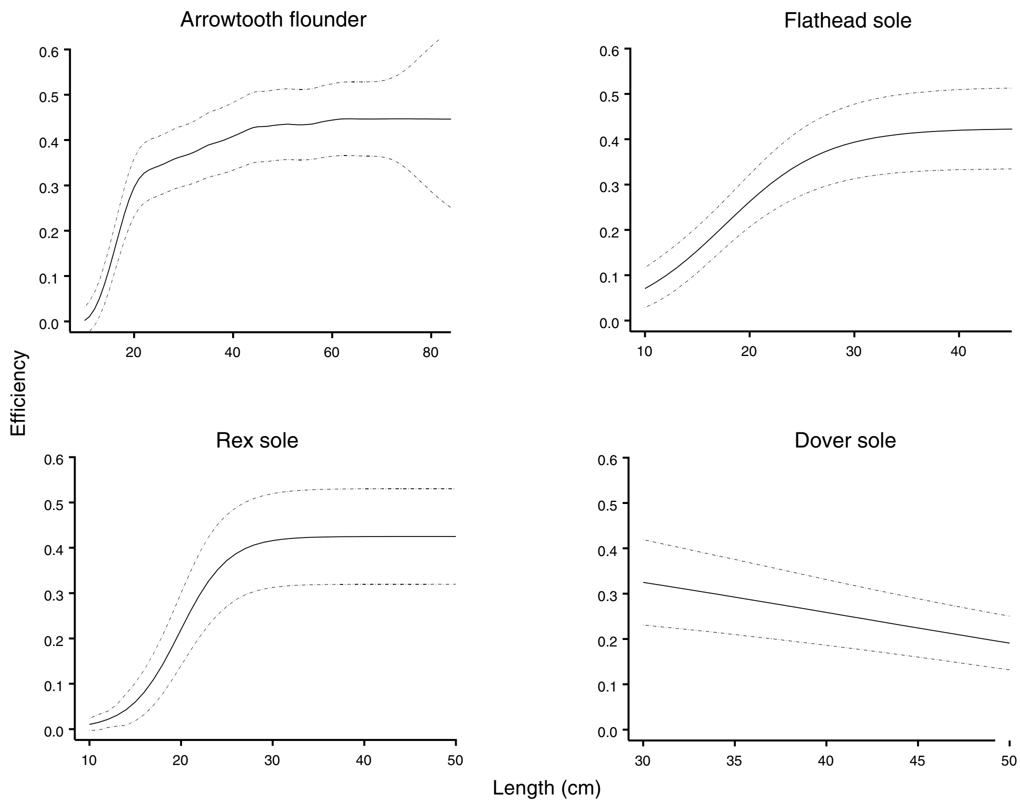

Figure 5

Whole-gear efficiency (solid line), and 95% confidence intervals (dotted lines), as a function of fish length for each of the four flatfish species: arrowtooth flounder (*Atheresthes stomias*), flathead sole (*Hippoglossoides elassodon*), rex sole (*Glyptocephalus zachirus*), and Dover sole (*Microstomus pacificus*).

2001). Although the two trawls have bridles that are identical in length and thickness, we found the similarity in the k_b estimates surprising because the bridles on the Poly Nor'eastern trawl are obscured over their entire length by mud clouds during trawling (Somerton, 2003), whereas those on the 83-112 Eastern trawl are mostly unobscured and likely visible to fish. This indicates that either the lower bridle, even in a mudcloud, is more visible to a flatfish than it seems to be when viewed with a video camera or that visibility of the lower bridle is not particularly important for flatfish herding—at least for the type of bridles used on AFSC bottom survey trawls.

For flathead, rex, and Dover sole, 55% (average value of h) of the individuals within the bridle contact path and 23% of the individuals within the entire bridle path were herded into the net path. Assuming that herded fish have the same probability of being captured as fish originally in the net path, then the herded fish comprise about 32% of the catch. For arrowtooth flounder, herded fish comprise 25% of the catch. This finding indicates that herding contributes substantially to the catch of these species and cannot be ignored when computing swept area estimates of abundance.

Assumptions with the herding experiment

The objective of the herding experiment was to change the size of the area experiencing a herding stimulus without altering other aspects of trawl geometry or performance. However, as in our previous experiment (Somerton and Munro, 2001), and those of Ramm and Xiao (1996) and Engås and Godø (1989a), both the net width and the bridle angle changed in response to the change in bridle length (Table 2). Because of these unintended changes in trawl geometry, the width of the bridle area did not change in proportion to the change in bridle length. Thus, the increase in the width of the bridle path (i.e., W_d–W_n) was 8.1 m between the short length and standard length bridles, but only 6.6 m between the standard length and the long length bridles. A better design for a herding study would be one in which the incremental changes in bridle path width, or, better yet W_{on}, were approximately equal among bridle lengths. By studying bridle geometry as a function of bridle length, it should be possible to choose the correct experimental bridle lengths to achieve this equality.

One assumption with the herding model is that flatfish are stimulated to herd by the bridles only from the footrope attachment of the lower bridle out to a distance L_{on}, but not beyond. This is an over simplification of the herding process, but in our previous study (Somerton and Munro, 2001) video recordings substantiated this assumption. Because the bridles are obscured by the mudclouds on the Poly Nor'eastern trawl, not only were we unable to verify the fish reaction to the bridles but the mud clouds themselves may have provided a herding stimulus as they reportedly do for some roundfish (Main and Sangster, 1981a, 1981b). If so, the effective length of the bridle over which herding occurs could be longer than L_{on}. We attempted to answer this question by positioning a video camera to allow us to observe flatfish behavior at the inner edge of the mud cloud, but were unsuccessful.

Another assumption is that the estimates of L_{on} can be extrapolated from the bridle measurement experiment to the herding experiment. On all vessels that we use for experiments, the tailchain extensions are adjusted in length depending on the size of the vessel and storage location of the doors when out of water. On the herding and bridle measurement experiments, the difference in the sizes of the vessels was so large that the tailchain length was approximately 10 m longer in the bridle measurement experiment. Because the cable used for the tail chain extensions is quite similar in diameter to that used for the bridles (i.e., 19 vs. 16 mm), the difference in tailchain length can be viewed as an equivalent difference in bridle length. Although unsubstantiated, our belief is that the combined forces on the lower bridle are such that a lengthening of the bridle by 10 m would result in a minimal change in the length of the bridle held off the bottom and therefore simply add a 10-m increment to L_{on}.

Whole-gear efficiency

We are aware of two previous studies in which whole-gear efficiency and the efficiency of the subsidiary trawling processes were experimentally estimated. One of these studies, that of Dickson (1993b), focused on Atlantic cod and haddock and therefore produced results that were not directly comparable to ours. The other, that of Harden Jones et al. (1977), is comparable because it was focused on a flatfish (plaice, *Pleuronectes platessa*) and used a bottom trawl similar in design to the Poly Nor'eastern trawl. In the latter study, gear efficiency was estimated by determining the fate (i.e., capture or escape) of individual fish tagged with acoustic transponders which allowed them to be located with a sector scanning sonar. For all fish passing between the doors, 44% were subsequently caught. This result is quite similar to the maximum efficiency of the Poly Nor'eastern trawl for three of the species in our study (mean=43%). In the Harden Jones et al. (1977) study, fish entering the trawl within the bridle path (between the wings and doors) had a 22% chance of being caught and fish entering the trawl within the net path had a 61% chance of being caught. Again, based on the maximum efficiency of the Poly Nor'eastern trawl, there was a 19% mean chance of being caught (calculated as $k_b k_n$) for fish entering the trawl within the bridle path and a 90% chance of being caught for fish entering the net path. Thus, compared with the Harden Jones et al. (1977) study, the bridle efficiency of the Poly Nor'eastern trawl for flatfish was less, net efficiency was greater, but the whole-gear efficiency was nearly the same.

For some bottom trawl surveys, including those conducted by the AFSC, swept area calculations are based on wing spread rather than door spread and the selectivity or catchability parameters in stock assessment models are formulated according to this convention. To convert efficiency estimates presented here to the estimates appropriate for the net spread convention, the values must be multiplied by the quotient of the door spread and net spread, which for the Poly Nor'eastern trawl is approximately equal to 3 (47.8 m/16.1 m).

Such efficiency estimates can be used to estimate survey catchability, which, in turn, can be used to constrain the survey catchability parameter in stock assessment models. In situations when the survey time series is relatively short, constraining the catchability parameter can lead to improved predictions of stock biomass and harvest rate (Somerton et al., 1999).

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Appendix

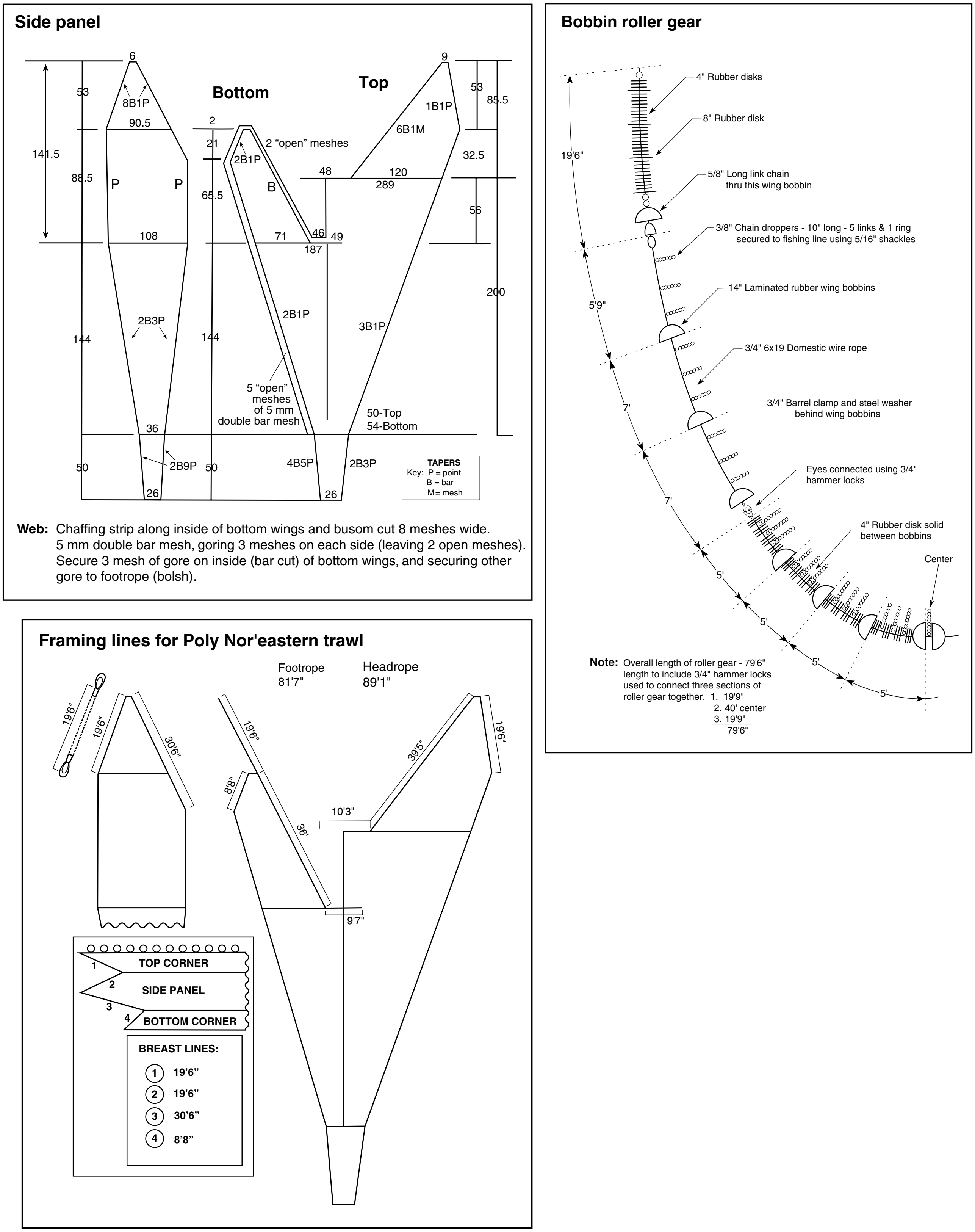
Description and construction diagram for the trawl and the auxiliary net

Poly Nor'eastern survey bottom trawl The Poly Nor' eastern is a high-rise, 4-seam, trawl rigged with rubber bobbin roller gear designed for use on moderately rocky terrain (Appdx. Fig.1). The net is constructed of 12.7-cm stretched-mesh polyethylene web (4-mm thickness top and sides, 5-mm thickness in the bottom and intermediate sections) and has a double 8.9-cm (4-mm thickness) codend with a 3.2-cm nylon mesh liner. The 27.2-m headrope supports twenty 30.5-cm diameter and four 20.3-cm diameter trawl floats that provide 220 kg of total lift. The webbing is hung from a 24.9-m bolsh line consisting of 0.95-cm diameter bare stranded wire wrapped with 0.95-cm diameter polypropylene rope, that attaches to a 24.7-m chain (1.6-cm long-link) fishing line. The 24.2-m, 1.9-cm diameter stranded-wire footrope is rigged with three sections of roller gear that attach to the fishing line with 25-cm pieces of 0.95-cm chain. The 12.2-m center section of the roller gear consists of eight 36-cm rubber bobbins separated by 10-cm rubber disks. To either side of the center segment is a 6.0-m section that consists of four 36-cm rubber bobbins separated by pieces of rubber hose to protect the wire footrope. In addition, 5.9-m footrope wing extensions consisting of 1.9-cm diameter stranded-wire rope with 10-cm and 20-cm rubber disks span the lower "flying" wing section on each side of the net. Riblines, constructed of 1.9-cm diameter Duralon 2 in 1 braided rope (Samson Inc., Ferndale, WA), are hung along 98% of the stretched length of the netting.

The net is connected to a pair of 1.8×2.7 m steel "V" doors, weighing approximately 816 kg each, by two 3-m door legs, consisting of 1.6-cm long-link chain; a 12.2-m door leg extension, consisting of 1.9-cm diameter bare stranded wire; and triple 54.9-m bridles, consisting of 1.6-cm diameter bare stranded wire, on each side of the net. Additional 46-cm and 23-cm-long extensions, consisting of 1.3-cm long-link chain, connect the upper and middle bridles to the respective wing tips of the trawl.

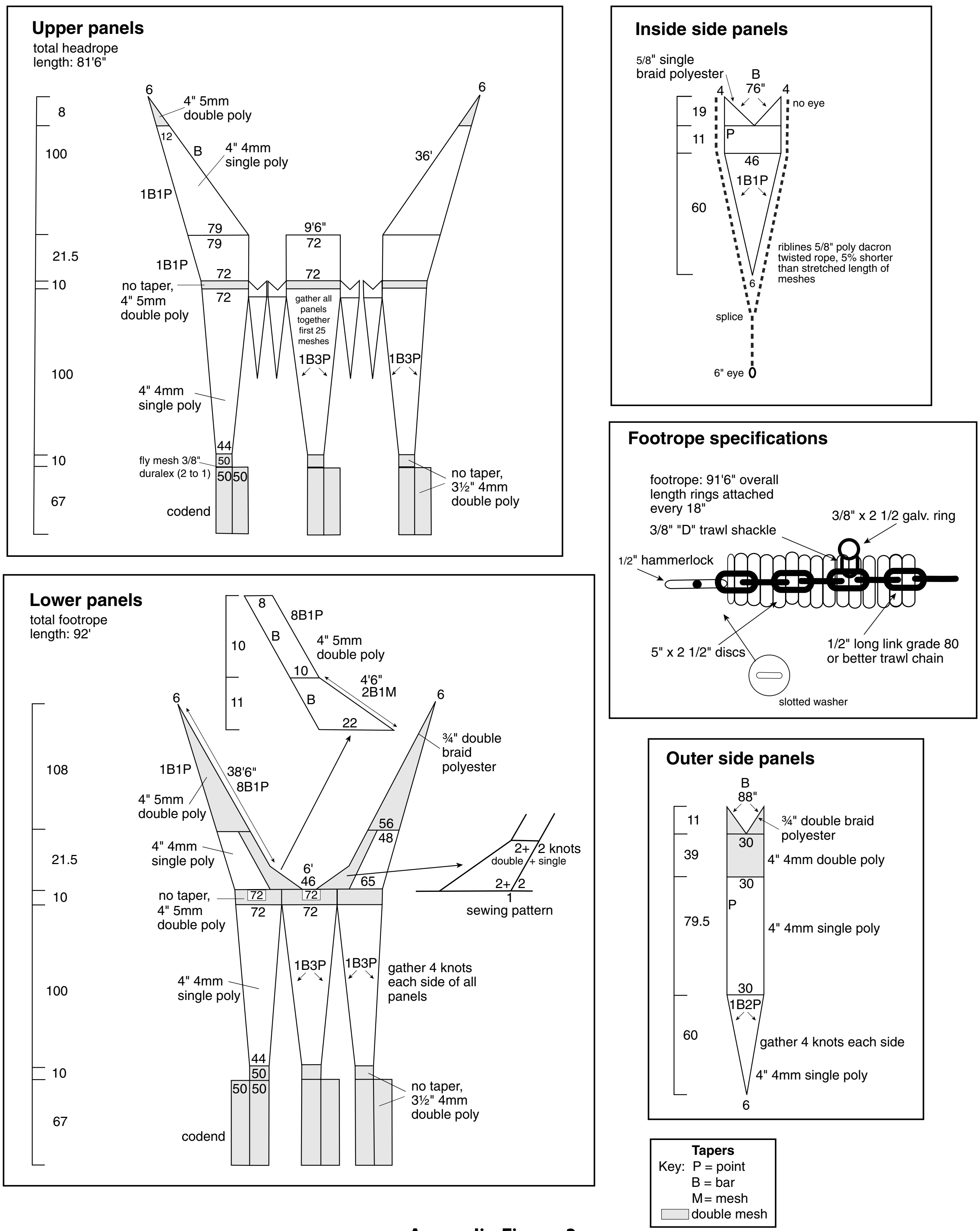
Auxiliary net for Poly Nor'eastern trawl gear The auxiliary net is a 2-seam trawl fitted with small side panels designed to help maintain steady footrope contact with the bottom during periods of intermittent contact by the Poly Nor'eastern footrope; it also fitted with three codends for catch retention should the net sustain damages (Appdx. Fig. 2). The 24.8-m headrope, constructed of 1.9-cm diameter double braid polyester rope, is lashed to the survey trawl bolsh line. The 28.0-m footrope, constructed of 1.3-cm long-link chain passing through 12.7-cm diameter rubber disks, is lashed to the 1.9-cm diameter double braid polyester fishing line from which the netting is hung. A delta plate located just aft of each survey trawl wing extension is used to connect both the front ends of the headrope and the fishing line to the trawl footrope.

With the exception of the 8.9-cm stretched-mesh codends, the net is constructed of 10.2-cm stretched-mesh polyethylene web (4 mm in body and codend and 5 mm in the wings and mouth area of the lower panel). For added protection, netting was doubled on the leading wing edges of the upper panel, the wings and mouth areas of the lower panel, the forward meshes of the side panels, the aft 10 meshes of the intermediate section, and throughout the codends. Riblines, constructed of 1.6-cm diameter poly dacron twisted rope, were hung along 92.5% of the stretched length of the netting.



Appendix Figure 1

Diagram of the Poly Nor'eastern bottom trawl.



Appendix Figure 2

Diagram of the auxiliary net that was attached under the Poly Nor'eastern bottom trawl to capture fish escaping under the footrope.