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# Factors influencing net width and sea floor contact of a survey bottom trawl

Kenneth L. Weinberg*, Stan Kotwicki[1]

*Alaska Fisheries Science Center, National Marine Fisheries Service, 7600 Sand Point Way NE, Seattle, WA 98115-0070, USA*

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ABSTRACT

Increased understanding of the factors affecting trawl geometry can lead to reduced variance in trawl catch efficiency, a primary goal of successful bottom trawl surveys. To this end, variation in net width and footrope distance from the bottom, two important determinants of the catch process, were related to certain aspects of vessel operations, catch weight, and environmental conditions using generalized additive modeling (GAM). Net width was most affected by the interactive effect of towing depth and trawl wire length, generally increasing with increasing depth and wire lengths, except at the deepest sites where the net narrowed slightly. Net width also increased linearly with increased towing speed and wave height, and varied non-linearly with the negative log of sediment particle diameter. Conversely, net width decreased with increasing catch weight, particularly catches of heavy benthic invertebrates, such as snails and sea stars. Footrope distance from the bottom decreased the more a net was used and with increasing catch size, particularly for heavy benthic invertebrates. Footrope distance from the bottom increased with decreasing sediment particle diameter and with the interactive effect of depth and trawl wire length. Our results suggest that the precision of survey catch per unit effort estimates can be improved through the implementation of minor changes in trawling procedures, prediction of area-swept in the absence of suitable net measurement data, and validation of tow performance.

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## 1. Introduction

Numerous survey programs have adopted the bottom trawl to assess demersal fish resources. Its widespread use, in part, stems from its inherent ability to sample multiple species over a broad range of depths and environmental conditions owing to its supple frame. However, along with this flexibility comes its susceptibility for introducing potential sources of bias and variability into survey data caused by inconsistent trawl performance (i.e., trawl geometry), hence fluctuating catch efficiency (Koeller, 1991). Maintaining consistency in trawl performance from tow-to-tow and year-to-year ensures changes in the catch per unit effort (CPUE), used to calculate estimates of relative abundance for stock assessments, reflect changes in population distribution and density. As such, survey scientists are continually investigating sources of trawl performance variability and looking for ways to mitigate or reduce this variability, thereby improving the precision of abundance estimates derived by trawls. Mitigation through implementing changes to survey procedures should be performed only after careful consideration of the potential for disruption to time series analyses, of course, and may best be delayed until a time when multiple improvements can be made simultaneously, in conjunction with a calibration experiment to compare the effects of the new techniques on the survey CPUE.

Two important determinants of the catch process related to trawl performance are herding and escapement of fish under the footrope. Reducing the variability of the path width of the trawl reduces the variability in catch efficiency associated with varying headrope heights (Ona and Godø, 1990), as well as minimizing inconsistency in the horizontal herding process (Engås and Godø, 1989a; Somerton and Munro, 2001). Similarly, reducing the variability in the footrope contact with the bottom reduces the error in sampling CPUE caused by variation in catch efficiency at the footrope (Engås and Godø, 1989b; Walsh, 1992; Somerton et al., 2007).

Improving the precision of trawl performance requires an understanding of the effects of various environmental and towing performance variables on trawl geometry. Several variables have been identified as having an impact on the spreading of a trawl or the bottom tending performance of its footrope. These include: the length of towing wire, bottom depth, and the ratio of wire length to depth (scope ratio; Wathne, 1959, 1977; Byrne et al., 1981; Carrothers, 1981; Godø and Engås, 1989; Rose and Walters, 1990; Koeller, 1991), bottom type (Godø and Engås, 1989), towing speed and currents (Somerton and Weinberg, 2001; Weinberg, 2003), trawl design, rigging, vessels, and increasing drag forces from increasing codend diameter (i.e., catch; O'Neill et al., 2005).

* Corresponding author. Tel.: +1 206 526 6109; fax: +1 206 526 6723.
*E-mail address:* ken.weinberg@noaa.gov (K.L. Weinberg).
[1] Equal authorship.

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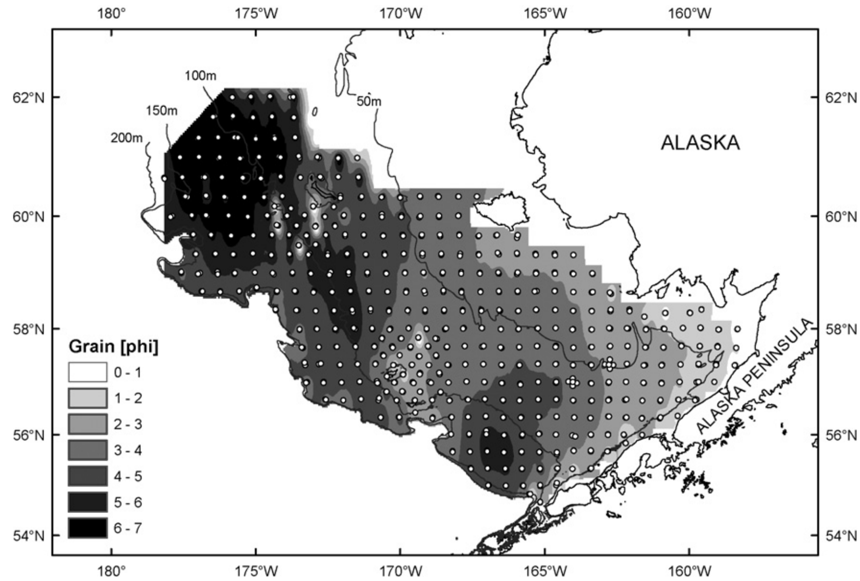


**Fig. 1.** Kriged surficial sediment grain diameter, expressed in units of phi, superimposed over a map of the stations completed during the 2004 and 2005 Eastern Bering Sea surveys.

However, the effect of these variables on net width and bottom contact in the presence of a myriad of other variables within a survey setting remains unclear.

Generalized additive models (GAMs) furnish a quantitative means to explore both linear and non-linear additive processes. In this study, we examine a variety of variables using GAM modeling to predict their additive contributions to the spreading forces of the net and contact characteristics of the footrope with the seabed. Variables assessed were collected under normal survey conditions and fit into three distinct categories: (1) vessel operations, (2) catch weight, and (3) environmental conditions.

## 2. Methods

### 2.1. Survey area, vessels and trawl gear

This study analyzed successful tows used for stock assessments from both the 2004 and 2005 Alaska Fisheries Science Center (AFSC) annual bottom trawl surveys of the eastern Bering Sea (EBS) conducted in the late spring and early summer (Acuna and Kotwicki, 2006; Lauth and Acuna, 2007). The EBS survey incorporates 376 stations into a systematic grid design with 350 stations placed in the center of 37 km × 37 km cells (20 nm$^2$) and 26 stations placed in the corners of several cells important to king crab *Paralithodes* sp. stock assessments (Fig. 1). The survey area is approximately 463,000 km$^2$ covering the eastern Bering Sea shelf between the Alaska Peninsula and approximately 62°N in depths ranging 20–200 m. The sea floor in this area descends gradually along a southwest gradient and is relatively smooth, composed of sediments varying from sand with some localized areas of cobble and rock (in the shallow water) to soft mud in deeper water. Tidal currents are typically less than 0.5 m/s, even still, when combined with sufficient wind are capable of dramatic shifts in a trawl vessel's course over ground causing the net to "crab" or be towed off to one side, instead of directly behind the vessel. Bottom temperatures during the survey vary by year in accordance with the timing of surface ice melt, but typically fall between −2.0 and 8.0 °C. Besides fish and crab, the EBS environment supports a wide assortment of benthic invertebrates, many of which are available to the survey sampling gear in vast concentrations.

During both 2004 and 2005 operations were conducted aboard two nearly identical, 40 m stern trawlers, F/V *Aldebaran* and F/V *Arcturus*. Both vessels have been used for the EBS survey since 1993. Their hulls, superstructures, 1525 hp single main engines, variable pitch propellers, winches and trawl wires were all identical. The survey period was divided between two captains for each vessel (i.e., four overall) with long-term EBS survey experience. The same captains fished the same areas aboard the same boats in both years. The two vessels fished alternate north-south columns of stations, beginning in the east and ending in the west for most of the survey, such that coverage between vessels was similar.

The 83-112 Eastern bottom trawl is designed for trawling on soft substrates. It is a two-seam, low-rise flatfish trawl connected on each side to a 1.8 m × 2.7 m V-style door weighing 816 kg, by a pair of 55 m bridles made of bare stranded cable. It has a 25.3 m long headrope with 116.4 kg of lift distributed evenly along its length. The 34.1 m long footrope is 5.2 cm in diameter consisting of a steel cable, protected by a single wrap of both polypropylene rope and split rubber hose. The footrope is weighted with 75 kg of chain, hung evenly along its length forming loops from which the lower edges of the wing and throat webbing are attached. The nylon netting is 10.2 cm (stretched-mesh) in the wings and throat sections and 8.9 cm in the intermediate and codend. The codend is lined with 3.2 cm nylon mesh netting used to retain small specimens. Stauffer (2004) presents a detailed description of the trawl, rigging, and net cut plans.

Each vessel was provided with four nets. During 2004, nets were changed only if they had sustained significant damage or appeared to be operating abnormally. This practice led to a confounding of net effects with spatial effects. Consequently, during 2005, nets were systematically swapped nets between vessels after 20–30 tows to reduce confounding effects. Although this procedure did not completely randomize net effects it provided a practical improvement that led to the use of all eight nets during the survey, seven being fished by both vessels.

### 2.2. Towing practices and instrumentation

The EBS survey followed standardized procedures for towing protocol and performance validation designed to reduce

**Table 1**
Range of scope ratios (wire/depth) used during successful tows of the 2004 and 2005 Eastern Bering Sea bottom trawl surveys

| Wire length | Survey scope table | Actual depth range | Scope ratio | Frequency |
|---|---|---|---|---|
| 91 | | 24–24 | 3.79–3.79 | 1 |
| 137 | <40 | 22–47 | 6.23–2.91 | 86 |
| 183 | 40–53 | 39–54 | 4.58–3.16 | 105 |
| 229 | 54–70 | 55–70 | 4.16–3.09 | 158 |
| 274 | 71–86 | 71–87 | 3.97–2.85 | 120 |
| 320 | 87–104 | 88–104 | 3.64–2.96 | 91 |
| 366 | 105–123 | 105–123 | 3.45–2.93 | 74 |
| 411 | 124–143 | 124–144 | 3.34–2.82 | 78 |
| 457 | 144–164 | 145–166 | 3.20–2.70 | 23 |
| 503 | 165–187 | 167–187 | 2.94–2.91 | 2 |

Depths and wire lengths have been rounded to the nearest meter. Depth range overlap between wire length categories resulted from differences between the vessel's echosounder used to determine the amount of wire to deploy and the average depth of the tow determined from a trawl-mounted bathythermograph.

between-station variability in trawl gear performance (Stauffer, 2004). Tows were made with equal lengths of trawl wire per side and the trawl winches locked. Gradual decreasing scope ratios as a function of increasing depth were used both within and between depth-intervals in accordance with a stepwise scope table developed for this survey (Table 1). Tows were 30 min from the time winches were locked to when wire retrieval was initiated, at a constant vessel speed of 3.0 kn during daylight hours. For the purpose of this study, tow duration was defined as the time between initial footrope contact with the sea floor as determined with a bottom contact sensor and haulback (i.e., engaging the trawl winches for wire retrieval). Haulback was selected for the end of the tow instead of the standardized survey off-bottom time used for stock assessments (i.e., when the footrope makes last contact, usually 15–120 s later) because net width and footrope distances off the bottom vary radically during this period as a result of initial increases in vessel speed, in addition to increases in the trawl speed through the water associated with the intake of trawl wire.

Mean net width, measured from wing tip to wing tip, for each tow was calculated from data collected to the nearest 0.1 m at 5 s intervals by Netmind acoustic sensors and later corrected for the temperature effect on sound speed through sea water according to Mackenzie (1981) using an assumed salinity constant of 32 ppt. Wingspread sensors were mounted on the top bridles, 0.3 m forward of the wings.

Estimates of mean footrope distance from the bottom or height above the bottom (cm), a proxy for footrope performance, were calculated from data collected using a calibrated bottom contact sensor with a self-recording tilt meter mounted to the center of the footrope, as described by Somerton and Weinberg (2001). The height of the footrope above the bottom was calculated from the change in tilt angles recorded at 0.5 s intervals and averaged over 1 s.

### 2.3. Variables selected for study

The variables considered can be classified into three distinct categories. The first category consisted of factors related to vessel operations. It included captain, year, tow speed, net age, wire, depth and inverse scope. Because the vessels used in the survey were nearly identical but were operated by separate pairs of captains, we attributed any potential vessel effect to differences in fishing style by the captains. The variable tow speed (tow speed) was defined as the mean vessel towing speed over ground obtained by a GPS. Net age (net age) was defined as the number of tows performed with a particular net to date. Since the length of trawl wire deployed during a tow is determined from the depth of the tow as required by the survey standardized scope table, we decided the bivariate term (depth, wire) was most appropriate for modeling this interaction. Alternatively, we also looked at the inverse ratio of wire to depth (inverse scope) based on its strong relationship to net width as reported by Rose and Walters (1990). Mean net width (width) per haul was included as a variable in the footrope performance model.

The second category was comprised of the weights from three components of the catch. Catch data were log transformed to account for highly skewed data towards low catches. Each catch group was made up of species that we felt could have a different influence on the drag of the net, thus affecting either net width or footrope contact performance or both. The first catch group, heavy benthic invertebrates (log(heavy benthic invertebrates)), consisted of snails *Gastropoda*, bivalves *Bivalvia*, sea stars *Stelleroidea*, sea urchins *Echinoidea*, sea anemones *Actiniaria*, tunicates *Ascidiacea*, sponges *Porifera*, hermit crabs *Paguridae* sp., and empty shells. This catch group could have an independent effect on net drag because heavy invertebrates exert a downward pressure on the lower panels of the net as they tumble back causing the intermediate and codend to hang down or even drag along the sea floor. The second catch group, comprised primarily of fish, total catch excluding the heavy benthic invertebrates (log(remaining catch)), could also have an independent effect on net drag due to the masking of codend mesh thereby limiting the water flow through them. Unlike heavy invertebrates, fish tend to swim back into the codend without exerting the downward pressure on lower net panels. The third catch group, total catch (log(total catch)), is the sum of the first two components. Since the total catch group can be derived from the other two, all three groups could not be included in the model. Therefore, one of the three had to be removed. We describe our selection process in more specifically Section 2.4.

Our third variable category consisted of several factors related to the environment (i.e., wave height, wind direction, gear offset, tidal currents, and sediment grain diameter). Wave height (wave height) was estimated by the captain in feet and consisted of the combination of sea swell and wind-generated waves. Wind direction (wind direction) was also estimated by the captain and expressed in degrees (0–180°) relative to the vessel heading. Both of these estimates are prone to subjective captain bias. However, because all four captains possess extensive years of service in the Bering Sea aboard these vessels performing the EBS surveys in addition to year round commercial fishing, we felt their capabilities for assessing metrological conditions were equal, and if any bias did exist it would be negligible. The extent to which wind, waves, and currents caused the net to be towed off to one side of the vessel (gear offset) was estimated as the angle between the vessel heading taken from the gyro compass and reported by the captain and the vessel course measured as a straight line between the beginning and ending positions of the tow. Tidal currents, a proxy to bottom currents, were predicted for each tow using Oregon State University's tidal inversion software (http://www.oce.orst.edu/research/po/research/tide/region.html; Egbert et al., 1994; Egbert and Erofeeva, 2002). Tidal current velocities were first divided into two directional components, one tangential to the course of the vessel and the other perpendicular, then combined with vessel towing speed and vessel course to estimate the water flow parallel to the vessel course (parallel flow) and the water flow perpendicular to the vessel course (cross flow). Lastly, surficial sediment grain diameter (grain diameter) was estimated at each station using historical data (Smith and McConnaughey, 1999) interpolated by kriging (Paul Spencer, AFSC unpubl. data). Sediment data were expressed in units of phi ($\Phi$, negative $\log_2$ of the diameter in mm), where higher values corresponded to smaller particle size (Wentworth, 1922). Wentworth's

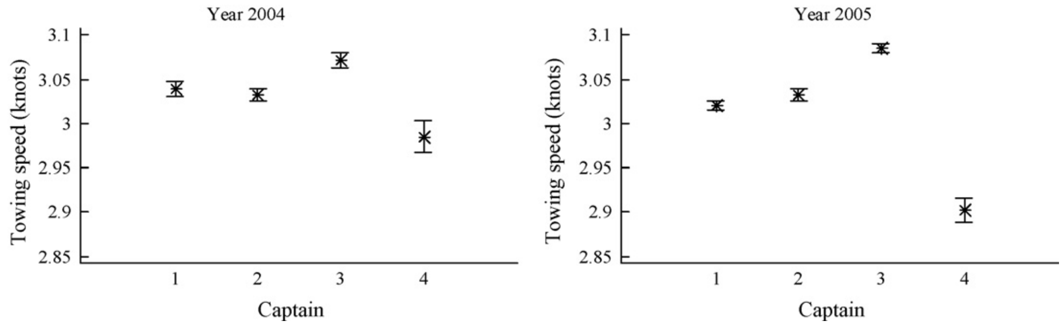


**Fig. 2.** Mean towing speeds and 95% confidence intervals by captain and year for the 2004 and 2005 Eastern Bering Sea surveys. Note how the variability in towing speed for each captain was small compared to the difference between captains; how captain 4 was the only vessel operator who favored a towing speed under 3 kn; and the significant difference in towing speed between second half captains 3 and 4, the difference widening during the second year.

scale ranged from boulder to granule (−8 to −1 Φ) in the gravel category, very coarse sand to very fine sand (−1 to 4 Φ) in the sand category, and coarse silt to very fine clay (4 to >8 Φ) in the mud category.

### 2.4. Data analyses

#### 2.4.1. Net width

The variable effects on net width were modeled with GAM using the mgcv package in R (Wood, 2006). Backwards elimination removed non-significant terms, one at a time, until only significant terms remained. Initial models were constructed separately by year to ascertain whether the individual term effects from one year were similar to those of the second year. Preliminary analyses showed a strong correlation between captain and tow speed ($P < 0.001$ ANOVA; Fig. 2) leaving us with the choice of either including captain as a categorical factor in the model or speed as a continuous variable. Since the main goal of the study was to identify the conditions having the greatest effect on the trawl, we elected to keep speed in the model. Our initial GAM for net width included 13 variables. Smoothers were fit to each term by allowing the software to choose the proper number of knots (i.e., limited to ≤4 for univariate terms and ≤10 for bivariate terms) to achieve the best fit. Univariate terms were fit with a cubic spline smoother; bivariate terms were fit with a thin plate smoother (Wood, 2003). The full model was expressed as:

$$\begin{aligned} \text{width}_{\text{year}} \sim & s(\text{tow speed}) + s(\text{net age}) + s(\text{inverse scope}) \\ & + t(\text{depth, wire}) + s(\log(\text{total catch})) \\ & + s(\log(\text{heavy benthic invertebrates})) \\ & + s(\log(\text{remaining catch})) + s(\text{gear offset}) \\ & + s(\text{grain diamter}) + s(\text{wave height}) + s(\text{weather direction}) \\ & + s(\text{parallel flow}) + s(\text{cross flow}), \end{aligned}$$

where *s* and *t* indicate spline and thin plate smoothing functions.

Variable elimination began with those highly related to one another. For example, inverse scope could be determined from (depth, wire). Similarly, log(total catch) could be determined from log(heavy benthic invertebrates) and log(remaining catch) categories. For these variables, we had to first choose which of the related terms provided the greatest predictive power. As such, term reduction began with comparing generalized cross-validation (GCV) scores, where the lower score indicated the better model, from GAMs in which one of the two scope-related terms was removed. After the least significant scope related term was removed, we then proceeded in the same manner to eliminate the least significant of the three catch-related terms based on lowest GCV score. Thereafter, non-significant variables were removed one at a time, the order determined based on highest *P*-value, provided at least two of the following three selection criteria described by Wood and Augustin (2002) were met:

(1) The $P > 0.05$ or 95% confidence intervals about the predicted curve contain 0.
(2) The GCV score is lower with the elimination of the variable.
(3) The effective degrees of freedom are close to 1.0 for the univariate smooth of the variable.

The selection process for our final model involved several additional steps. First, two combined-year models were developed, one with a year effect the other without, by including only those terms that met the selection process in both years and demonstrated similar trends. The better of the two combined-year models was then determined based on the lower GCV score. Second, the GCV score from the best combined-year model was compared to the summed GCV scores from the two individual year GAMs. Third, a test for non-additivity was performed for all second-order interactions of all univariate terms to determine if the additivity assumption was valid (Chan et al., 2003). Finally, the GAM containing smoothed terms was compared to a simple GAM model having linear univariate terms and smoothed bivariate terms. Model comparisons were based on both GCV and Akaike information criterion (AIC; Burnham and Anderson, 1998) to determine the best overall model.

#### 2.4.2. Footrope performance

The procedures utilized for GAM construction and term selection for predicting net width were also used to determine the best model for predicting footrope distance off the bottom. Our initial GAMs for each year included 14 terms, the same 13 variables used in the net width analyses, plus an additional variable, mean net width (width):

$$\begin{aligned} \text{footrope}_{\text{year}} \sim & s(\text{width}) + s(\text{tow speed}) + s(\text{net age}) \\ & + s(\text{inverse scope}) + t(\text{depth, wire}) + s(\log(\text{total catch})) \\ & + s(\log(\text{heavy benthic invertebrates})) \\ & + s(\log(\text{remaining catch})) + s(\text{gear offset}) \\ & + s(\text{grain diameter}) + s(\text{wave height}) \\ & + s(\text{weather direction}) + s(\text{parallel flow}) + s(\text{cross flow}), \end{aligned}$$

where *s* and *t* indicate spline and thin plate smoothing functions.

After determining which of the highly related terms mentioned earlier provided the most information about footrope performance, backward elimination was again used to remove least significant variables, one by one, if they did not meet at least two of the three

**Table 2**
Summary statistics for successful tows during the 2004 and 2005 Eastern Bering Sea bottom trawl surveys

| Variable | Min. | Max. | Mean | S.D. | Median |
|---|---|---|---|---|---|
| Towing speed (knots) | 2.65 | 3.18 | 3.02 | 0.07 | 3.03 |
| Net age (no. of tows net used to date) | 6.00 | 128.00 | 57.50 | 36.56 | 57.00 |
| Net spread (m) | 13.53 | 20.62 | 16.86 | 1.12 | 16.85 |
| Sound speed through the water (cm/s) | 1438.29 | 1481.95 | 1458.87 | 7.41 | 1460.37 |
| Depth of tow (m) | 22.00 | 173.00 | 80.93 | 33.41 | 74.00 |
| Main wire length (m) | 91.0 | 503.0 | 270.85 | 90.09 | 274.0 |
| Scope ratio (wire length/depth) | 2.70 | 6.23 | 3.49 | 0.49 | 3.37 |
| Inverse scope ratio | 0.02 | 0.37 | 0.29 | 0.03 | 0.30 |
| Total catch (kg) | 86.74 | 13285.00 | 1610.20 | 1203.26 | 1328.00 |
| Heavy benthic invertebrates (kg) | 1.20 | 3170.24 | 288.77 | 375.61 | 173.19 |
| Catch less heavy benthic invertebrates (kg) | 79.43 | 13031.97 | 1321.42 | 1106.08 | 1037.72 |
| Bottom temperature (°C) | −1.50 | 8.80 | 3.25 | 1.65 | 3.50 |
| Wave height (m) | 0.00 | 4.57 | 1.25 | 0.73 | 1.22 |
| Wind direction (°) | 0.47 | 179.87 | 92.88 | 54.35 | 92.59 |
| Parallel flow (knots) | 2.30 | 3.97 | 3.08 | 0.28 | 3.07 |
| Cross flow (knots) | 0.00 | 0.95 | 0.21 | 0.17 | 0.17 |
| Gear offset (°) | 0.03 | 52.91 | 8.41 | 6.43 | 7.44 |
| Sediment grain size (Φ) | 0.37 | 6.87 | 3.94 | 1.36 | 3.89 |

selection criteria, until only significant variables remained in the model. Combined-year models, with and without a year effect, were constructed using only those significant variables in common between years that demonstrated similar trends. The better of the two combined-year models based on the lower GCV score was then compared to the summed GCV scores from the two individual year GAMs. A test for non-additivity for all second order interactions of all univariate terms was performed to ensure term effects were additive. Finally, our best non-parametric model containing smoothed terms was compared to a model using linear terms, and once again both GCV and AIC scores were used to determine the best overall model for predicting footrope distance off the bottom.

## 3. Results

### 3.1. Sampling summary

The 2004 and 2005 EBS surveys conducted 739 stock assessment tows, of which 655 had valid net width measurements. General statistics for the variables examined are presented in Table 2. Briefly, mean towing speed for all tows was 3.0 kn, ranging between 2.7 and 3.4 kn. Parallel tidal flow averaged 3.1 kn and varied between 2.3 and 4.0 kn. Cross flow averaged 0.2 kn and varied from 0.0 to 1.0 kn. Wave heights averaged 1.2 m, and varied from 0 to 4.6 m. Bottom temperatures, used to correct sound speed through water for calculation of net width, ranged from −1.5 to 8.8 °C. Catch weight averaged 1.5 t, with a maximum of 13.3 t. The heavy benthic invertebrate component of the catch averaged 289 kg, with a maximum of 3.2 t.

Surficial sediment particle diameter generally decreased from east to west, with sandy bottom gradually changing to a softer, silty mud in the deeper area of the southwest region and some shallower sites in the northwest region of the survey area (Fig. 1). Kriged surficial sediments at our survey stations ranged from coarse sand to fine silt (0.4–6.9 Φ); however, 82% of these stations were characterized by fine sand (2–3 Φ), very fine sand (3–4 Φ), coarse silt (4–5 Φ), and medium silt (5–6 Φ).

### 3.2. Net width

Backwards elimination reduced our full net width GAM model with 13 variables down to 6 significant variables in 2004 and 7 in 2005. The deviance explained by these models was 77.4% and 82.3%, respectively (Table 3). Significant terms in both years included: the bivariate term (depth, wire) and the univariate terms tow speed, grain diameter, wave height, and the catch divided into the two components, log(catch heavy benthic invertebrates) and log(remaining catch). The variable net age was significant during 2005 only.

The form and the extent of the predicted effect that each significant term has on the response variable, in addition to the various other terms in the model, are best illustrated in plots. Fig. 3 (2004) and Fig. 4 (2005) depict the effects of the bivariate term on net width in a contour plot and univariate terms in line diagrams. They also demonstrate the similar trends between years for the six variables in common. Net width increased with increasing depth and wire length (except at the very deepest stations), towing speed, wave height, and decreasing sediment particle size out to about 5 Φ. Conversely, net width decreased, as a function of increasing catch weight, particularly catches of the heavy benthic invertebrate group. Net width also decreased with increasing net age, but only in 2005 when nets were systematically exchanged.

The similar trends seen during both years increased our confidence in the observed effects and supported the pooling of data into combined-year models, one with a year effect and one without. Net age was dropped from the combined-year models since its significance was detected during 1 year only. The sum of the GCV scores for yearly GAMs (0.51), as well as the GCV for the combined-year GAM without the year effect (0.44), were greater than the GCV score for the combined-year model with year a factor (0.28), indicating the latter was the best (Table 3).

A comparison of the combined-year GAM with the year effect to a simpler model comprised of the smoothed bivariate and linear univariate terms, and in which grain diameter was represented by a polynomial function, resulted in both lower GCV (0.28 and 0.29, respectively) and AIC (999.6 and 1008.2, respectively) values for the GAM having all smoothed terms indicating no improvement was achieved by simplifying the model. Thus, the best overall model for predicting net width was the version having the year effect and comprised of all smoothed terms. The non-additivity test for this model was non-significant ($P = 0.18$), meaning that any interaction between terms was unlikely to affect the results of our GAM.

Our final combined-year GAM for predicting net width concurs with historical perspectives on the factors affecting net width. Fig. 5 shows that the mean effect of each variable, which depending on the circumstances, either added to or subtracted from, the 2004 estimated mean of 17.2 m or the 2005 estimated mean of 16.5 m, given the range of conditions encountered during the surveys (Table 3). The deviance explained by the final model was 79.1%. Of the model's six terms, net width was most responsive to the

**Table 3**
Significant terms for individual and combined year net spread models, their effective degrees of freedom (EDF), *F*-statistics, and *P*-values, in addition to overall generalized cross-validation (GCV) scores, deviance explained (DEV), and sample sizes (*N*)

| Year (spread) | Smoothed term | EDF | *F* | *P*-value | GCV | DEV (%) | *N* |
|---|---|---|---|---|---|---|---|
| 2004 (17.2 m) | | | | | 0.25 | 77.4 | 330 |
| | Depth and wire interaction | 6.61 | 41.18 | <0.001 | | | |
| | Tow speed | 1.09 | 7.15 | <0.001 | | | |
| | Grain size | 2.85 | 7.11 | <0.001 | | | |
| | Wave height | 1.18 | 10.51 | <0.001 | | | |
| | log(heavy benthic invertebrates) | 1.00 | 26.88 | <0.001 | | | |
| | log(remaining catch) | 1.00 | 9.21 | 0.002 | | | |
| 2005 (16.5 m) | | | | | 0.26 | 82.3 | 303 |
| | Depth and wire interaction | 6.67 | 42.19 | <0.001 | | | |
| | Tow speed | 1.00 | 14.11 | <0.001 | | | |
| | Grain size | 2.94 | 40.89 | <0.001 | | | |
| | Wave height | 1.00 | 37.59 | <0.001 | | | |
| | Net age | 1.00 | 42.49 | <0.001 | | | |
| | log(heavy benthic invertebrates) | 1.00 | 11.92 | <0.001 | | | |
| | log(remaining catch) | 1.72 | 5.45 | 0.001 | | | |
| Combined, year not a factor (16.9) | | | | | 0.44 | 67.4 | 633 |
| | Depth and wire interaction | 6.08 | 44.43 | <0.001 | | | |
| | Tow speed | 1.00 | 39.51 | <0.001 | | | |
| | Grain size | 2.96 | 19.43 | <0.001 | | | |
| | Wave height | 1.83 | 8.92 | <0.001 | | | |
| | log(heavy benthic invertebrates) | 1.48 | 6.42 | <0.001 | | | |
| | log(remaining catch) | 1.25 | 6.92 | <0.001 | | | |
| Combined, year a factor: 2004 (17.2 m), 2005 (16.5 m) | | | | | 0.28 | 79.1 | 633 |
| | Depth and wire interaction | 7.32 | 69.55 | <0.001 | | | |
| | Tow speed | 1.00 | 14.32 | <0.001 | | | |
| | Grain size | 2.96 | 29.51 | <0.001 | | | |
| | Wave height | 2.29 | 26.57 | <0.001 | | | |
| | log(heavy benthic invertebrates) | 1.00 | 31.45 | <0.001 | | | |
| | log(remaining catch) | 1.59 | 6.86 | <0.001 | | | |

Predicted mean net spread when all model terms have a zero effect is shown in parentheses.

interaction of towing depth and wire length, its overall influence varying the calculated annual width by as much as 2.5 m (−1.5 m to nearly +1.0 m). Net width increased as a function of increasing depth and wire length. The rate of increase was faster in the shallower waters (under 70 m in depth and 200 m of trawl wire) than in deeper waters, and leveled off or even decreased slightly from the maximum when sampling at the deepest bounds and using scope ratios below 3:1. The range in mean effects of the five other terms was closer to 1 m, and with the exception of sediment grain diameter, approximated straight linear functions, positively sloped for towing speed and wave height, and negatively sloped for catch of heavy benthic invertebrates and the remaining catch. The relationship of sediment grain diameter and net width looked somewhat sinusoidal, albeit a large degree of uncertainty resulting from low sample size was associated with predictions in areas of coarse sand (<2 Φ). Aside from this, net width increased by about 0.7 m as grain diameter decreased from 2 to 5 Φ, but then contracted from its maximum in areas of fine silt or soft mud (>5 Φ).

### 3.3. Footrope contact

Backwards elimination reduced the full footrope distance GAM consisting of 14 variables down to 8 significant terms in 2004 and 7 in 2005. The deviance explained by these two models was 66.1% and 59.8%, respectively (Table 4). The 2004 model included: the bivariate term (depth, wire) and the univariate terms; tow speed, net age, grain diameter, wave height, cross flow, and the two catch components, heavy benthic invertebrates and remaining catch. The 2005 model included all the same variables as 2004, except for cross flow.

The predicted effects of the model terms on the distance of the center of the footrope off the bottom are shown in Fig. 6 (2004) and Fig. 7 (2005). Trends between years were similar for some, but not all, of the variables. Distances increased as a function of decreasing sediment particle diameter and to a lesser extent, with increasing depth and wire. Conversely, footrope distances off the bottom decreased as a function of increasing catch weights, particularly catches of the species in the heavy benthic invertebrate group, as well as with increasing net age. Both towing speed and wave height exhibited contradictory relationships with the footrope distance off the bottom between years. In 2004, distances decreased linearly with increasing towing speed and wave height, but in 2005 the distance of the footrope off the bottom increased linearly. The effect of cross flow was significant in 2004 only, and although associated with a high degree of uncertainty, indicated increasing footrope distances with cross flows in excess of 0.5 kn (Fig. 6).

Variables showing similar trends between years were incorporated into combined-year GAMs consisting of five terms: the bivariate (depth, wire), and the univariate terms; grain diameter, net age, and the two catch components, catch of the heavy benthic invertebrates and the remaining catch. Wave height, towing speed and cross flow were dropped due to our stringent selection rules; the first two because they showed opposing trends in successive years and are therefore inconsistent predictors of footrope distances off the bottom, and the latter because its significance was only detected during 1 year. The sum of the GCV scores for yearly GAMs (4.24), as well as the GCV for the combined-year GAM without year a factor (3.02), were greater than the GCV score for the combined-year model with year a factor (2.50), indicating the latter was the best model (Table 4).

A comparison of the combined-year footrope performance GAM with year as a factor to a simpler model comprised of the smoothed bivariate and linear univariate terms, and in which grain diameter was represented by an exponential function, resulted in both lower

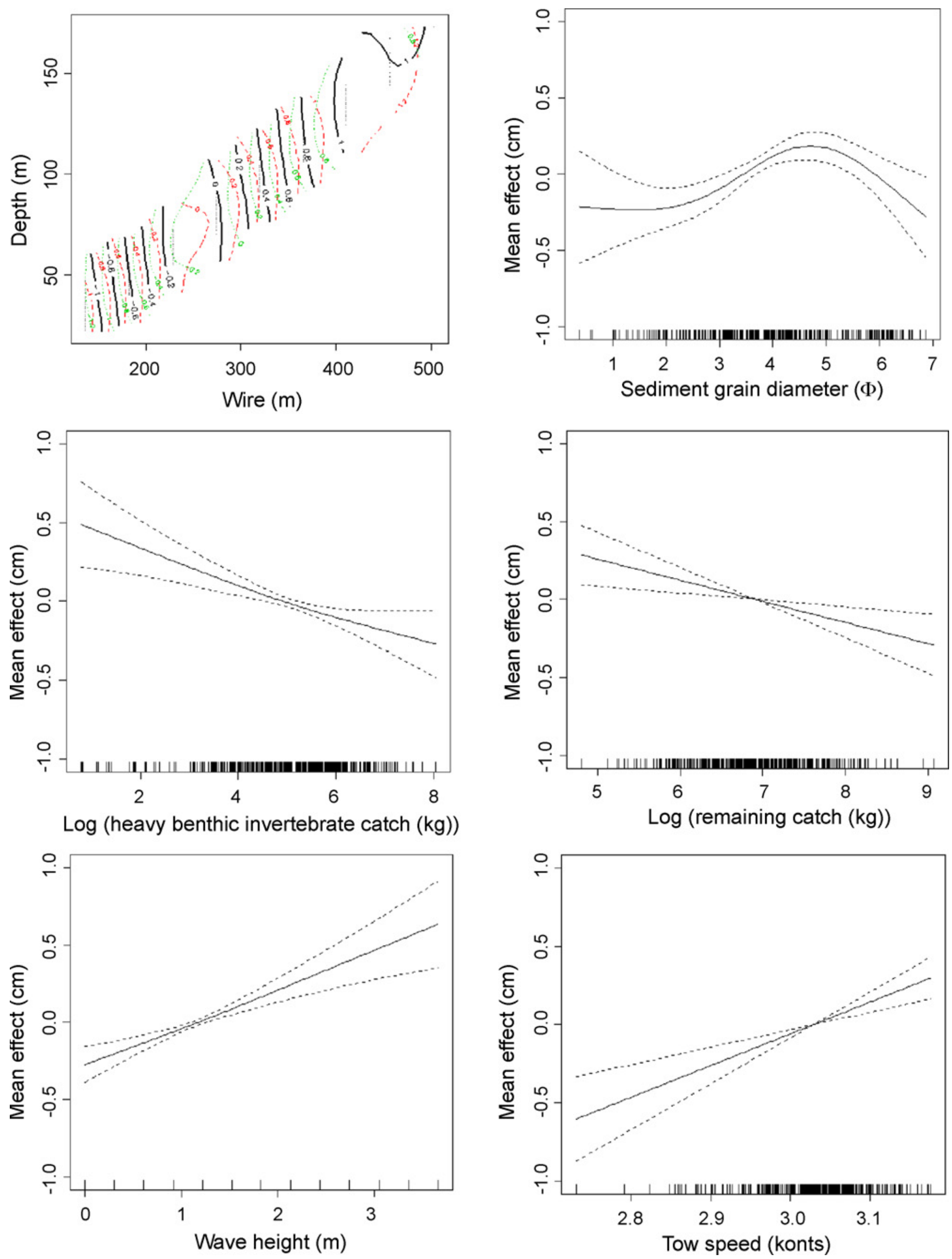


**Fig. 3.** Mean additive effects (solid lines) of significant terms on net width for the 2004 survey GAM. Dashed lines show 95% confidence intervals (red for lower and green for upper in top left panel). Observed survey values are represented by dots for the bivariate term (top left panel) and hash marks above the *x*-axis for all other terms. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

GCV scores (2.50 and 2.59, respectively) and AIC values (2541.9 and 2567.8, respectively) values for the GAM having all smoothed terms, indicating no improvement was achieved by simplifying the model. Thus, the best overall footrope performance model predicting footrope distances off the bottom was the version incorporating the year effect. The non-additivity test for this model was non-significant ($P = 0.68$).

The final combined-year GAM with year a factor predicted 6.4 and 4.8 cm mean footrope distances off the bottom for 2004 and 2005, respectively, under conditions when the mean effects from all variables was zero. This model explained 56.9% of the deviance or observed variability during typical EBS survey conditions (Table 4). Of the five model terms, the footrope was most affected by sediment grain diameter (−1 to +3 cm), the distances increasing as grain diameter decreased (Fig. 8). Footrope distances off the bottom also increased with increasing depth and wire (−1 to +1 cm). Additionally, within each scope table step, the distance off bottom increased as the ratio of wire to depth decreased. In contrast, increasing weight of both heavy benthic invertebrates (+3 to −0.5 cm) and the remaining catch (+2 to 0 cm) brought the footrope closer to the bottom, as did longer periods of net use (+0.5 to −1.5 cm).

## 4. Discussion

### 4.1. Interpretation of model results

The primary goal of this study was to develop robust models capable of quantifying the multi-faceted variable effects related

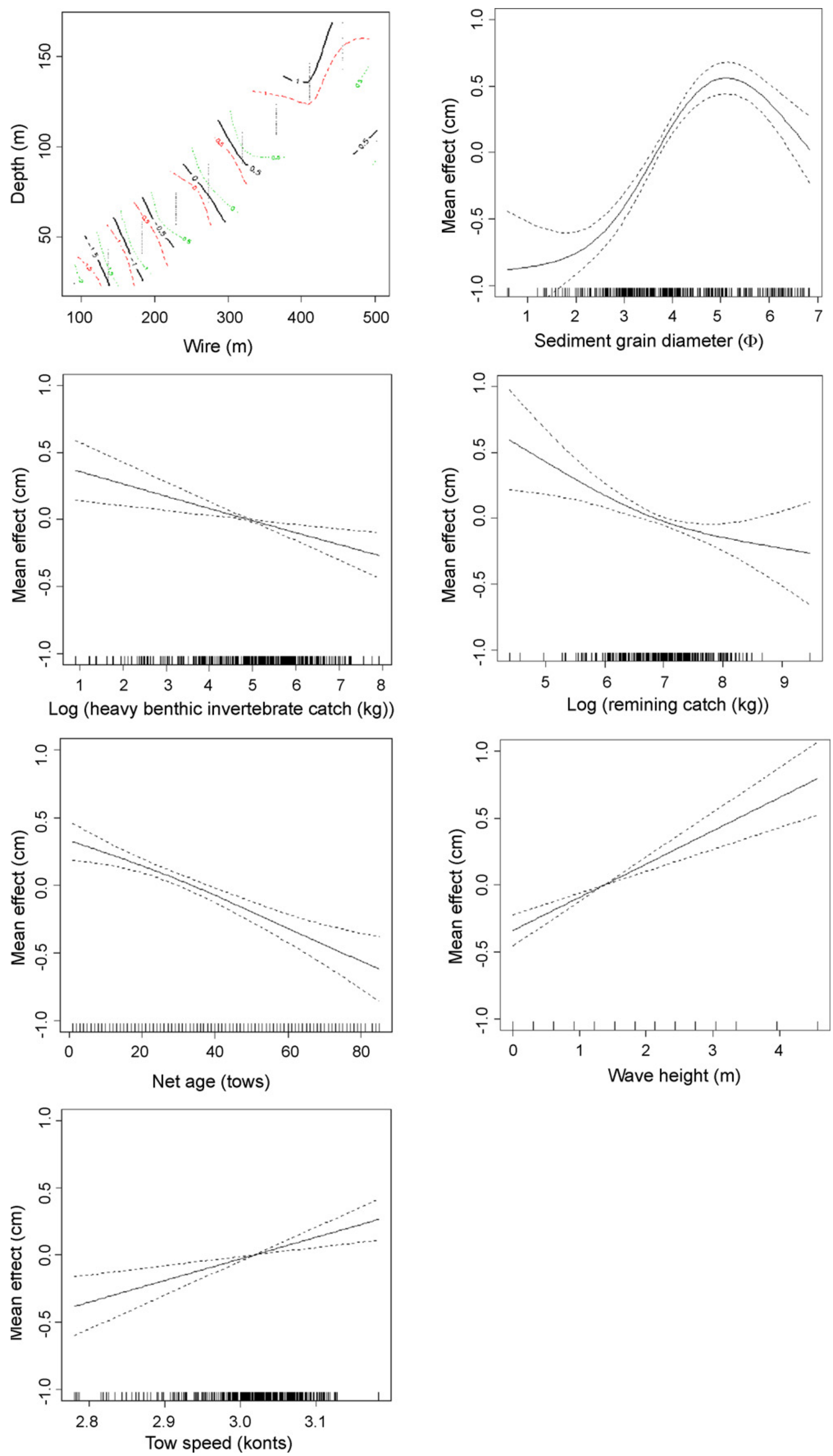


**Fig. 4.** Mean additive effects (solid lines) of significant terms on net width for the 2005 survey GAM. Dashed lines show 95% confidence intervals (red for lower and green for upper in top left panel). Observed survey values are represented by dots for the bivariate term (top left panel) and hash marks above the *x*-axis for all other terms. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

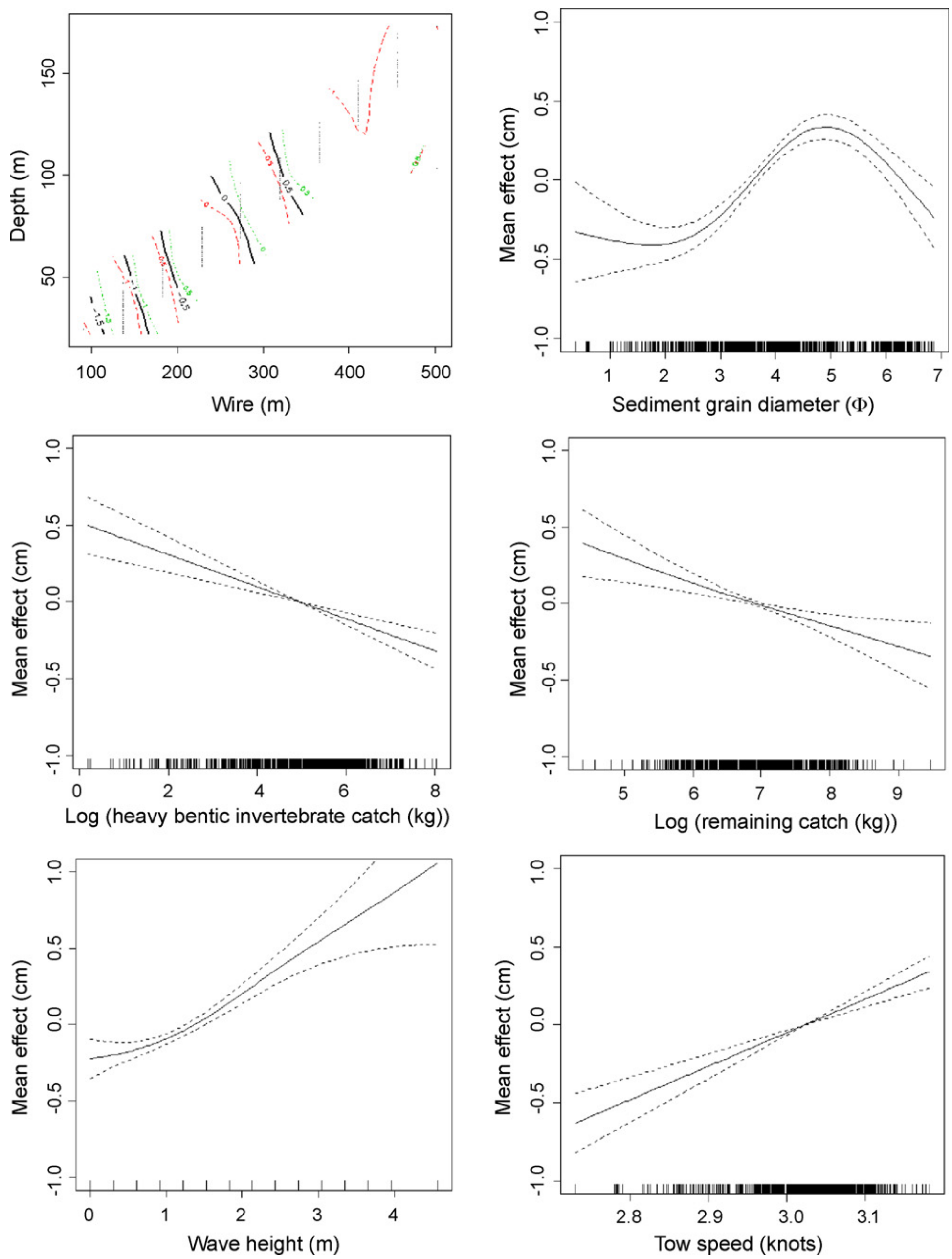


**Fig. 5.** Mean additive effects (solid lines) of significant terms on net width for the final combined-year GAM. Dashed lines show 95% confidence intervals (red for lower and green for upper in top left panel). Observed survey values are represented by dots for the bivariate term (top left panel) and hash marks above the *x*-axis for all other terms. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

to trawling practices, changing environmental conditions, and catch sizes on the swept area and footrope bottom tending performance of our 83-112 Eastern survey trawl. While the findings are specific to the EBS bottom trawl survey, reflecting the variables for which we had data, the methods presented can be applied elsewhere. Many of the variables we analyzed were excluded from final models either because they were found to be non-significant during 2004 and 2005 or they did not meet our final model selection criteria, such as demonstrating similar trends in both years. These same parameters may be of greater importance under different conditions, both spatially and temporally (e.g., for surveys enduring more frequent storm events, sampling more topographically diverse terrain, experiencing stronger currents, or using substantially different trawl equipment and towing procedures), and, as such, warrant consideration in other studies.

Towing speed and its affect on a trawl ground contact is a prime example of this. Intuitively, we expect that as towing speed increases so will net drag and the flow across the face of the trawl doors. At some point this increase in flow will overpower the ground sheer of the doors imposing a lifting effect on the trawl that would be apparent in the bottom contact sensor data. This may be the case for many trawl systems, particularly those with considerable headrope flotation (Somerton and Weinberg, 2001). However, we saw no clear evidence of this for the 83-112 Eastern given the narrow range of recorded towing speeds. Had the range in towing speeds been wider, the significance of this variable may have been more detectable.

**Table 4**
Significant terms for individual and combined year footrope performance models, their effective degrees of freedom (EDF), *F*-statistics, and *P*-values, in addition to overall generalized cross-validation (GCV) scores, deviance explained (DEV), and sample sizes (*N*)

| Year (height) | Smoothed term | EDF | *F* | *P*-value | GCV | DEV (%) | *N* |
|---|---|---|---|---|---|---|---|
| 2004 (6.2 cm) | | | | | 2.35 | 66.1 | 336 |
| | Depth and wire interaction | 6.00 | 5.19 | <0.001 | | | |
| | Tow speed | 1.00 | 23.20 | <0.001 | | | |
| | Net age | 1.86 | 14.62 | <0.001 | | | |
| | Wave height | 1.00 | 26.80 | <0.001 | | | |
| | log(heavy benthic invertebrates) | 2.68 | 20.94 | <0.001 | | | |
| | log(remaining catch) | 2.03 | 4.28 | 0.006 | | | |
| | Grain size | 2.66 | 34.10 | <0.001 | | | |
| | Cross flow | 2.05 | 2.29 | 0.079[a] | | | |
| 2005 (5.0 cm) | | | | | 1.89 | 59.8 | 326 |
| | Depth and wire interaction | 7.03 | 4.17 | <0.001 | | | |
| | Tow speed | 1.00 | 35.11 | <0.001 | | | |
| | Net age | 2.80 | 3.87 | 0.009 | | | |
| | Wave height | 2.16 | 4.48 | 0.004 | | | |
| | log(heavy benthic invertebrates) | 2.18 | 11.47 | <0.001 | | | |
| | log(remaining catch) | 1.88 | 4.46 | 0.004 | | | |
| | Grain size | 2.84 | 21.99 | <0.001 | | | |
| Combined, year not a factor (5.6 cm) | | | | | 3.02 | 47.6 | 677[2] |
| | Depth and wire interaction | 6.33 | 5.00 | <0.001 | | | |
| | Grain size | 2.83 | 29.43 | <0.001 | | | |
| | Net age | 1.60 | 1.35 | 0.257 | | | |
| | log(heavy benthic invertebrates) | 2.31 | 19.72 | <0.001 | | | |
| | log(remaining catch) | 2.59 | 8.61 | <0.001 | | | |
| Combined, year a factor: 2004 (6.4 cm), 2005 (4.8 cm) | | | | | 2.50 | 56.9 | 677[b] |
| | Depth and wire interaction | 6.57 | 6.20 | <0.001 | | | |
| | Grain size | 2.84 | 49.21 | <0.001 | | | |
| | Net age | 2.02 | 14.23 | <0.001 | | | |
| | log(heavy benthic invertebrates) | 2.24 | 27.18 | <0.001 | | | |
| | log(remaining catch) | 2.31 | 8.08 | <0.001 | | | |

Predicted mean footrope distance off-bottom when all model terms have a zero effect is shown in parentheses.

[a] The cross current parameter remains in the 2004 model despite its non-significant *P*-value because the EDF were not close to 1.0 and the GCV score was better than the model without cross current.

[b] Because spread was a non-significant variable, tows in which net width was estimated for stock assessment purposes were included in the combined year footrope performance models.

We acknowledge that by using survey data in an analysis, such as this, there is a chance of getting false results due to the possibility of accidental relationships between variables (e.g., the storm effect occurred when towing in deeper water only), as opposed to conducting a specific experiment to address particular variables and their contribution to total net width or footrope contact performance. On the other hand, it would be nearly impossible to conduct an experiment that could test for the additive effects of numerous variables over an entire survey area. The likelihood of these accidental relationships was minimized by running the models for each year separately, and in the final model using only those variables in common for both years. Furthermore, these variables had similar effects in both years intimating incidental relationships between variables were unlikely to affect the results twice in the same manner. To further assure the strength of the final model a test for non-additivity for all univariate terms was performed (Chan et al., 2003). This test verified the assumption about the additivity of variable effects being acceptable.

### *4.1.1. Net width*

Variation in net width is less influential on AFSC estimates of catch per swept area than for other surveys calculating CPUE on a catch per tow basis, because the EBS survey continuously measures the distance between wing tips and is thus capable of mathematically correcting for any variation. Even still, changing net widths can contribute to species- and size-specific changes in capture efficiency caused by varying bridle angles of attack, differences in fish herding response and swimming endurance (Engås and Godø, 1989b; Winger et al., 1999).

Of the six significant variables, depth and wire had the greatest impact on the spreading of the net. An increase in net width with increasing depth and wire length and a slowing or leveling off as sampling extended into deeper waters was anticipated. The decrease in net width predicted at the deeper stations was not expected but can likely be attributed to using a scope ratio that was too small (<3:1). Deploying too little wire increases the upward pulling force on the doors thus reducing the weight of the door on the sea floor and the ground sheer component responsible for the spreading of the doors, and subsequently, the net.

The final net width model selected towing speed, to be a better predictor of net width than parallel current flow, our proxy for speed of the trawl through the water, based on tidal model predictions. Lack of significance of the current flow parallel to the direction of the tow indicates that in fact ground sheer and not water flow is the primary spreading force for our survey trawl given the range of tidal currents and towing speeds examined.

The final model also showed net width was affected by surface waves, increasing as a function of increasing wave height. This may result from an increase in ground shear of the doors directly related to the pulling forces originating at the vessel's stern. As the wave lifts the stern to its crest, the forward velocity of the trawl doors increase, effectively spreading them farther apart. Then as the wave passes by, the stern of the vessel drops, effectively decreasing the spreading force, however, not as quickly, thus resulting in an overall increase in mean width during the tow.

Predicting the effect of catch weight on net width was better explained by separating the catch into two categories, rather than modeling it in its entirety. Each catch category contributes to the

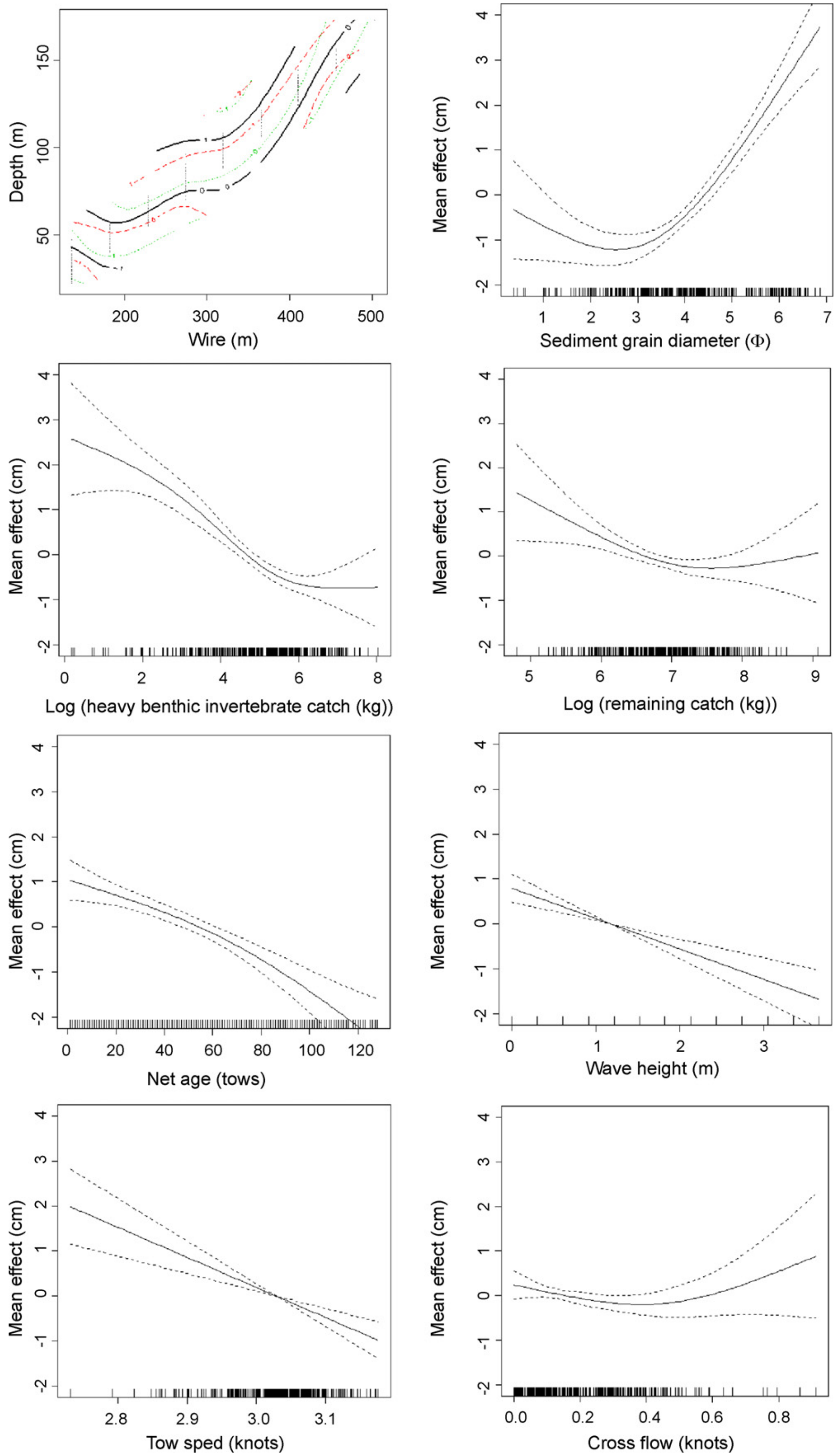


**Fig. 6.** Mean additive effects (solid lines) of significant terms on footrope distance off the bottom for the 2004 survey GAM. Dashed lines show 95% confidence intervals (red for lower and green for upper in top left panel). Observed survey values are represented by dots for the bivariate term (top left panel) and hash marks above the *x*-axis for all other terms. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

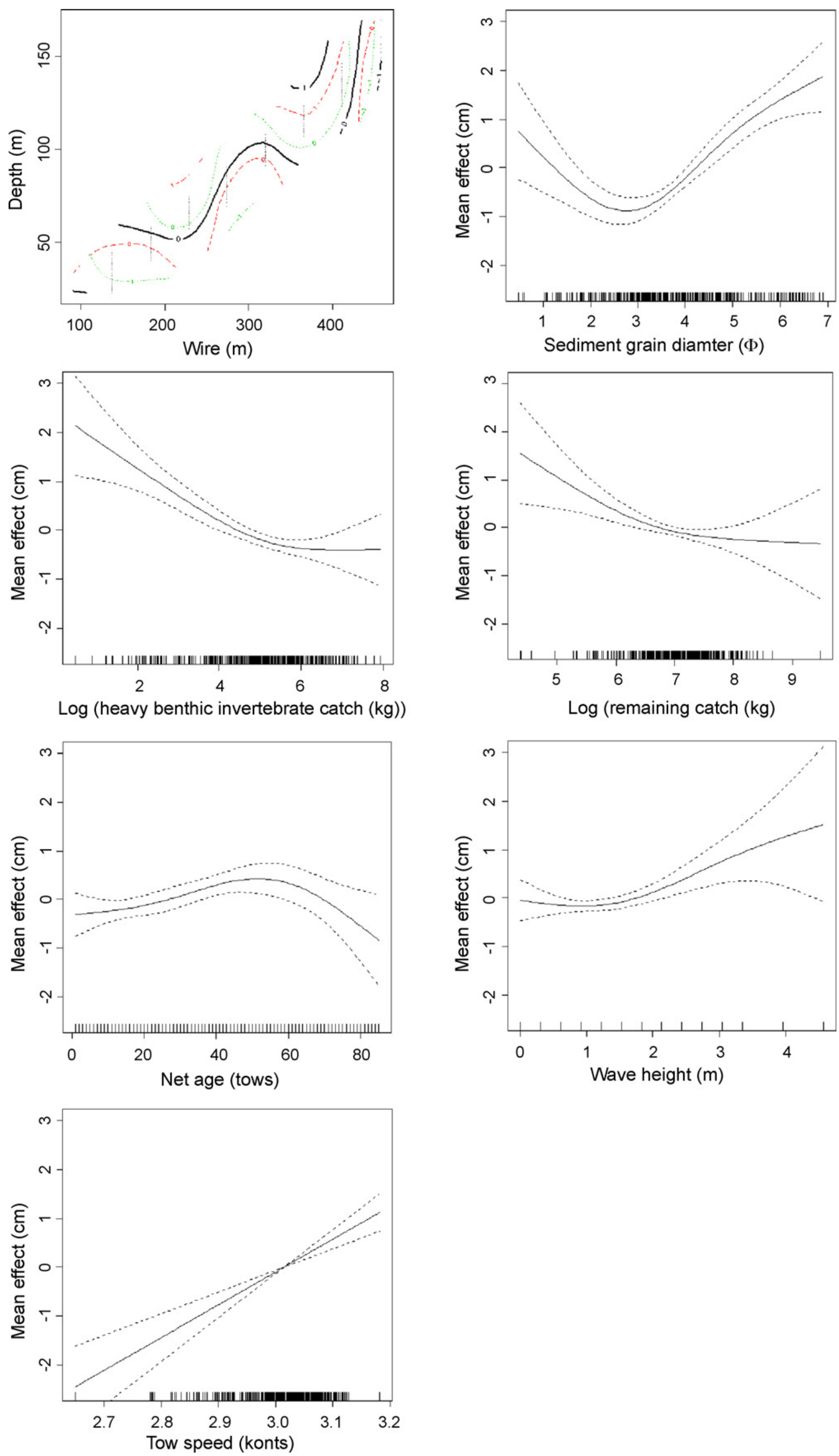


**Fig. 7.** Mean additive effects (solid lines) of significant terms on footrope distance off the bottom for the 2005 survey GAM. Dashed lines show 95% confidence intervals (red for lower and green for upper in top left panel). Observed survey values are represented by dots for the bivariate term (top left panel) and hash marks above the *x*-axis for all other terms. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

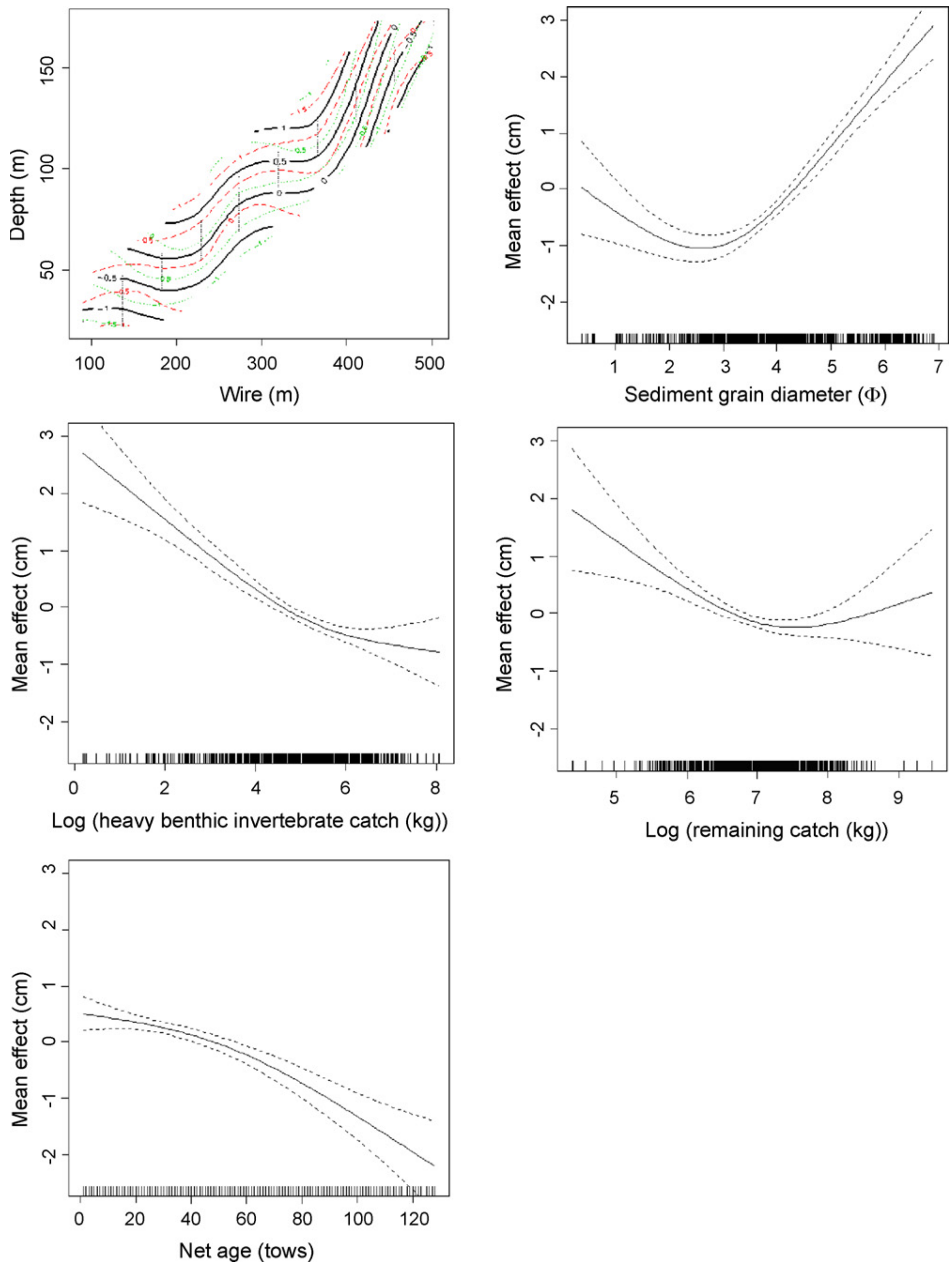


**Fig. 8.** Mean additive effects (solid lines) of significant terms on footrope distance off the bottom for the final combined-year GAM. Dashed lines show 95% confidence intervals (red for lower and green for upper in top left panel). Observed survey values are represented by dots for the bivariate term (top left panel) and hash marks above the *x*-axis for all other terms. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

total net drag in different ways. The weight of the heavy benthic invertebrates tumbling along the lower panel before coming to rest in the lower half of the codend exerts a downward pressure on the trawl and at times may be enough to cause friction of the net on the bottom. Fish, on the other hand, swim or float back eventually blocking the flow of water through the codend mesh, thereby impacting the horizontal component to the total drag of the net. The amount of horizontal drag increases with increasing codend diameter as fish accumulate.

The effect of decreasing grain diameter, the last of the six significant variables in our model, had an increasing effect on net width except in the case of the very finest particles. These are associated with soft-bottomed areas (Fig. 1), where oscillating acoustic net width signals are often received. In these areas, the trawl doors penetrate the soft sediment. As the trawl is pulled forward, mud builds in front of the doors, increasing the drag and spreading them farther apart until the forward pull of the vessel eventually tugs them free. The release of the doors from the mud is followed by a dramatic decrease in spread and destabilization period. We suspect the time and the degree of net narrowing outweighs the time and degree involved with the net maintaining maximum spread levels, thus lowering the overall mean width for the tow in these areas. In sandy, denser substrate the doors do not dig in as deep nor spread as far as on mud bottoms.

#### 4.1.2. Footrope performance

The catching efficiency of a trawl at the footrope can have a large impact on survey estimates of CPUE (Engås and Godø, 1989a). The greater the gap between the footrope and the sea bed the greater the probability of fish escapement occurring (Weinberg et al., 2002). Stock assessment models can apply trawl efficiency coefficients to account for fish loss under the gear but estimating trawl gear selectivity is expensive and may be constrained by physical parameters, such as bottom topography and biological parameters like fish density (Godø et al., 1999).

The results from the footrope performance model lead us to think that limited opportunities exist for improving the footrope performance of the 83-112 Eastern trawl, short of physically changing the net, such as by adding weight to the center of the footrope or relieving the strain on the mesh that lift the footrope. However, changes to survey gear, as well as fishing procedures, are usually not considered an acceptable option without extensive calibration experiments if preservation of a survey time-series is important. Five variables were shown to have a significant effect on the ground contact of the 83-112 Eastern at its center. Decreasing sediment diameter and decreasing scope ratios at any of the survey scope table steps increased the gap between footrope and the sea floor. Conversely, catch weights brought the footrope down, more so for the heavy benthic invertebrate class, as did the increased use of a trawl (net age), albeit nominally. Adding more wire and reducing towing speed are generally believed to help ground a trawl. Therefore, modifying the survey stepwise scope table so as to maintain scope ratios above 3:1 (Table 1) and lowering the overall survey towing speed (Weinberg, 2003) may very well lead to a decrease in the variability of footrope performance by reducing the footrope distance above the bottom.

Overspreading of the trawl is believed to increase the tension on the footrope of the 83-112 Eastern (Rose and Nunnallee, 1998). In cases of overspreading, von Szalay and Somerton (2005) reasoned the footrope could be pulled so taut that it would lift farther off the bottom allowing fish to escape underneath, thus varying the catch efficiency of the trawl. If this were the case, then reducing net width variability would reduce the error in CPUE estimates due to fish loss beneath the footrope. The 2004 and 2005 survey data showed tows with the greatest net widths and footrope distances off the bottom were related to greater depths, increased wire, smaller scope ratios, more wire, and small sediment particle diameter, but net width did not significantly affect footrope distances off the bottom.

Increases in footrope distances off the bottom in areas of decreasing particle diameter could be explained in another way. That is, if the trailing edge of the bottom contact sensor actually penetrated the soft bottom associated with small particle diameter, tilt angles would change in such a way so as to give the false impression that the footrope was lifting. The calibration experiments converting tilt angles into distances off the bottom are made on a hard surface (Somerton and Weinberg, 2001) and do not account for possible instrument penetration that would result in higher tilt angles and convert into greater footrope distances off the bottom. The degree to which the sensor penetrates would be a function of sediment density; penetration would be greater in silt than in sand, provided the silt is not compacted into clay. If the widening of the net were to cause an increase in the footrope distance off the bottom as suggested by von Szalay and Somerton (2005) and Rose and Nunnallee (1998), but was not detected in this model, then the sensor penetration thesis would also explain the conundrum presented from a recent AFSC experiment in which the footrope distances increased when net width was held constant by a constraining line between the trawl wires over a wide range of depths but was partially conducted in the soft bottom area in the SW corner of the EBS survey area (Fig. 1; Weinberg and Kotwicki, unpublished data).

## 4.2. Model applications

The primary reasons for standardizing survey design, trawls, and trawling practices are to reduce the variability in catch efficiency of the trawl by reducing both systematic biases and random variability in trawl geometry. Changes in trawl geometry brought about by both trawling practices and environmental conditions cause systematic biases. Bias can occur, for example, when a certain survey area always has a lower catch efficiency than other survey areas, such as may be the case for variable herding response of fish at different depths due to varying bridle angle of attacks. These biases can cause false impressions of fish distributions over a survey area, when part of the variability in fish distribution is actually caused by differences in catch efficiency. Similar effects can be brought about by changes in substrate, weather conditions, catch rates, or vessel operators. On the other hand, random variability which also contributes towards the total error in CPUE estimates is inherent to the flexible nature of the trawl.

There are several ways in which we can modify trawling procedures and survey protocols based upon the results of study, and in so doing, increase the precision of our area-swept estimates. One method for stabilizing net width across depth and changing substrate composition is to constrain the spreading of the doors by attaching a line between the main wires ahead of the doors (Engås and Ona, 1993; Rose, 1993). However, as Rose (1993) pointed out, the effect of the constraining line on fish behavior is unknown and requires further study. Shortening tow durations from 30 min to some lesser amount will reduce the catch of heavy benthic invertebrates, as well as the overall catch, thus reducing the variability in net width and footrope distances off the bottom associated with these larger catches, but it will also increase the relative proportion of the tow associated with variable catch efficiency that occurs after the winches are engaged to retrieve the warp (von Szalay, 2004). Establishing a rule to suspend towing operations, for example, in seas >3.5 m, will also help reduce variability in trawl geometry. Using autotrawl systems will help to stabilize footrope contact (Kotwicki et al., 2006). Also, providing vessel operators with performance feedback, such as Fig. 2, and real-time or post-tow speed plots, will potentially increase awareness and diligence, thus helping to reduce target speed variability.

Other applications for our GAM models include predicting swept-area in the absence of acoustic net mensuration data and validating tow performance while at-sea or during post-cruise analyses. Of these, the ability to predict net width when data is lacking or insufficient, such as would come about from instrument malfunction, lack of equipment, or intermittent signal reception is perhaps the most important. For these tows, the area swept must be estimated and the manner in which an estimate is produced has an effect on the survey biomass estimate and its variance. For example, in 2004 and 2005, net widths for 84 tows, roughly 11% of all tows made, were estimated. There are many ways in which a mean estimate might be generated, such as averaging between nearby stations, using an overall survey average, or using the mean from some relevant stratum; but for the EBS survey, net width estimates have been routinely based on a regression of net width and inverse scope by vessel (Rose and Walters, 1990). We compared our GAM predictions for the 84 missing net width values against the simple EBS regression to see which method provided the best fit with the least amount of error. The AIC value for the GAM (997) was smaller than the AIC from the EBS regression (1288) indicating the GAM was a better model for predicting missing net width values. In order to get a more realistic estimate of the prediction error, the *k*-fold cross-validation technique described by Efron and Tibshirani (1993) was used to estimate the prediction error (mean square error) for the GAM (0.29) and the inverse scope regression

(0.45), in addition to the mean absolute errors (0.40 and 0.51 m, respectively). These results showed a 36% improvement in the prediction error and a 22% improvement in the absolute error when using the GAM model.

Tow validation is not always straightforward, and sometimes requires considerable scrutiny while at-sea or during post-cruise editing. Tows suspected of poor trawl performance based on net width or bottom contact can be compared to model predictions using the prevailing set of environmental conditions. When at-sea, the decision to reject a tow and resample a station can be based on some pre-determined acceptable limit (e.g., 95% confidence bounds). Conversely, the decision to keep a suspect tow may be based on the additive effects of the conditions in which the tow was made and thereby offer a feasible explanation for the observed value. For example, a tow having a narrower net width than other tows made at the same depth using the same scope ratio, was found to have occurred over a substrate comprised of sand and pebble, while towing at a speed below the survey standard, in calm seas, and contained a large catch with significant amounts of sea stars and empty snail shells, all variables that reduce net width.

A broad range of variables other than those studied here may be useful in prediction models aimed at increasing our knowledge of trawl performance and which could lead to the lowering of survey variance. Some of these include: surface and benthic current conditions, vessel speed through the water, net symmetry, trawl wire tension, autotrawl winch control settings (if applicable), door spread and angle, vessel heave, bottom gradient, and light penetration. The more we understand about the factors affecting trawl geometry the closer our survey CPUE estimates will reflect true changes in population distribution and density.

## Acknowledgments

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