Snow crab selectivity by the NMFS trawl survey

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Size or age structured fishery management models typically include functions and parameters describing the processes of growth, natural mortality and survey selectivity. When the time series of catch and survey data used by the model is relatively long and the estimates of growth and natural mortality are well determined, as is true for the most of the major Bering Sea fish stocks, then the estimates of survey selectivity may be confidently estimated as part of the model fitting process. However, for species such as snow crab, that cannot be directly aged, growth and natural mortality are relatively ill determined and, as a consequence, estimates of survey selectivity produced in the model fitting process are potentially biased due to the inherent parametric correlations in the model. In such situations, model outputs could be improved if survey selectivity were set at, or constrained by, selectivity estimates derived from experimental data (Somerton et al. 1999). Here we examine the research leading to and culminating in the 2010 NMFS-BSFRF cooperative study, which focused on the problem of estimating snow crab survey selectivity from experimental data.

To better understand the research approaches that have been taken, it is important to clearly understand the goal. Survey selectivity is considered in the snow crab management model as a size-dependent proportionality between the true population abundance and that estimated by the annual EBS bottom trawl survey using swept area methodology. It is typically described mathematically using a logistic function, with the asymptote or maximum value of this function referred to as “q”. In contrast to this, trawl selectivity is the proportion by size of the crabs in the path of the trawl that is actually caught, and, equivalent to survey selectivity, the asymptote of this function can be referred to as “Q”. In all of the approaches described here, survey selectivity is estimated from estimates of trawl selectivity, which, in turn, are estimated from data collected using trawl selectivity experiments.

Trawl selectivity experiments can be generally grouped into two categories: 1) bagging experiments, where auxiliary mesh bags are attached to the outside of the trawl to capture animals that have escaped and 2) side by side trawling experiments, where the test trawl is fished simultaneously next to another trawl that is assumed to capture everything in its path (Wileman et al. 1996). Both approaches have been previously applied to the bottom trawl used on the NMFS EBS survey to estimate its selectivity for snow crab.

The first experiment, which was conducted in 1998 using the bagging methodology, obtained an estimate of the crab density in the trawl path by attaching a heavily weighted auxiliary bag under the trawl to capture crab escaping beneath the footrope (Somerton and Otto, 1999). The estimated trawl selectivity function, based on the ratio of the trawl catch to the combined catch of the trawl and the auxiliary bag, was logistic in shape and rose to a maximum of about 0.85. Although this study demonstrated that the NMFS trawl did not capture all snow crab in its path, the estimated trawl selectivity is likely a poor proxy for survey selectivity for two reasons. First, to compensate for the increased catch and drag of the auxiliary bag, tow length was shortened from the standard 30 min to 15 min, and previous research (Somerton et. al 2002) indicated that snow crab CPUE increases when tow length is reduced. Second, the experimental area was moved into shallower, sandier areas where invertebrate bycatch was less and net performance was better. Thus the experimental tows were not conducted exactly like the standard survey tows and the experimental area was not representative of the snow crab survey area but instead was restricted to the shallowest and most southerly part (Fig.1).

The second experiment, which was conducted in 2009 jointly by NMFS and BSFRF using the side-by-side methodology, paired the NMFS survey trawl with a *nephrops* trawl used by BSFRF to conduct experimental crab surveys. However, similar to the bagging experiment, there were also compelling reasons to question the validity of these trawl selectivity estimates as a good proxy for survey selectivity. Again, to compensate for the high bycatch of other invertebrates and debris, NMFS tow duration had to be reduced from the standard 30 minutes to only 5 minutes and the experiment was conducted in a restricted area that was not representative of the entire snow crab distribution (Fig. 1)

The third experiment, which was a synthetic side-by-side experiment, joined together data from the independently conducted 2009 BSFRF and NMFS bottom trawl surveys. The analysis focused on 27 NMFS statistical blocks (Fig. 1) where NMFS conducted a single 30 min tow at the center and BSFRF conducted 4, 5 min tows randomly located within the block perimeter. Although the BSFRF tows differed in both time and location from the NMFS tow, the 4 tows were averaged and used as a proxy for a single side-by-side tow. In addition, because the 27 statistical blocks encompassed a much larger geographic area than the previous two experiments, spatially varying covariates known to influence trawl performance, including depth, sediment size and net spread (Weinberg and Kotwicki 2008; von Szalay and Somerton, 2005), were included as part of the selectivity estimation model. The best model fitted to this data was logistic in form, with a Q of about 0.70, and contained a single covariate, net spread. Although the results from the third experiment, presented at the January 2010 Science and Statistical Committee (SSC) meeting of the North Pacific Fisheries Management Council, were based on standard NMFS survey tows, the non-synchronous nature of the sampling again brought into question the representativeness of the results as a proxy for survey selectivity. Despite this shortcoming, this modeling effort clearly demonstrated that trawl selectivity for snow crab varies spatially and that, to obtain an unbiased estimate, sampling must be conducted at stations covering a broad geographic range that representatively samples the variety of conditions occurring in the survey area.

Based on this knowledge, during the 2010 NMFS bottom trawl survey, NMFS and BSFRF again jointly conducted side-by-side towing, but unlike all previous experiments, sampling occurred over a broad geographic area in order to capture the biological and environmental variability of the snow crab population. The results of this experiment are the focus of this report.

Methods

Side-by-side trawling was conducted at 92 standard NMFS stations (Fig. 2) chosen to best represent the size distribution of male snow crab (Fig. 3) as well as to capture the variability of depth and sediment type within the area occupied by the snow crab population (Fig. 4).

At each of the 92 locations, the NMFS and BSFRF vessels started towing simultaneously on parallel courses that were roughly 0.1-0.2 nm apart. The NMFS vessel towed the standard survey trawl at 3 knots for 30 min while the BSFRF vessel towed the *nephrops* trawl at 2 knots for 5 min. On both vessels the snow crab catch was separated by sex then sub-sampled, if the catches were larger than 300 individuals in the aggregate, before measurement of carapace width in mm. Since the NMFS trawl sampled almost 7 times more area than the BSFRF trawl, the catches were much larger and therefore the sub-sampling proportion was typically lower. In addition, at all NMFS survey stations where snow crab were caught, depth and net width were measured at the time of sampling and the sediment type, expressed in units of phi (-log of grain diameter), was later interpolated from the AFSC EBS sediment database.

A statistical model relating the paired catches from the two trawls as a function of sex, carapace width and the spatial covariates was determined as follows (a detailed mathematical development is provided in the appendix). Unlike the 2009 study (an unpublished manuscript presented at the January 2010 SSC meeting), where the catches were expressed as the catch ratio (i.e., $\frac{C_{nmfs}}{C_{bsfrf}}$), this study expressed the catches as the catch proportion (i.e. $\frac{C_{nmfs}}{C_{bsfrf} + C_{nmfs}}$), which is consistent with the standard approach used by the International Council for the Exploration of the Sea (ICES) working groups (Wileman et al 1996). One particularly important advantage of doing this is that the data from size intervals in which $C_{bsfrf} = 0$ are unusable for calculating catch ratios but are acceptable for catch proportions. To minimize the number of size intervals where this was an issue, interval size was increased (10 mm for males and 5 mm for females) and size intervals larger than a cutoff size (125 mm for males and 70 mm for females) were pooled together. In addition, since extremely small crabs may not have been completely separated from the catch, data from sizes < 25 mm were ignored. Also consistent with the ICES methodology, the error structure was modeled as a binomial rather than a normal random variable, as in the 2009 report, using the number of crabs measured by each vessel. However, departing from the ICES methodology, the underlying model structure was not a logistic function of size, but instead was a nonparametric smooth function estimated using Generalized Additive Modeling (GAM). Methodology for inclusion of the spatial covariates into the model was similar to the 2009 study, where the variables depth, sediment size, and net width were added individually until the model with the lowest value of the Akaike Information Criterion (AIC; Burnam and Anderson 1998) was determined. This procedure was repeated for the addition of other covariates, either singly or jointly, until the overall minimum AIC was achieved. As described in the Appendix, once an acceptable model of the catch proportion was achieved, the catch proportion was then transformed back to trawl selectivity.

This analysis produced a trawl selection function. To obtain a survey selection function appropriate for the snow crab population, this trawl selection function was evaluated at and averaged over the 275 NMFS trawl stations having a catch of at least one individual snow crab. For each of these stations, trawl selectivity was predicted for each size interval utilizing the measured depth and predicted sediment size. The selectivity in each size interval was then averaged over all stations using weights equal to the product of the catch and the size of the sampling block (standard station blocks have an area of 400 sq nm, but stations within the two high density sampling strata (Fig. 2) have a smaller area).

Precision of these estimates of survey selectivity as a function of size were estimated using bootstrapping, which is a method intended to mimic replication of the side-by-side experiment. This was done as follows: 1) the experimental data was re-sampled by choosing 92 stations, with replacement (a single station can be chosen more than once or not at all). Since this might result in samples that are geographically concentrated and unrepresentative of a true replication of the experiment, the 92 stations were grouped into 4 geographic quadrants, and the re-sampling was restricted to the stations in each quadrant (this technique is called block bootstrapping); 2) analysis of each bootstrap sample proceeded as describe above, however the model form and the specific covariates included were maintained as in the original model; 3) bootstrap re-sampling and data analysis were repeated 100 times and the approximate empirical 95% confidence intervals were determined for each 1 cm size interval as the 3rd and the 97th elements of the sorted array. The upper and lower bounds of all intervals were then smoothed as a function of size.

Results

Based on the catches of the NMFS survey vessel at the 92 experimental stations, the carapace width frequency distribution in the experimental area was dominated by an extremely high abundance of both sexes near 45 mm (Fig. 5). For both sexes, few large individuals were encountered and males >125 mm and females >70 mm were extremely rare and patchily distributed.

The best fitting model describing trawl selectivity (proportion captured) included a smooth function of width and a smooth bivariate function of sediment size and depth (for males; R^2=0.94, n=824). For males, proportion captured, when averaged by width, rapidly rises to a relative peak near 45 mm, slowly rises from this size to about 100 mm, and thereafter rises sharply (Fig. 6). For females, proportion captured again rapidly rises to a maximum near 55 mm, then decreases slightly at larger sizes. Over the size range 45-70 mm, the estimated proportion captured was greater for females than for males, which was consistent with the 2009 study. These patterns of change with increasing size were clearly not a logistic function in shape and therefore required the use of a non-parametric smooth function. When evaluated at the range extremes of sediment size, the capture proportion for males is higher in sand and lower in mud (Fig.7); when evaluated similarly for depth, the capture proportion is higher in shallow water and lower in deeper water.

Survey selectivity for both sexes varies with size in a pattern similar to trawl selectivity. The uncertainty of the survey selectivity estimates (Fig. 8) increased with size as the abundance of each sex declined. For males, this resulted in an increasing spread of the 95% confidence intervals starting at about 100 mm, while for females, the increase started at about 50 mm. For both sexes the uncertainty at the largest modeled size (males, 125 mm; females, 70 mm) was quite high due to the high incidence of catch proportions based on the combined catch of only a single crab.

Discussion

The survey selectivity function was calculated as a weighted average of a spatially varying trawl selectivity function over the entire portion of the survey inhabited by snow crab. One question is whether this spatial extrapolation and averaging made a difference or could the trawl selection function itself be used as a reasonable proxy for the survey selection function? Both of these functions are plotted together in Fig. 9. For males, the two functions are very similar because one of the criteria for choosing the experimental stations was that the male size distribution at these stations was a good representation of the population size distribution. However, for females, the two functions are quite different because of the decision to optimize the choice of stations for males. From this perspective, it is clear that the results of the 1998 bagging experiment and the 2009 NMFS-BSFRF side-by-side experiments, which both occurred in limited geographic areas, likely represent poor proxies for survey selection (Fig. 1).

The spatial variability in the trawl selection function is related to the spatial variability in the geometry of the trawl. We believe that the most important dimension is the distance between the footrope and the sea floor (Weinberg and Kotwicki, 2008), because video observations have indicated that most snow crab escape capture by passing under the footrope. Several studies have been conducted on how this distance varies under a variety of environmental conditions, but for the two covariates shown to be significant in this study (depth and sediment size) it has been found that footrope distance off bottom increases with depth (vonSzalay and Somerton 2005) and with decreasing sediment particle size (increasing phi; Weinberg and Kotwicki 2008). Since these attributes have distinct spatial patterns over the snow crab distribution (Fig. 4), such variation leads to variation in trawl selectivity.

This variability in trawl selectivity interacts with the spatial variability in snow crab distribution to produce the survey selectivity. Both sexes of snow crab undergo an ontogenetic migration which is generally southward in direction (Fig. 3). For males (except for the largest sizes which likely perform a seasonal migration), this migration takes them into progressively deeper water with a sandier bottom type (Fig. 10). Thus, for snow crab, trawl selectivity not only varies with size because small animals escape more readily under the footrope but also because selectivity varies with habitat type and the preferred habitat of snow crab changes with time over their lifespan.

The survey selectivity function proposed here is not logistic, but instead is a non-parametric smooth function of carapace width. Use of a smooth function is not new, because other studies on trawl selectivity (Lauth et al. 2004; Skalski and Perez-Comas, 1993) have also found that non-parametric functions described the selection data better than a logistic function. Furthermore, the use of a logistic function to describe survey selection rests on a very weak theoretical foundation. An early and still common use of the logistic function in fisheries is to describe the retention of fish of varying sizes trying to pass through a panel of webbing (Wileman et al 1996), where the smallest individuals may all pass through while the largest may all be retained. The logistic function can still be useful for describing selection by an entire trawl, where size selective processes such as herding and avoidance may be even more important than mesh selection in determining the size distribution of the retained catch. However, it was such "whole trawl" selectivity studies that departures from logistic form were recognized (Lauth et al. 2004; Skalski and Perez-Comas, 1993). Survey selectivity is still more complicated because, as in the case of snow crab, trawl selectivity varies spatially as well as by size. With each stage of increasing complexity from mesh selectivity to survey selectivity the theoretical foundation for the use of the logistic function diminishes. It is true that, if scaled correctly, survey selectivity is a proportion, however it does not necessarily follow that its dependency on animal size is strictly logistic in shape.

Although a smooth function describes the selectivity data better than a logistic function, there are two distinct drawbacks to its use. First, few large crabs were sampled during the 2010 side-by-side experiment, consequently there were few data to define the selection at large sizes. When a more rigid function (i.e. less parameters) like the logistic is used to describe the data, the estimated selection values at large sizes are influenced by the values at smaller sizes. However, when a smooth function is used the estimated selection values are determined only by the available data at large sizes. This aspect, along with the low number of large crabs and their patchy distribution, jointly contribute to the high uncertainty of the selectivity estimates at large size.

The second drawback is that nearly every fishery management model used at the AFSC, including the snow crab model, uses one of the various forms of the logistic function, perhaps because of its mathematical and computational convenience compared to a smooth function. A smooth function does not have a parameter equivalent to "q" of the logistic, which has received so much attention by both assessment modelers and the fishing community. In addition, moving from a parametric to a non-parametric representation of the selection process may require considerable work on model re-development, especially on how the uncertainty associated with the proposed survey selection function could be used in a Bayesian framework to constrain model estimates of survey selectivity.

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Figure 1. Location of the 2009 joint NMFS-BSFRF side-by-side trawling experiment (shown with pink shading); locations the 3 BSFRF survey areas encompassing the 27 NMFS survey blocks (shown with a red line); and locations of the 1998 auxiliary bag experiment sampling areas (blue circles).

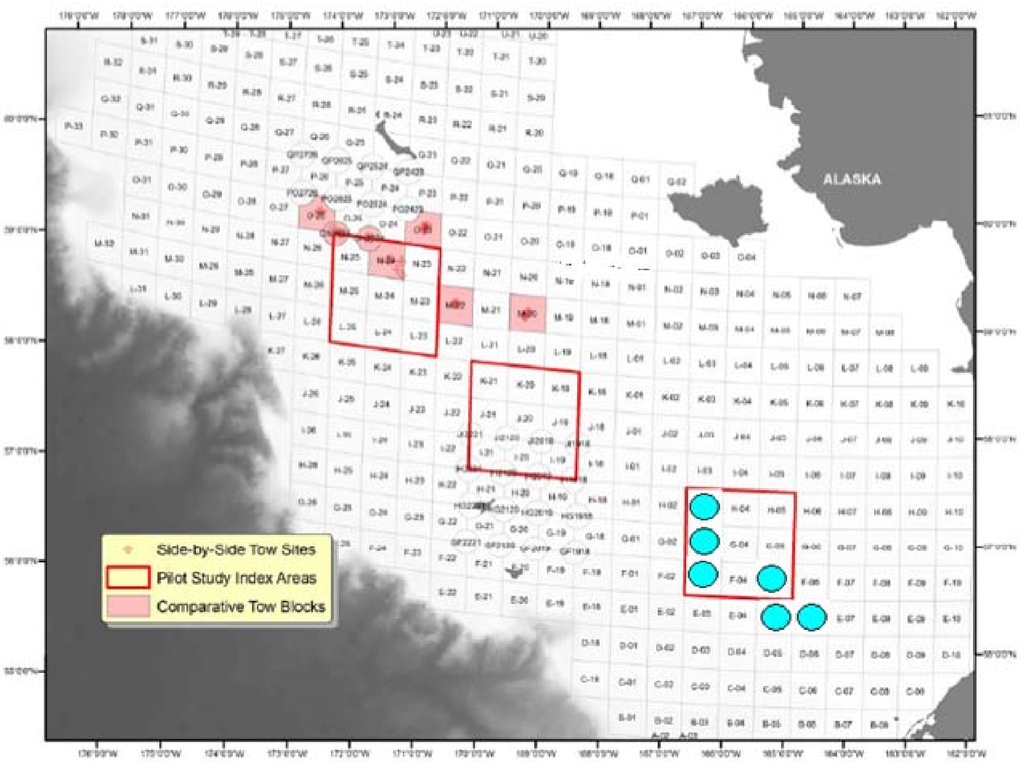


Figure 2. Locations of the sampling sites where NMFS and BSFRF jointly conducted side-by-side towing during the 2010 EBS bottom trawl survey.

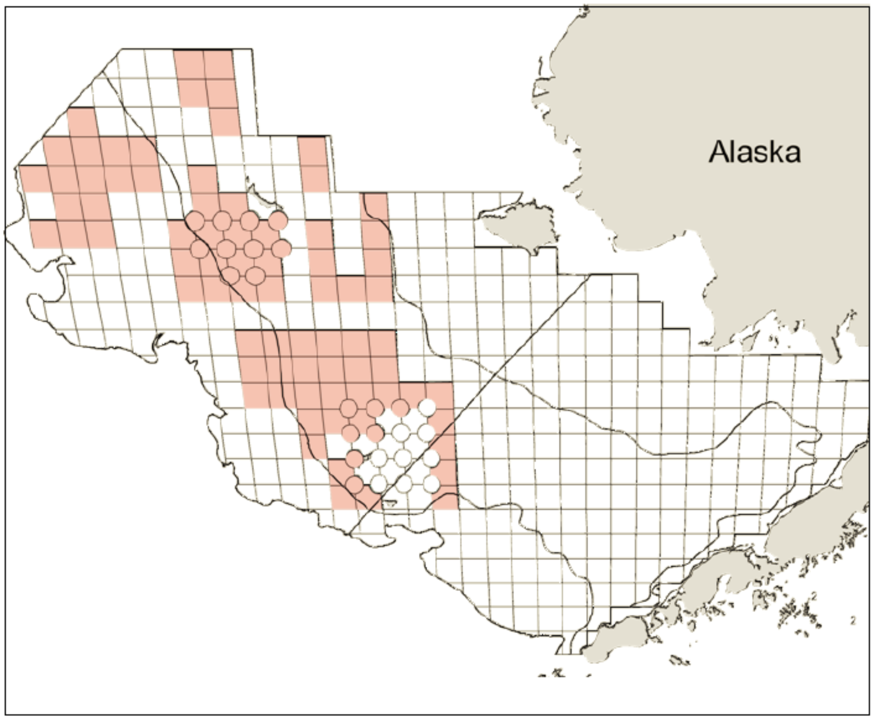


Figure 3. Distribution of large and small size classes of both sexes of snow crab and the sampling grid used on the 2010 side-by-side experiment. Note that for both sexes, there is southward movement into deeper water over their life spans.

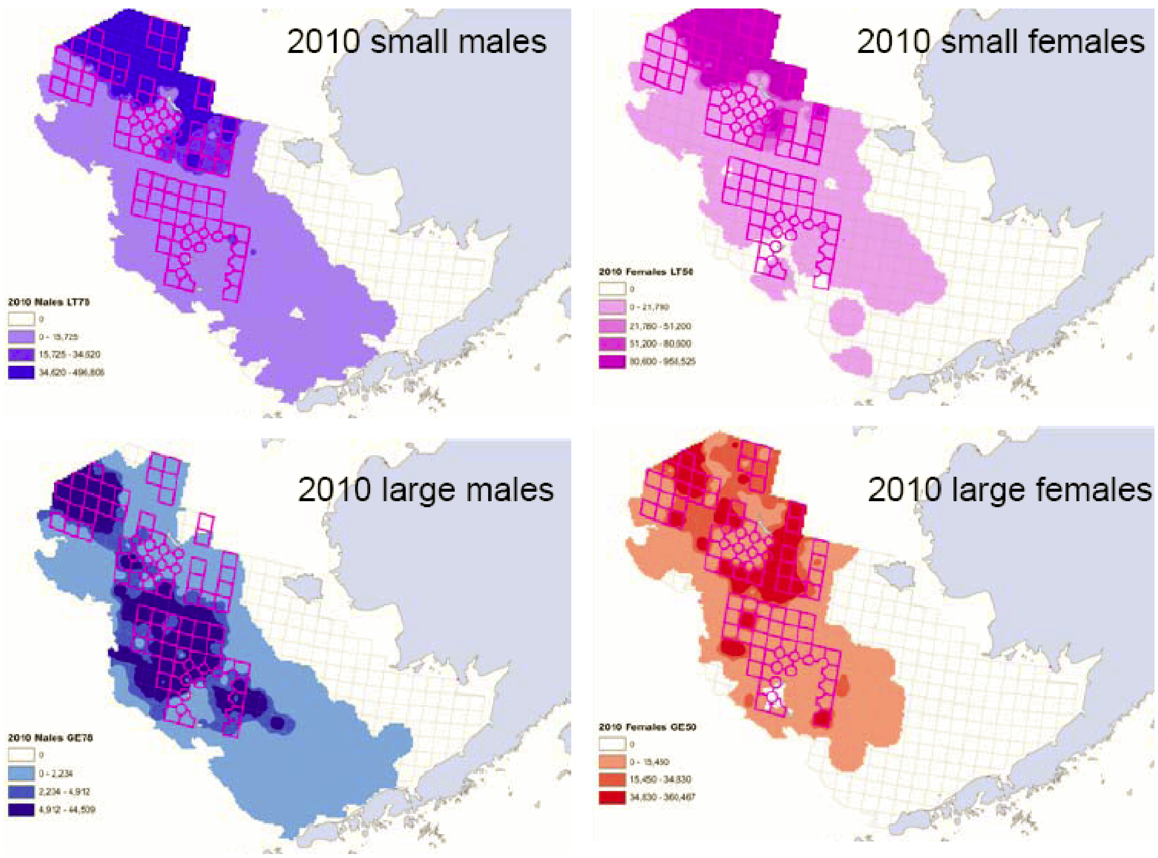
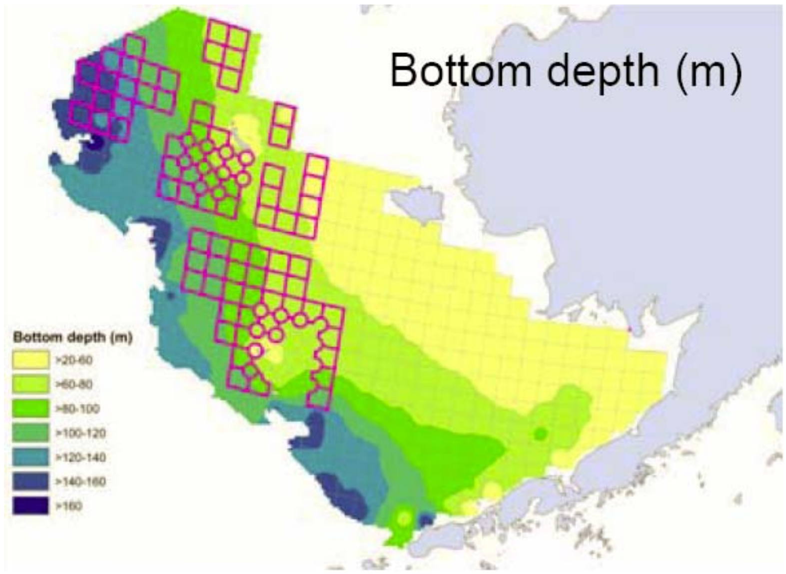


Figure 4. Depth and sediment size distributions in the EBS are shown along with the 2010 NMFS-BSFRF side-by-side sampling stations.



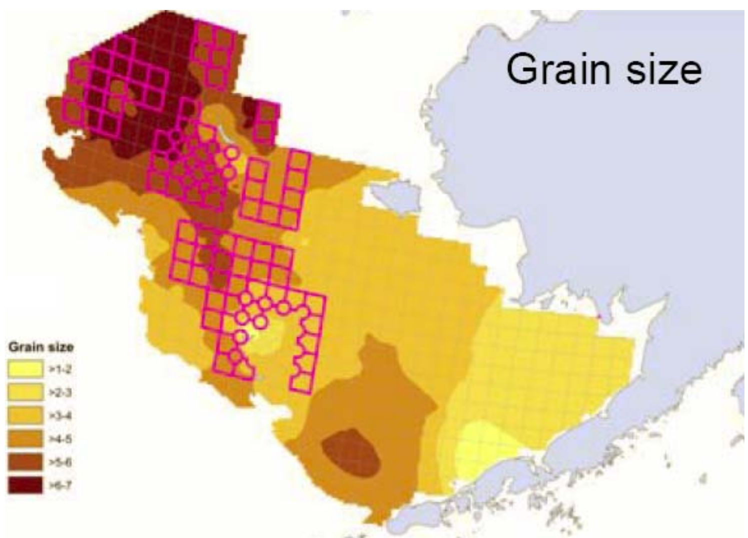


Figure 5. The carapace width frequency distribution of the crabs sampled aboard the NMFS vessel during the NMFS-BSFRF experiment.

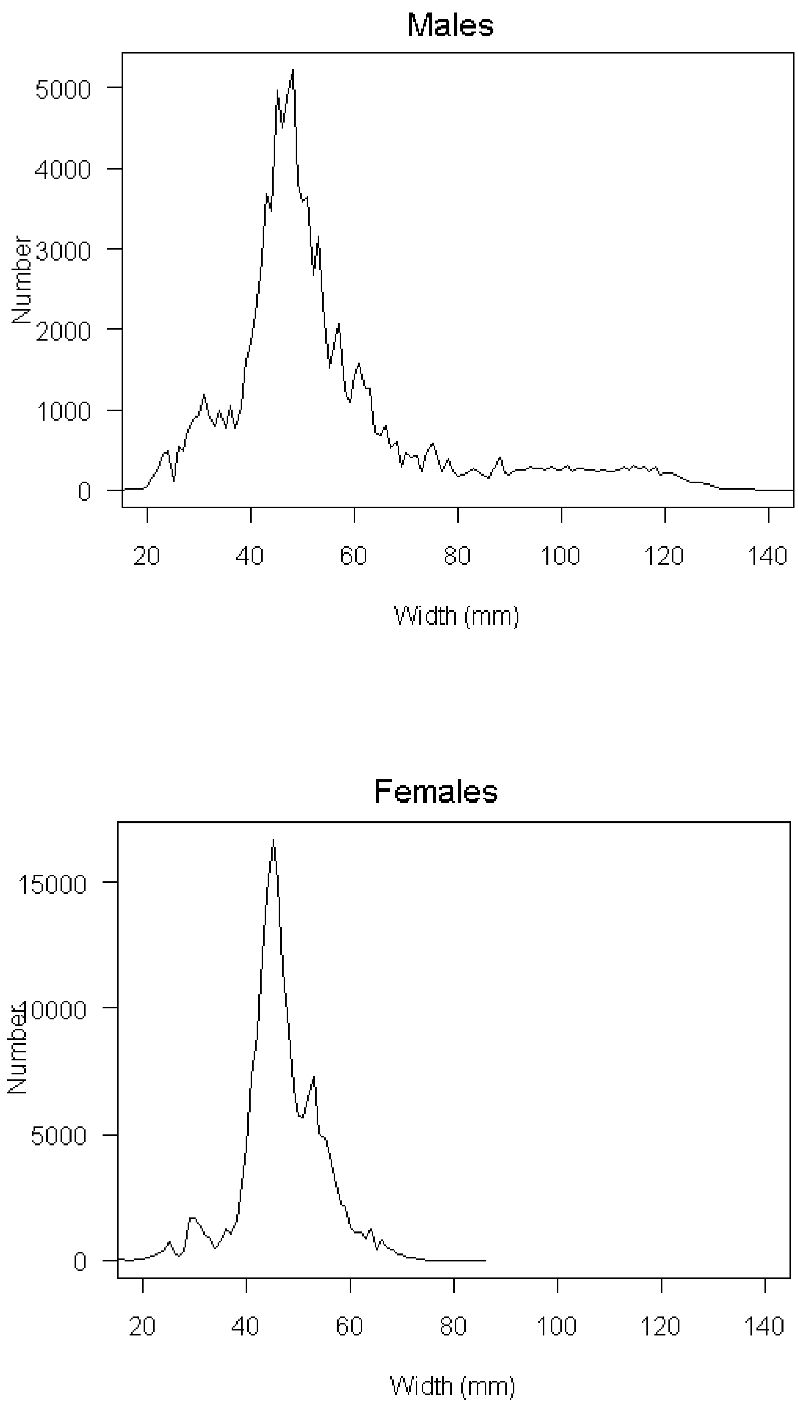


Figure 6. Trawl selectivity functions for males (black line) and female (blue line) snow crab.

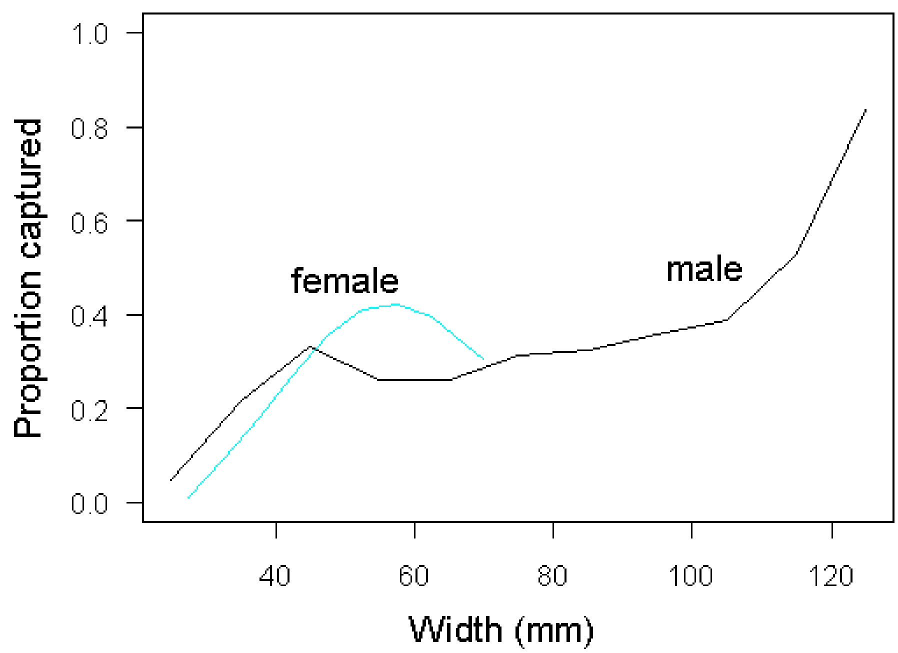


Figure 7. Trawl selection function evaluated at the extremes of sediment size and depth.

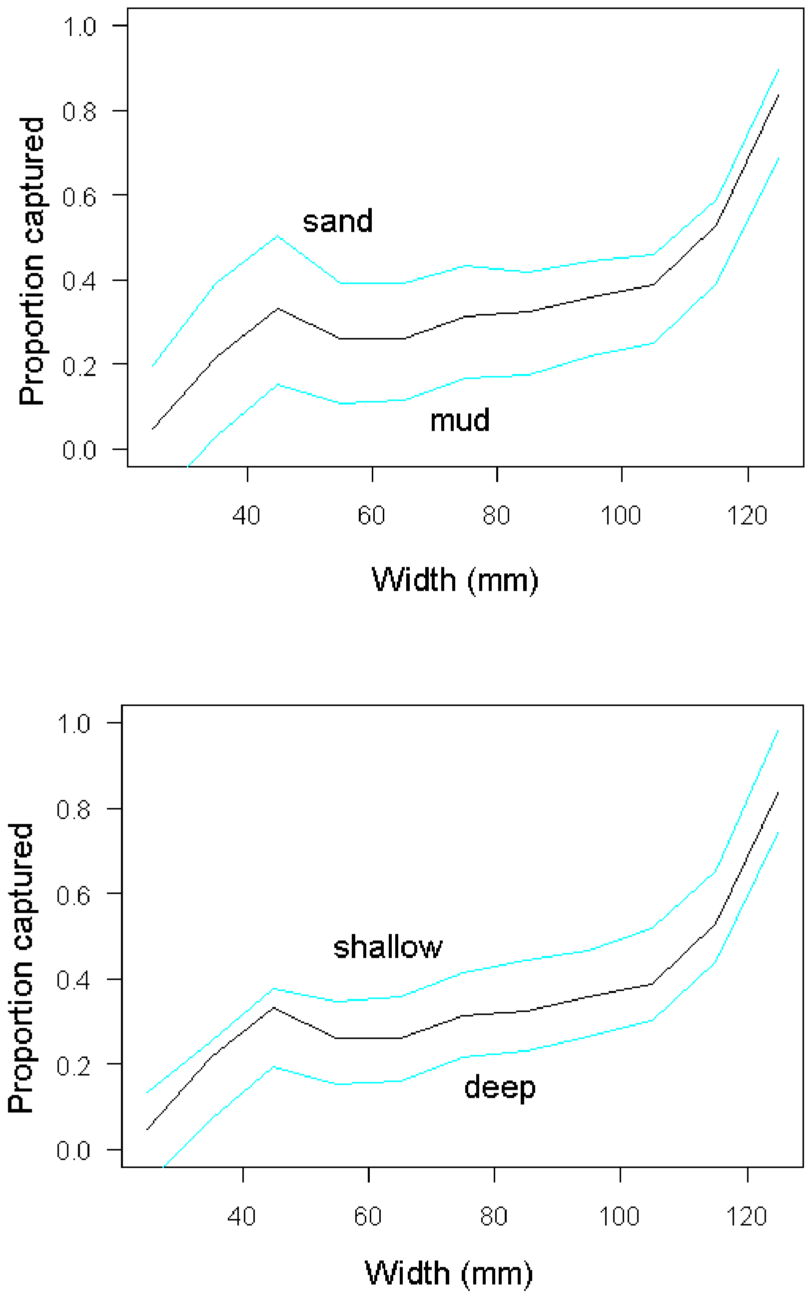


Figure 8. Survey selection function, including approximate 95% empirical confidence limits.

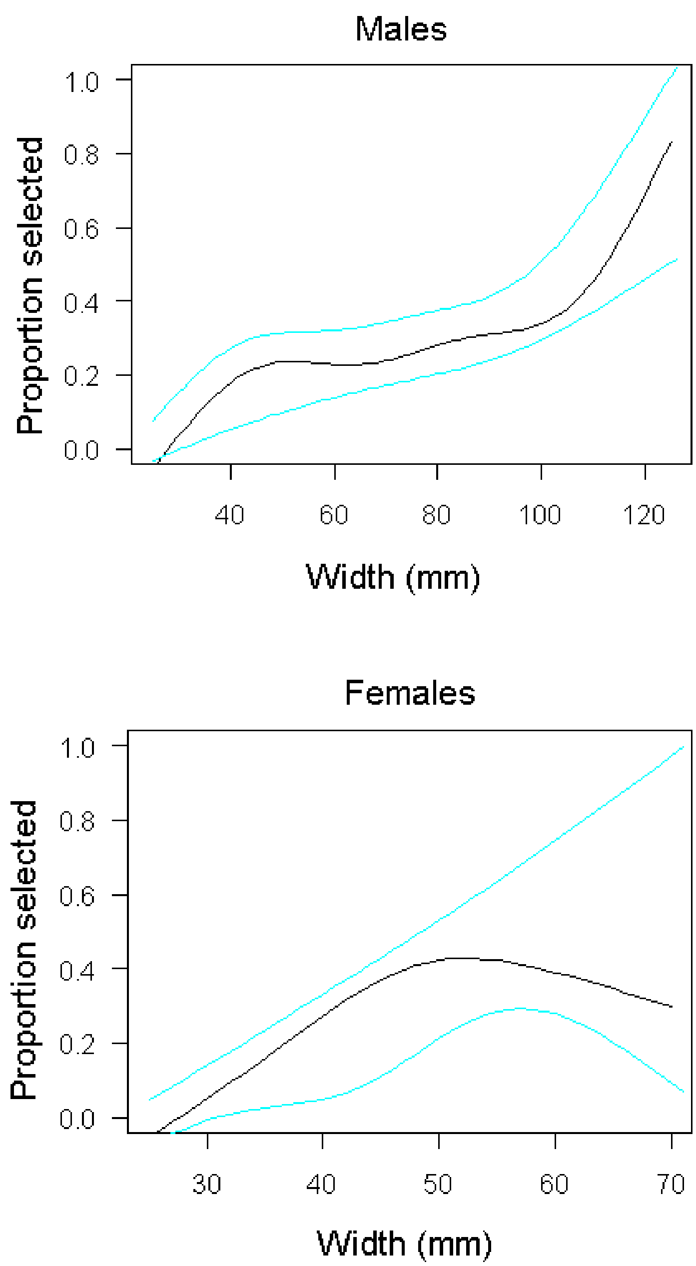


Figure 9. The survey selectivity (black line and circles) evaluated over the 275 positive snow crab stations and the trawl selectivity (blue line) evaluated over the 92 stations where the NMFS-BSFRF side by size trawling was conducted.

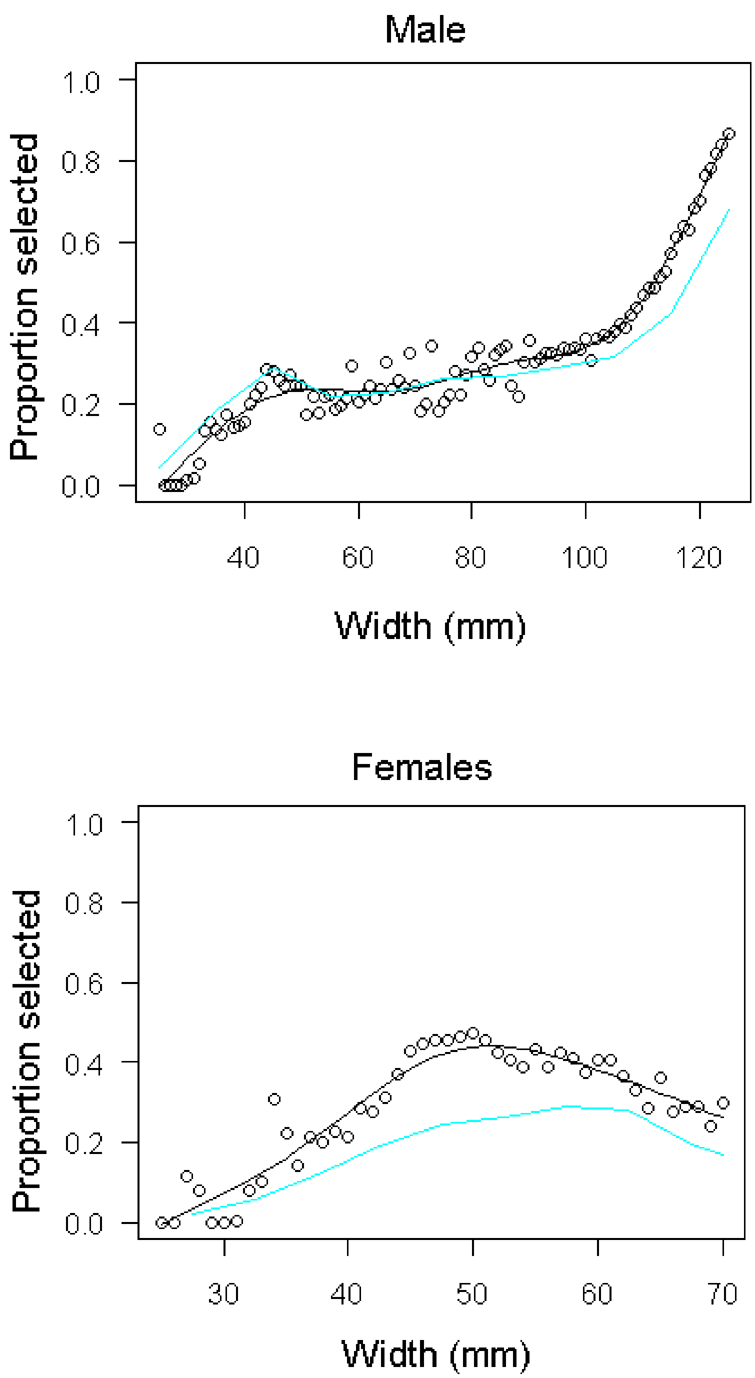
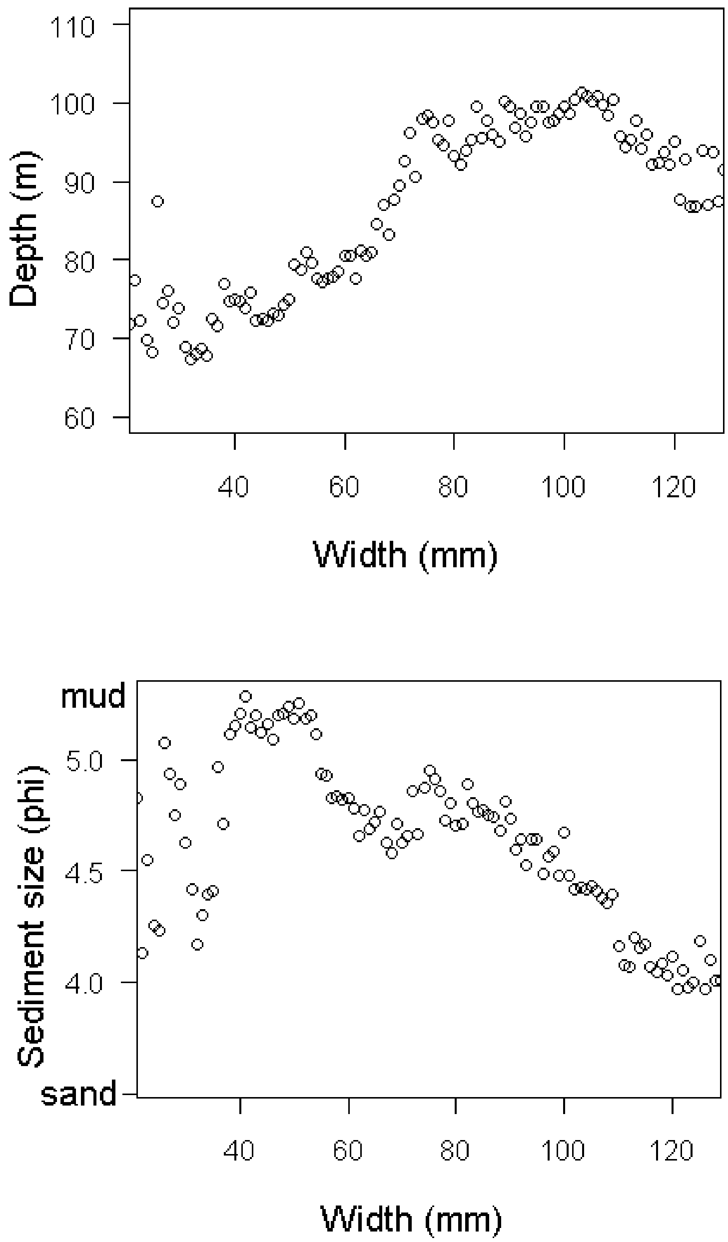


Figure 10. Mean depth and sediment size (in phi units) for male snow crab as a function of carapace width from the 2010 EBS survey.



Appendix 1. Development of the trawl selectivity model.

Assuming the that BSFRF *nephrops* trawl catches all crabs in the tow path, then the interpretation of the catch ratio (i.e., $\frac{C_{nmfs}}{C_{bsfrf}}$) as an estimator of the selectivity of the NMFS trawl is perfectly clear. However the weakness of this estimator, is that it is undefined when C_{bsfrf} =0, and simply discarding all cases where this is true will lead to biased estimates. In response to this frequent problem, ICES working groups (Wileman et al., 1996; Millar 1992) developed an alternate estimator which is statistically conditioned on the combined catch in a size interval, that is, the catch proportion (i.e. $\frac{C_{nmfs}}{C_{nmfs}+C_{bsfrf}}$). Since this is not as intuitive as the catch ratio, we will develop the concepts behind its use here. Consider first a situation where the NMFS and BSFRF trawls have identical swept areas and that all crabs were measured without sub-sampling. Also consider all of the crabs in the combined swept area as pooled together, and let the proportion of these that were in the path of the NMFS trawl be equal to P. In the case of equal swept area, then P is on average = 0.5. Further, let the selectivity of the BSFRF trawl =1 and that of the NMFS trawl = r. Combining all of this together leads to the relationship:

$$\frac{C_{nmfs}}{C_{nmfs}+C_{bsfrf}} = \frac{P\,r}{P\,r+(1-P)} = \frac{r}{r+1}$$

When the swept areas (A) are not identical, then:

$$P = \frac{A_{nmfs}}{A_{nmfs}+A_{bsfrf}} \quad ,$$

In addition, when the sub-sampling proportion (S) also differs between vessels (Millar, 1994), then:

$$R = \frac{S_{bsfrf}}{S_{nmfs}}, \text{ and}$$

$$\frac{C_{nmfs}}{C_{nmfs} + C_{bsfrf}} = \frac{r}{r + R\dfrac{A_{bsfrf}}{A_{nmfs}}} \ .$$

Letting $\Phi = \dfrac{C_{nmfs}}{C_{nmfs} + C_{bsfrf}}$, then the estimation function is:

$$\Phi = S(width) + S(X)$$

Where S represents some nonparametric smooth function and X includes one or more of the covariates depth, sediment and net width. This equation is fit to the catch proportions for each width interval for each paired tow using GAM, with binomial error. Binomial, rather than Normal, error was used because Φ is a proportion and often has the value of 1 or 0 (this invalidates the use of the Normal approximation to the Binomial distribution). The trawl selection function is then obtained by back transformation:

$$r = \frac{\Phi R\dfrac{A_{bsfrf}}{A_{nmfs}}}{1 - \Phi} \ .$$