

Abstract.—Snow crab (*Chionoecetes opilio*) and Tanner crab (*C. bairdi*) fisheries in the eastern Bering Sea are managed by using swept-area estimates of biomass based on an annual survey conducted with a 83-112 eastern bottom trawl. Estimates of net efficiency (i.e. the capture probability of crab that occur between the wing-tips of the trawl net) are needed to correct the biomass estimates for any size selectivity by the trawl. Data on net efficiency were obtained experimentally by attaching an auxiliary net beneath the trawl net to capture crab escaping under the trawl footrope. Net efficiency is then the quotient of the trawl catch divided by the combined catch of the trawl and auxiliary nets. Mathematical models of the relationship between net efficiency and carapace width were formulated and fitted to the experimental data. Net efficiency for both species first decreased with increasing carapace width until a minimum efficiency was reached near 50 mm carapace width. At larger sizes, efficiency increased asymptotically with carapace width. Net efficiency for mature female Tanner crab was lower (0.47) than for males and immature females combined (0.72) at the same mean carapace width as mature females (66–107 mm). Net efficiency did not differ between morphologically mature and immature male Tanner crabs of the same carapace width.

Net efficiency of a survey trawl for snow crab, *Chionoecetes opilio*, and Tanner crab, *C. bairdi*

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The commercial fisheries for snow crab (*Chionoecetes opilio*) and Tanner crab (*C. bairdi*) in the eastern Bering Sea are managed by using swept-area estimates of biomass (Alverson and Pereyra, 1969) provided by an annual Alaska Fisheries Science Center (AFSC) bottom trawl survey. In addition to catch and swept-area data, such biomass estimates require a value for the sampling efficiency of the trawl¹ (i.e. the proportion of animals that are captured within the area spanned by the trawl doors; Dickson, 1993a). Trawl efficiency can be considered as a function of sweep efficiency (the proportion of animals within the path of the doors, bridles, and sweeps that are herded into the net path) and net efficiency (the proportion of animals that are captured within the path of the trawl net; Dickson, 1993a). For snow and Tanner crabs, owing to a lack of any contradictory evidence, sweep efficiency was assumed to be zero and net efficiency was assumed to be unity. The assumption of zero sweep efficiency has been subsequently supported by experiments on herding,² but the assumption of complete net efficiency has been contra-

dicted by studies in which low-light video cameras have documented that even large male crabs could often escape under the footrope.³ Such observations prompted us to experimentally estimate net efficiency of the 83-112 eastern trawl, the trawl used for the eastern Bering Sea surveys.

Previous studies of net efficiency, which were focused at various species of groundfish, indicated that efficiency generally increases with body size (Engås and Godø, 1989; Walsh, 1992). For snow and Tanner crab, however, biological attributes other than size could also influence efficiency. For example, mature males have longer legs and thicker chelae, in relation to their carapace width, than either mature females or immature males. Not only could the difference in body shape result in differing net efficiency, differ-

¹ Throughout this paper we will refer to the trawl as an entire fishing gear comprising the net, bridles, and doors.

² Somerton, D. A., and P. T. Munro. 1998. Estimating the sweep efficiency of a bottom trawl. Manuscript in preparation.

³ Munro, P. T. 1998. Alaska Fisheries Science Center, 7600 Sand Point Way NE Seattle, WA. Unpubl. data.

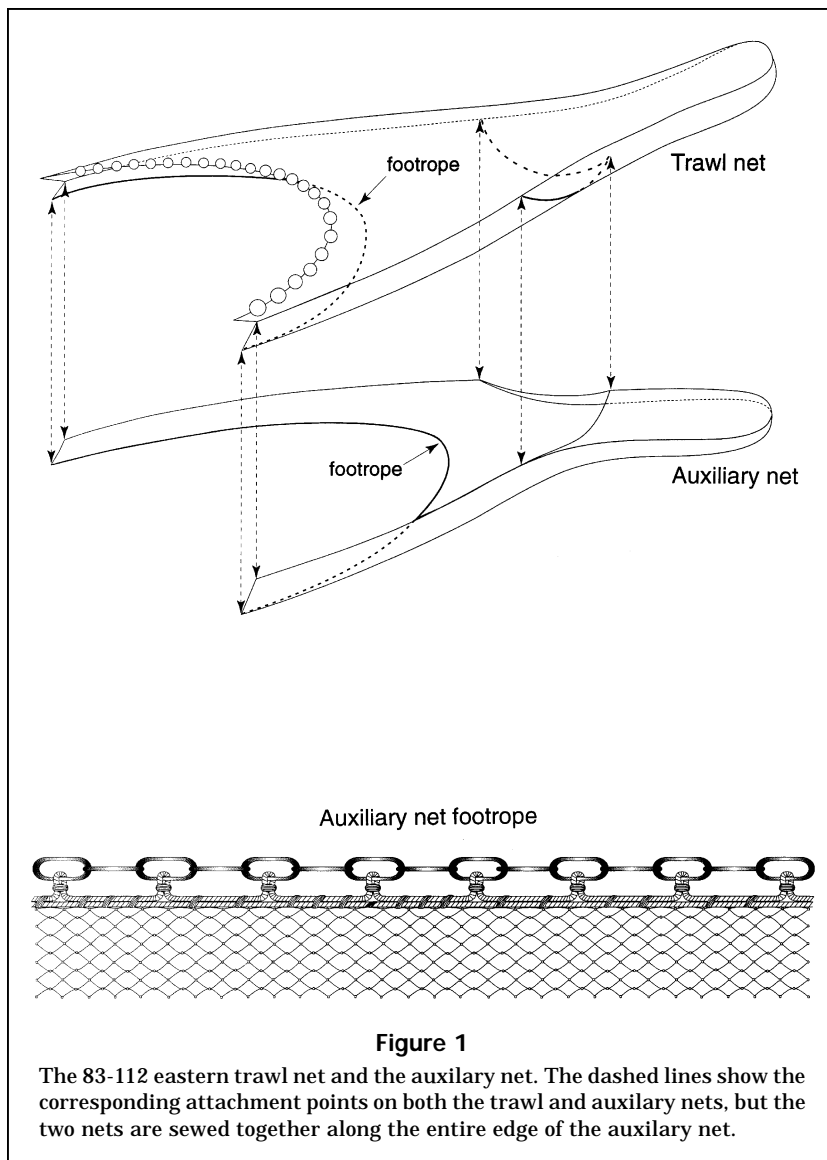
ences in behavior between sexes or between mature and immature individuals but could also lead to differences in efficiency. Of particular concern is a possible difference in net efficiency between mature and immature males because such a difference could lead to a bias in the estimates of the carapace width at maturity and thereby affect commercial minimum width regulations.

We estimated net efficiency with an experimental approach pioneered by Engås and Godø (1989) that uses an auxiliary net attached beneath the trawl net to capture crab escaping under the footrope. If the auxiliary net spans the fishing width of the trawl net, from wing-tip to wing-tip, and captures everything passing beneath the footrope, then efficiency is estimated as the quotient of the trawl catch divided by the total catch of both the trawl and auxiliary net (Walsh, 1992; Dickson 1993b). The crux of such an experiment is then to design an auxiliary net with a footrope that exerts sufficient bottom contact to capture everything passing beneath the trawl footrope without causing enough added drag to alter the fishing efficiency of the trawl. Unlike the trawls examined in the studies of Engås and Godø (1989) and Walsh (1992), the 83-112 trawl lacks bobbins or rollers on the footrope and instead has a footrope consisting of a simple, rubber-wrapped cable. This difference in trawl design required several distinct differences in the design of the auxiliary net. In this paper we examine the application of this auxiliary net to estimate the efficiency of the 83-112 eastern trawl for snow and Tanner crabs.

Materials and methods

Description of the trawl and auxiliary net

The 83-112 eastern trawl is a two-seam trawl with a 25.3-m headrope and a 34.1-m footrope consisting of a simple rubber-wrapped cable intended to remain in close contact with a smooth bottom (Fig. 1; see Armistead and Nichol, 1993, for a detailed net plan). The trawl is towed behind 1.8 × 2.7 m steel "V" doors



weighing 816 kg each, which are connected to each wing with two 55-m bridles. Wing and throat sections of the net are made of 10.1-cm (stretched measure) nylon mesh, the intermediate section is made of 8.9-cm mesh and the codend is made with a double layer of 8.9-cm mesh lined with 3.1-cm mesh.

The auxiliary net was hung beneath the trawl net, attached at the wing tips and along the top of the wings (Fig. 1). Unlike the auxiliary net designs of Engås and Godø (1989) and Walsh (1992), our auxiliary net lacked a headrope, used the belly mesh of the trawl as the top panel, and had a single codend rather than three separate codends. The mesh used in the auxiliary net was the same as that for the trawl, but the footrope was longer (38.2 m) and was constructed of 16-mm long-link steel chain intended to be sufficiently heavy to excavate buried crab. An

additional feature of the auxiliary net was that the footrope was not attached anywhere along the length of the trawl footrope but instead joined it only at the wing tips. The auxiliary net footrope was intended to be positioned 2–3 m behind the trawl footrope along the center line of the trawl, but this position was not verified in the field.

Description of the experiment

The net efficiency experiment was conducted aboard a chartered 40-m stern trawler (FV *Arcturus*), from 20 July 1997 to 8 August 1997, immediately following completion of the annual AFSC trawl survey of the eastern Bering Sea. The experimental site was located east of the Pribilof Islands (57°11.4'N, 166°26.5'W) at depths between 75 and 90 m on a smooth bottom.

All hauls were made by using the same trawling procedure and towing speed (3 knots) as those used during the AFSC survey but tow duration (15 min) was only one half of the standard. Trawl net width, from wing-tip to wing-tip, was measured on all hauls with a SCANMAR net mensuration system.

The experiment began with test hauls of both the standard trawl and the trawl with the attached auxiliary net (experimental trawl) to determine if trawl performance was altered by the auxiliary net. All test hauls were conducted with the codends left open and with a video camera attached so that the trawl footrope near its center could be viewed. After three hauls of the experimental trawl, it became evident that the additional drag of the auxiliary net resulted in a reduction in the opening width of the trawl net. To help correct this problem, the bridles were shortened from the standard length of 55 m to 28 m. The shorter bridles were used for the remainder of the experiment.

All crab were removed from each catch and sorted into two groups: mature females, which were recognized by the presence of an enlarged abdomen, and all other crab. For simplicity, we will refer to the group "all other crab" as "mixed sexes." Carapace width, to the nearest 1 mm, was measured with vernier calipers on all individuals. On some hauls, randomly selected male Tanner crab were subsequently removed from the mixed sexes baskets and measured for both carapace width and chela height (right hand side) to allow determination of morphometric maturity.

Estimating net efficiency

Net efficiency (E_n) typically is an increasing function of body size (Engås and Godø, 1989; Walsh, 1992). To provide more flexibility, however, we mod-

eled the relationship between net efficiency and carapace width as a function of two width-dependent processes: the probability of entering the net at the footrope (P_f) and the probability of entering the net through the belly mesh after escaping under the footrope (P_b). Algebraically this relationship can be expressed as

$$E_n = P_f + (1 - P_f)P_b \quad (1)$$

The probability of entering the trawl at the footrope, was described with a three-parameter logistic function:

$$P_f = \frac{a}{1 + be^{(-cw)}}, \quad (2)$$

where a , b , and c = parameters; and w = carapace width.

This function was chosen because it provides predicted values of P_f that increase with w asymptotically to a value of a and permits cases where efficiency is less than unity even at the largest body sizes. The probability of entering the trawl through the belly mesh was described by a two-parameter decreasing logistic function:

$$P_b = 1 - \frac{1}{1 + de^{(-fw)}}, \quad (3)$$

where d and f = parameters.

This function was chosen because it provides predicted values of P_b that decrease with w asymptotically to a value of zero.

The model resulting from substituting Equations 2 and 3 into Equation 1 was fitted to values of net efficiency for each 1-mm increment of carapace width by using a maximum likelihood procedure where the number of crab captured in the trawl net at each carapace width was described by a binomial random variable (Millar, 1992). The parameters of the model were estimated by minimizing the negative logarithm of the likelihood function:

$$L = - \sum_w (n_w \log E_{n,w} + (N_w - n_w) \log(1 - E_{n,w})), \quad (4)$$

where, at each value of carapace width w ,

- n_w = the number of crab captured in the trawl net;
- N_w = the total number of crab in the trawl and auxiliary nets combined; and
- $E_{n,w}$ = the net efficiency.

N_w and n_w were calculated by pooling together the data from all good tows. For mature female crab, a simplified model consisting of only the P_f term was fitted to data because the smallest mature females were too large to fit through the belly meshes of the trawl net. In both cases, the models were fitted to the data by using the S+ function MS (Venables and Ripley, 1994).

The 95% confidence intervals for $E_{n,w}$ were estimated by using a bootstrap analysis (Efron and Tibshirani, 1993) which considered between-haul variability but ignored within-haul binomial variability which is relatively small. Each bootstrap estimate of $E_{n,w}$ was calculated by randomly sampling individual hauls with replacement from the original data, then by fitting the model to the data from the chosen hauls pooled together. After replicating the bootstrap process 240 times, values of $E_{n,w}$ at each increment of carapace width were then ranked. The upper and lower confidence intervals were chosen as the values of $E_{n,w}$ ranked 7th and 234th at each width increment.

Two tests of model form were conducted. First, to determine if the P_b term was a significant contribution to the model, the goodness of fit of the model, including both the P_f and P_b terms (five parameters), was compared to that of a model including only the P_f term (three parameters) by using a likelihood ratio test (pages 153–155 in Hilborn and Mangel, 1997). Second, to determine if the models for mixed sexes differed between crab species, the summed likelihoods of the model fit to each species were compared with the likelihood from a model fitted to the combined data for both species by using a likelihood ratio test. For both tests, significance of the likelihood ratio was evaluated by using a chi square statistic with degrees of freedom equal to the difference in parameters between the models being tested (Hilborn and Mangel, 1997).

In addition to the tests on model form, two tests were also conducted for differences in net efficiency between biological subgroups of Tanner crab. First, a test was conducted to determine whether net efficiency differs between mature females and mixed sexes restricted to the same range of carapace width as mature females. Because of the restricted range of carapace widths, we assumed that net efficiency could be modeled as a simple logistic function of carapace width and sex. This model was fitted by using the S+ function GLM (Venables and Ripley, 1994). Second, a test was conducted to determine whether net efficiency for mature male Tanner crab differed from that for immature male Tanner crab of equal size. Male crab were categorized as either immature or mature on the basis of height of their chela in relation to their carapace width by using the computer

technique of Somerton (1980). Both categories were then restricted to a common range of carapace width that was spanned by the smallest mature and the largest immature individuals. Net efficiency was then modeled as a function of maturity and carapace width by using logistic regression. Significance of the sex term in the first test and the maturity term in the second test were assessed with analysis of deviance (page 186 in Venables and Ripley, 1994). When a term was significant, the resulting model was evaluated to predict net efficiency for each biological class at the midpoint of the carapace width interval examined.

Results

Effect of the auxiliary net on trawl performance

The attachment of the auxiliary net to the trawl net resulted in a decrease in wing spread, presumably from increased drag on the bottom. During the testing phase when the codends of both the trawl and auxiliary nets remained open, average wing spread for hauls with standard 55-m bridles was 14.3 m ($n=3$), considerably less than the mean width of the standard net (mean=17.0, $n=29$) used during the preceding survey hauls with the same length of towing cable. To help compensate for the additional drag of the auxiliary net, we shortened the bridles to 28 m. This increased average wing spread to 15.4 m ($n=4$). When the codends were closed, however, the auxiliary net rapidly filled with epibenthic fauna, especially brittlestars, resulting in a progressive narrowing of the wing spread by as much as 3 m over the duration of a haul. After seven attempts at trawling in the initial study area, we were forced to locate a new study area with a lower abundance of brittlestars. The progressive narrowing was nearly eliminated by the change of sampling site, but the mean wing spread during the remainder of the experimental hauls (mean=15.9, $n=24$) was still significantly less (t -test, $t=5.18$, $P<0.001$) than the standard net.

Although the wing spread was less during the experiment than during the AFSC survey, the departure from the standard width may not have been great enough to affect footrope contact with the bottom. Footrope contact at the center of the trawl was evaluated by using a video camera for three tows of the standard trawl (mean width=17.5 m), three tows of the experimental trawl with standard bridles (mean width=14.3 m), and three tows of the experimental trawl with short bridles (mean width=15.3 m). In all cases, the footrope in the bosom of the trawl did not contact the bottom, as evidenced by the lack of mud clouds behind the footrope, but instead

skimmed over the bottom at an estimated height of 1–2 cm. No difference in the proximity of the footrope to the bottom could be visually detected among the three trawl configurations. Because the range in wing spread among the three configurations was greater than the difference between the survey average and the experiment average, it is likely that the addition of the auxiliary net did not alter the contact of the footrope in the center of the trawl where most of the escapement usually occurs (Walsh, 1992).

Description of the data

Thirty-one hauls of the experimental trawl were completed, but the data from the first seven were not used in subsequent analysis because of unusual trawl performance (the narrowing of wing spread associated with large catches of epibenthic fauna in the auxiliary net). For snow crab, width measurements were collected from 3458 individuals from the mixed sexes category, but from only three individuals from the mature female category. The low sample size for mature females prevented further analysis. Carapace-width frequency distributions indicated that a broad range of carapace widths was sampled, but the observations were concentrated in three carapace width modes (Fig. 2). For Tanner crab, width measurements were collected from 3487 individuals from the mixed sexes category, and from 579 individuals from the mature female category. Sampling for both categories covered a broad range of carapace widths, but for the mixed sexes category the observations were concentrated at smaller carapace widths. Plots of net efficiency against carapace width (Fig. 3) for the mixed sexes groups of both species showed an initial decline with increasing width until a minimum in net efficiency was reached in the range of 40–50 mm, then a steady increase as carapace width increased. For mature female Tanner crab, the narrow range of carapace widths and the large variance in net efficiency obscured any obvious change in net efficiency with carapace width (Fig. 3).

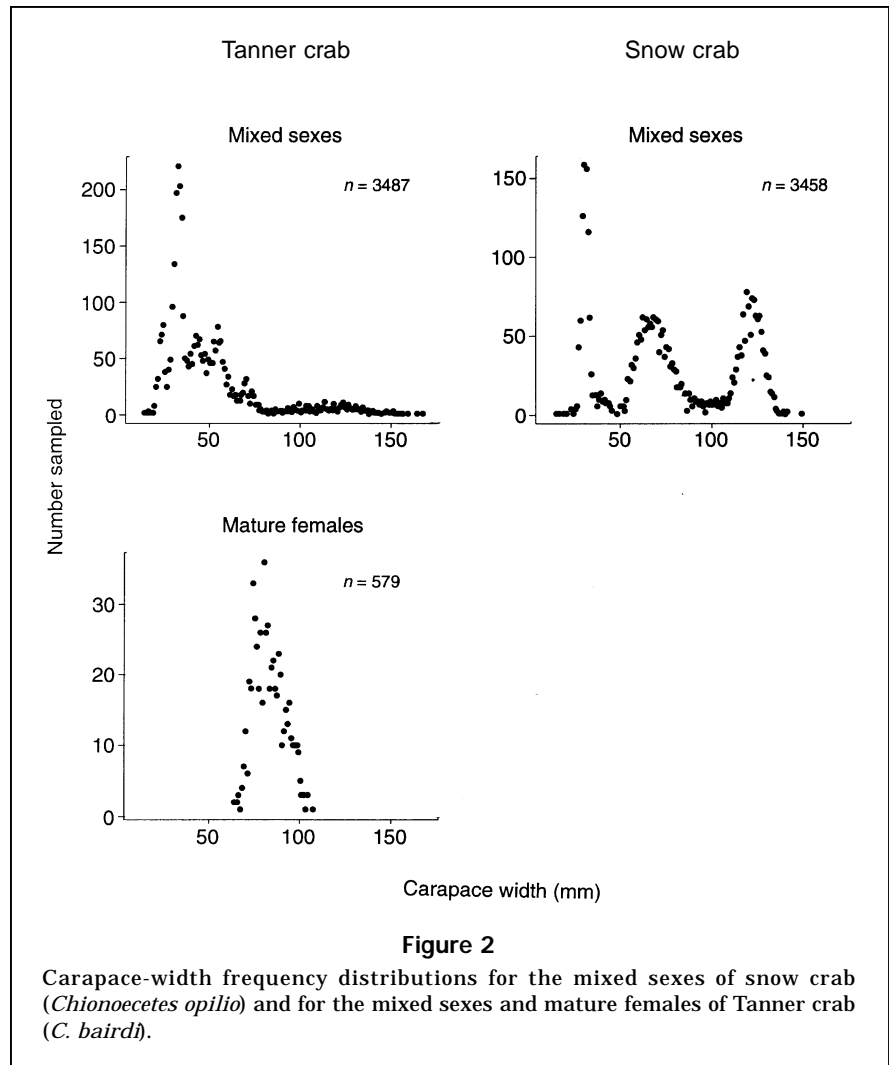


Figure 2

Carapace-width frequency distributions for the mixed sexes of snow crab (*Chionoecetes opilio*) and for the mixed sexes and mature females of Tanner crab (*C. bairdi*).

The fitted models

For the mixed-sexes category of both species, the models that included both the P_f and P_b terms fitted the data significantly better than the models with only the P_f term (Tanner crab, likelihood ratio=189.7, $P<0.001$; snow crab, likelihood ratio=60.5, $P<0.001$). This indicates that the apparent increase in net efficiency at small sizes is statistically detectable. Likewise, the separate-species model fitted the net efficiency data significantly better than did the combined species model (likelihood ratio=85.5, $P<0.001$). This indicates that the change in net efficiency with width differs between species. Plots of the fitted models (Fig. 3) indicated that the predicted values of P_b decline rapidly with increasing carapace width and become negligible at about 50 mm for Tanner crab and 60 mm for snow crab. For mature female Tanner crab, the model considering only the P_f term fitted the data significantly better than did the sample mean (likeli-

hood ratio=4.27, $P=0.014$), indicating that net efficiency increased significantly over the narrow width range of mature females (66–107 mm). Estimated parameter values for the fitted models are shown in Table 1.

For male Tanner crab, net efficiency for mature males (0.82, $n=99$) was not significantly different (analysis of deviance, $P=0.47$) than for immature males (0.81, $n=39$) at the center of the width interval spanned by the largest immature and the smallest mature individuals. This indicates that mature males are not preferentially selected by the survey trawl. For mature female Tanner crab, net efficiency (0.47, $n=578$) was significantly different (analysis of deviance, $P<0.001$) than the value for the mixed-sex group (0.72, $n=441$) at the midpoint of the mature female size range. This finding indicates that net efficiency was substantially less for mature females than for the mixed-sexes category (combined sexes excluding mature females).

Discussion

Experimental trawl performance

Net efficiency estimates from auxiliary net experiments are potentially subject to two sources of bias. First, bias may result if the efficiency of the experimental trawl differs from that of the standard trawl. Of particular concern is any distortion of trawl geometry caused by the auxiliary net that changes the position of the footrope and fishing line in relation to the bottom. In our case, trawl net width was reduced by the increased drag of the auxiliary net. We attempted to compensate for this increased drag by reducing the bridles to one half of their standard length, but the resulting trawl net width was still approximately one meter less than the standard. The decreased trawl net width, however, apparently did not alter the proximity of the footrope to the bottom

because our video observations did not reveal any conspicuous differences between the standard and experimental trawls. Although these observations were confined to the center of the footrope, previous video observations of the 83-112 trawl indicated that the center of the footrope tends to have lighter bottom contact than the wings and is therefore the area most likely to be impacted by the auxiliary net.

Second, bias may result if the experimental trawl cannot sample all habitats sampled by the standard trawl. To be effective, the footrope of an auxiliary net must fish harder on the bottom than the footrope of a trawl net. Consequently, the auxiliary net is more prone to damage from snagging on rocks and from filling with epibenthos and debris. Although, in our case, the chain footrope on the auxiliary net may have been effective at excavating buried crab, it also resulted in large catches of epibenthic fauna which, in turn, aggravated the problem of narrowed trawl width. We reduced the narrowing by moving the experiment to a location lacking high quantities of epibenthos, but by doing so we

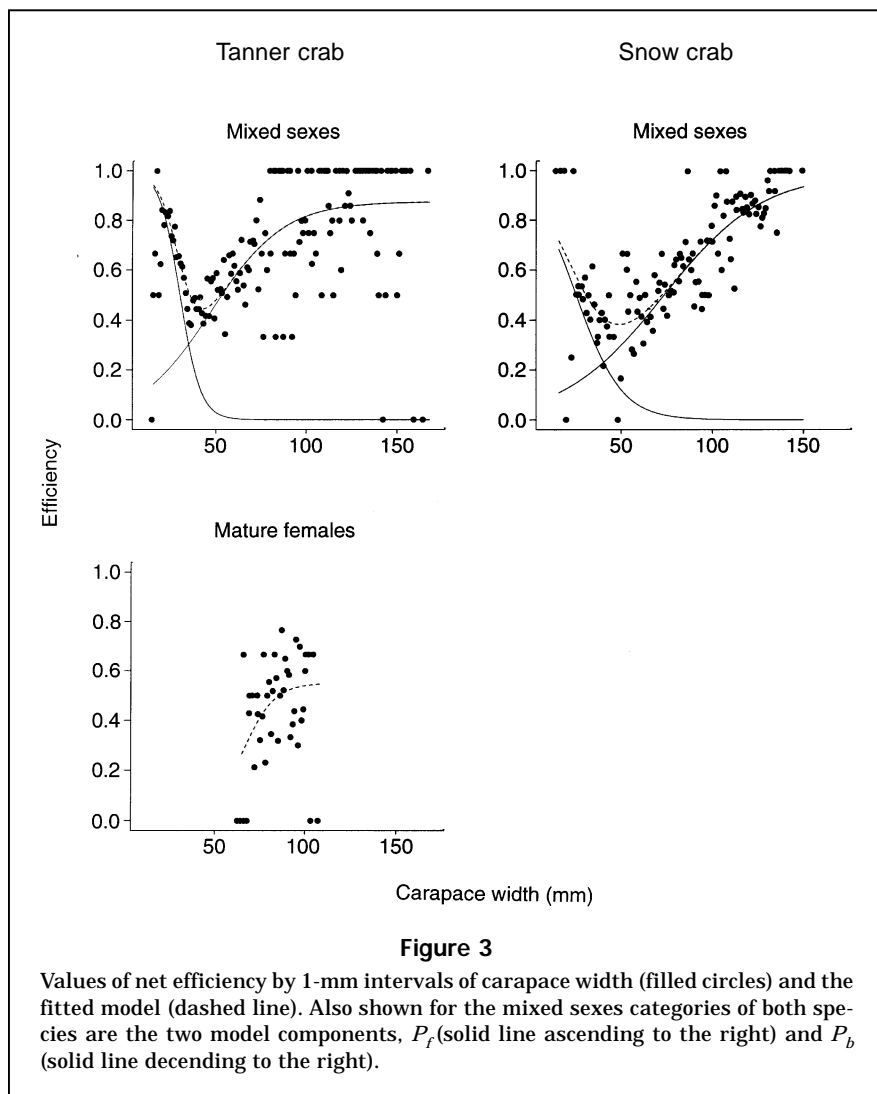


Figure 3

Values of net efficiency by 1-mm intervals of carapace width (filled circles) and the fitted model (dashed line). Also shown for the mixed sexes categories of both species are the two model components, P_f (solid line ascending to the right) and P_b (solid line descending to the right).

Table 1

Parameter estimates of the fitted models for the mixed sexes of snow crab (*Chionoecetes opilio*) and the mixed sexes and mature female categories of Tanner crab (*C. bairdi*).

Parameter estimates	Snow crab mixed sexes	Tanner crab mixed sexes	Tanner crab mature females
<i>a</i>	0.9894	0.8743	0.5500
<i>b</i>	14.49	10.95	2003.0
<i>c</i>	0.0366	0.0504	0.116
<i>d</i>	7.905	185.9	
<i>f</i>	0.0810	0.1742	

excluded from consideration a type of habitat occupied by snow and Tanner crabs. Thus the net efficiency estimates we obtained may not be representative of the entire area covered by the survey.

Model form

The form of the model that we chose to describe the relation between net efficiency and carapace width included a term (P_f) that increases with width to account for entry into the trawl over the footrope and another term (P_b) that decreases with width to account for entry of crabs through the belly meshes of the trawl after they have passed under the footrope. The model with both P_f and P_b terms fitted the mixed-sexes data of both species significantly better than the model with only a P_f term, confirming the significance of the apparent increase in net efficiency with decreasing size at carapace widths less than 50 mm. However, we have been unable to verify that the increased efficiency is indeed due to the entry of small crab through the belly meshes. Regardless of the mechanism, the important question is whether the increase in net efficiency at small size is a normal property of the 83-112 trawl or an artifact of the experiment. We attempted to answer this question by comparing the width distributions of crab captured in the trawl net of the experimental trawl with those captured in the standard trawl at the same or nearby stations during the survey preceding the experiment, but patchiness and small sample sizes made the results equivocal.

In light of this uncertainty, the composite form of the model is advantageous because it allows separation of the P_f and P_b effects. For example, if further research reveals that the increase in efficiency at small size is associated with the attachment of the auxiliary trawl, then an estimate of net efficiency without this effect can be obtained by deleting the P_b term and by evaluating the reduced model with the parameters from the fit of the complete model

(Table 1). For this reason, the bootstrapped confidence intervals we provide (Fig. 4) are computed two ways, by evaluating the full model and by fitting the full model but evaluating only the P_f term. However, because the P_b term decreases rapidly with carapace width, the full and reduced models predict nearly identical values of net efficiency at carapace widths above 50–60 mm, which includes the mature and commercial width ranges for both species.

Efficiency differences between biological subgroups

The survey trawl is less efficient for mature female Tanner crab than for the mixed-sexes group over the same range of carapace width. Since the mixed-sexes group is primarily male at these sizes, the difference in efficiency is likely due to between sex differences in both morphological features and behavior. Male Tanner crab have longer legs, in relation to their carapace width, than do mature females. Not only does this increase their effective size in relation to the trawl mesh but also may result in their bodies being held higher off the bottom in relation to the footrope. In addition, male Tanner crab may be caught more efficiently because they are less sedentary than females and less prone to bury themselves.⁴

The survey trawl efficiency does not differ between mature and immature male Tanner crab. We were concerned that mature males, which have larger claws and are perhaps more active than immature males, might be preferentially selected. If such selection did occur, it would lead to an underestimate of the carapace width at maturity which is used in establishing minimum width limits for the commercial fishery. Apparently such preferential selection of mature males does not occur.

In the foregoing, we estimated values of net efficiency or the capture probability of crab that occur between the wing-tips of the trawl net. For stock assessment purposes, however, it may be more convenient to consider these values expressed as trawl efficiency or the capture probability of crab that occur between the trawl doors. In situations where the bridles herd animals into the path of the trawl, further experiments to estimate sweep efficiency would be required to estimate trawl efficiency (Dickson, 1993a, 1993b). However, experiments on herding snow crab indicate that this species is not herded by the bridles of the 83-112 eastern trawl.² Thus, trawl efficiency can be estimated simply by multiplying net efficiency by the quotient of the net width divided by the door width (i.e. 0.30).²

⁴ Stevens, B. 1998. Kodiak Laboratory, National Marine Fisheries, P.O. Box 1638, Kodiak, AK. Personal commun.

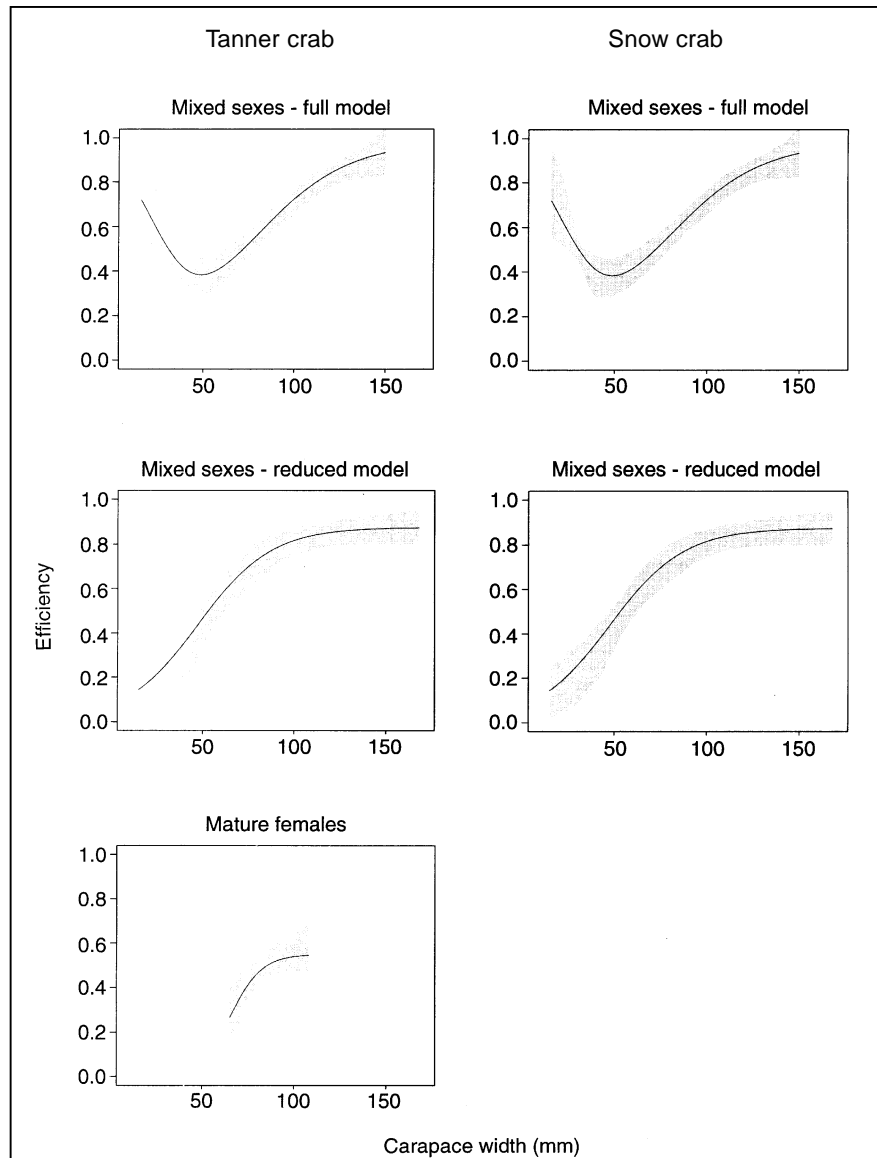


Figure 4

Fitted model and 95% bootstrap confidence intervals about the predicted value of net efficiency. For the mixed-sexes categories of both crab species, values of net efficiency are predicted in two distinct ways after fitting the full model (Equation 1) to the data. First, net efficiency was predicted by evaluating both P_f and P_b terms of the model (top row), based on the assumption that the entry of small crabs into the trawl net through the belly mesh occurs during normal trawl operations. Second, net efficiency was predicted by evaluating only the P_f term (i.e. setting $P_b=0$), based on the assumption that the entry of small crab through the belly mesh was an experimental artifact caused by adding the auxiliary trawl (second row).

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